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# Reliability modeling and data analysis of vacuum circuit breaker subject to random shocks

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*Abstract*—The electrical substation components are often subject to degradation due to over-voltage or over-current, caused by a short circuit or a lightning. A particular interest is given to the circuit breaker, regarding the importance of its function and its dangerous failure. This component degrades gradually due to the use, and it is also subject to the shock process resulted from the stress of isolating the fault when a short circuit occurs in the system. In this paper, based on failure mechanisms developments, the wear out of the circuit breaker contacts is modeled. The aim of this work is to evaluate its reliability and consequently its residual lifetime. The shock process is based on two random variables such as: the arrival of shocks and their magnitudes. The arrival of shocks was modeled using homogeneous Poisson process (HPP). By simulation, the dates of short-circuit arrivals were generated accompanied with their magnitudes. The same principle of simulation is applied to the amount of cumulative wear out contacts. The objective reached is to find the formulation of the wear function depending on the number of solicitations of the circuit breaker.

*Keywords*—reliability, short-circuit, models of shocks.

## I. Introduction

MEDIUM voltage substation components are often subject to degradation due to over-voltage or over-current, caused by a short circuit or a lightning. Vacuum circuit breaker (VCB) is a switching devise which can open or close a circuit in small fraction of second. This is achieved due to its separable contacts. The closing and opening of a circuit allows to establish or to interrupt the circulation of current through the circuit under usual or unusual working conditions, such as short circuit [1]. It has some special characteristics compared to the ordinary systems. For example, VCB is suffered erosion and such phenomena degraded system gradually with time as increasing resistance and wear out of its contacts [2, 3].

In electrical systems, shocks are often highlighted by the occurrence of short circuits. These are characterized by their frequency and amplitude of current for each short-circuits established [4]. They are often harmful and can destroy various systems and therefore the probability of survival under the shocks is of the main interest in the field of reliability theory [4].

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M. Finkelstein, F. Marais distinguishe between two major types; cumulative shock models (systems break down because of a cumulative effect) and extreme shock models (systems break down because of one single 'large' shock) [5]. The combined model when the failure is due to both causes is also studied by J. Cha, M. Finkelstein [6].

In this paper we study the case of vacuum circuit breaker reliability of two departures medium voltage (MV) of Amizour and Bejaia (Algeria) cities using the shocks processes. A brief overview of failure mechanism and shock models VCB contacts are given to justify the importance of degradation [7, 8]. Regarding its design and its function, the VCB is a component of choice to highlight the degradation modeling of the system which is presented in this article. The last section is concerned by data analysis, reliability analysis and simulation of data collected in rural industry.

### A. Failure mechanisms of circuit breaker contacts

The contacts of circuit breaker are susceptible to dangerous failures (i.e., those that would make the safety instrumented function unavailable). The main reasons for contact failure are:

- High contact resistance
- Contact erosion (mechanical wear from making and breaking)
- Contacts welding together

*1) The contact resistance:* When contacts are at rest, and current is passing, the actual areas which conduct the current are only a small proportion of the total contact surface. The parts of the surfaces touching each other may be metallic and conducting, or may be non-conducting due to surface films or particles. The area in electrical contact depends on the force with which the contacts are pressed together. This is the reason why the contact resistance of a joint is usually very much greater than the bulk resistance of the metal itself, and why the contact resistance is more dependent on the force between the contacts and the condition of the surface, than on the size of the contacts. The relation between contact "constriction" resistance, contact hardness, resistivity, and contact force is given by:

$$R_{S_0} = \sqrt{\frac{\pi H}{F_e}} \times \frac{\rho_0}{2} \tag{1}$$

*2) Erosion and wear contacts:* As two contacts carrying current separate, the current becomes progressively concentrated over a diminishing area. As the last points separate, the current density is sufficient to cause local melting and the formation of a molten bridge across the contacts. This subsequently bursts and an arc is established. The arc causes erosion on the arc spots of each contact, and metal transfer occurs due to the polarity of the contacts, with an evaporation coefficient given by:

$$K^{'} = 0.5 \times 10^2 \ \frac{U_{am}}{\sqrt{H}} A^3 \tag{2}$$

Where A is the ratio between the atomic mass and density. Mechanically, wear contacts can be due to the movement and friction of the contacts and electrically due to the arc effect (mainly the make-break contact). Contact wear directly affects the contact resistance and makes it increase dramatically if the wear is in an advanced state.

*3) Welding:* Welding of contacts can arise in two ways. Firstly ”dynamic welding” may happen when contacts bounce as they close under load. The arc thus generated produces pools of molten metal at the arc spots, and these coalesce to form a welded area when the contacts close finally.

### B. Shock and degradation modeling

The arrival of shocks was modeled using homogeneous Poisson process (HPP), and the degradation of VCB contacts is considered as slow degradation process.

*1) Model of shock:* Suppose a device subject to shocks. These are controlled by a counting process $N(t)$=$\{N(t); t \geq 0\}$ each shock causes damage $D_i$. When the cumulative damage $\sum_{i \leq N(t)} D_i$ exceeds a critical threshold $x$; the equipment is failed. The probability that the device works without fail in [0, t] is $R(t)$ as:

$$R(t) = \sum_{k=0}^{\infty} P(N(t) = k)\overline{P_k} \tag{3}$$

With: $P(N(t) = k)$ is the probability that the equipment has undergone exactly k shocks. $\overline{P_k}$: is the probability of surviving k shocks. The system fails when the amplitude of cumulative impacts from some given critical region. The representation of this model is:

$$\{X \leq t\} \Leftrightarrow \{\sum_{i=0}^{N(t)} A_i \in Z\}$$

Where: $X$ is the life of the system, $A_i$ is magnitude of the $i^{th}$ shock, $Z \in R$ is a critical region, and $N(t)$ is the number of shock occurred in the interval [0, t].

*2) Degradation modeling:* It is the case of the slow degradation model. The counting process is the arrival of shocks (Open-Close sequence) and the distribution of damage is the wear contacts. Wear contacts is a monotonic function of the amplitude of the short-circuit current (I) and the number of operating cycles (N). It is given by:

$$U(N) = \sum_{i=1}^{N} I_i^{\alpha} \simeq KNI^{\alpha} \tag{4}$$

The distribution of wear is the distribution of a sequence of random variables conditioned by shocks 1, 2 ... All these shocks are mutually exclusive and their union is the certain event. However, the total distribution of wear is given by:

$$F(u) = \sum_{N=0}^{\infty} F(u/N)P(N(t) = N) \tag{5}$$

### C. Application on two departures of MV EL Kseur substation

The arrival of short-circuit, the number of openings or closings and the amplitude of the current generated at each operation of the VCB, when the short-circuit occurs in the system are sufficient, to evaluate the reliability and the residual lifetime of the equipment.

*1) Statistical data:* The statistical processing of short-circuit was performed on both departures mentioned earlier. However, our study looks at the outset MV of Bejaia city; the same procedure is applied to Amizour’s departure.

1-1 *Failure rates*

Failure rate $\lambda$ is calculated from the data and damage incidents recorded over a period of one month. The failure rate of Bejaia’s MV departure is: $\lambda$ = Number of defects / number of days $\times$ 24hrs

$$\lambda = \frac{30}{30 \times 24}, \quad \lambda = 0.04[1/hrs]$$

The failure rate of Amizour’s MV departure:

$$\lambda = \frac{20}{30 \times 24}, \quad \lambda = 0.028[1/hrs]$$

1-2 *Validation of the exponential model*

The adjustment was done by considering the law of exponential distribution with parameter $\lambda$; the data used are the inter-arrival defects at 30kV MV departure to the Bejaia city. The period runs from first May to $30^{th}$ May.

The R which is both software and a language to implement the adjustment techniques with parametric laws, allowed us to validate the model obtained through the standard test of ”Kolmogorov Smirnov” adequacy. The results are presented in the following table:

| | |
|---|---|
| Equipement | Circuit Breaker |
| N | 30 |
| Adjusted Law | Exponential |
| Parameter | $\lambda$ =0.041 |
| $Dk_s$ | 0.1491 |
| d(n,0.05) | 0.2409 |
| Decision | Don’t rejected |

*2) Reliability modeling:* The reliability of the circuit breaker is given as follows:

$$R(t) = \sum_{k=0}^{\infty} P(N(t) = N)F(U)^{(N)} \tag{6}$$

With

$$F(u) = \sum_{j=0}^{\infty} F(u/j)P(N(t) = j) \tag{7}$$

Where:$P(N(t) = N)$ :the probability of having $N$ open-Close sequence in at time t,$F(U)^{(N)}$ is the probability of failure of the circuit breaker subject to a cumulative shocks of

"$N$" open-Close sequences, where $U$ is the cumulative wear. The arrival of shocks is modeled as homogeneous Poisson process with constant rate $\lambda$ and density of probability:

$$exp(-\lambda t)\frac{(\lambda t)^k}{k!} \tag{8}$$

When the short-circuit occur, a random number of openings are ranging from 1 to 4; it is therefore assumed that the operation cycles at each defect follows a discrete uniform distribution,$U_D(0,4)$.
Let; $N(t)$ is a number open-close sequence at time $t$; $t_k$ is a time between the $k^{th}$ and $(k+1)^{th}$ failure;

$$P(N(t_k)=n)=\sum_{i=1}^{4}P(N(t_{k-1})=n-i)P_u(X=i)$$

And knowing

$$P(N(t_1)=n)=P_u(X=n)$$

This yields the following recursive formula:

$$P(N(t_k)=n)=\sum_{i_k=1}^{4}[\sum_{i_{k-1}=1}^{4}...(\sum_{i=1}^{4}P(n-i_k-i_{k-1}-...$$
$$...-i_2)P(i_2))...P(i_{k-1})]P(i_k)$$

The existing expression $P(N(t_k)=n)$ is complex to calculate, the evaluating reliability of the circuit breaker in our case is difficult. So to solve the problem, we proceed by fits functions obtained by simulation.

*3) Simulation data in MATLAB:* In our study, we need the following information:

- Opening dates (VCB operation);
- Accumulated interrupted short circuit current;
- Cumulative wear generated for each operating cycles (one operating cycle is defined as an Open-Close sequence).

3-1 *Simulation of opening dates*

After statistical study on real data, we have inferred that the arrival of short-circuit is a homogeneous Poisson process of rate $\lambda$, and that the open-Close sequences follow a discrete uniform parameter $a=0$ and $b=4$ at each defect. So we study the random variable $X$ such that:
$X_i$ = {period between $k$ default $D_{i-1}$ and $D_i$}
$Y_i$= {number of openings following a default}
Such that $P(Y=i)$=$\frac{1}{5}$ (5 events were possible) To generate the random variable $Y_i$, at first we generate the random variable $P$ follows the uniform U[0, 1].

3-2 *Short-circuits simulation*

The simplifying assumption made to simulate the values of short circuit currents associated with each opening dates is to consider the uniform law for the distribution of these values in an interval determined by observation of the data acquired in our sample. We therefore ask: $I \simeq U$ [200, 600], with $X$ is the random variable representing the effective value of the switched current and it is between 200A and 600A.

3-3 *Cumulative wear simulation*

For each opening (i) generated, we associate a stream of randomly generated short-circuit under the uniform distribution U[200,600] and the wear caused by the opening, so (i) will be calculated by simulating the following formula:

$$(i)=k\sum_{j=0}^{i}Courant(j) \tag{9}$$

Our simulation program is obviously done with MATLAB.

*4) Methodology:*

4-1 *Find the function N(t)*

$N(t)$ is the cumulative number of open-close sequences at the time "$t$"

$$N(t)=a_nt^n+a_{n-1}t^{n-1}+...+a_1t^1+a_0t^0+\varepsilon \tag{10}$$

$$N(t)=\begin{cases}N(t) & t\geq 0\\ 0 & t<0,\end{cases}$$

4-2 *Determining the relative wear function*

By setting $(S)$ the threshold value of circuit breaker failure, which represents the maximum number of shocks that can support, we will have:

$$U_r=\frac{U(N)}{U(S)} \tag{11}$$

$D$: Date of operation cycle;
$SCC$: Short circuit current;
$CW$: Cumulative wear;
$S$: Threshold of number of operation cycles.

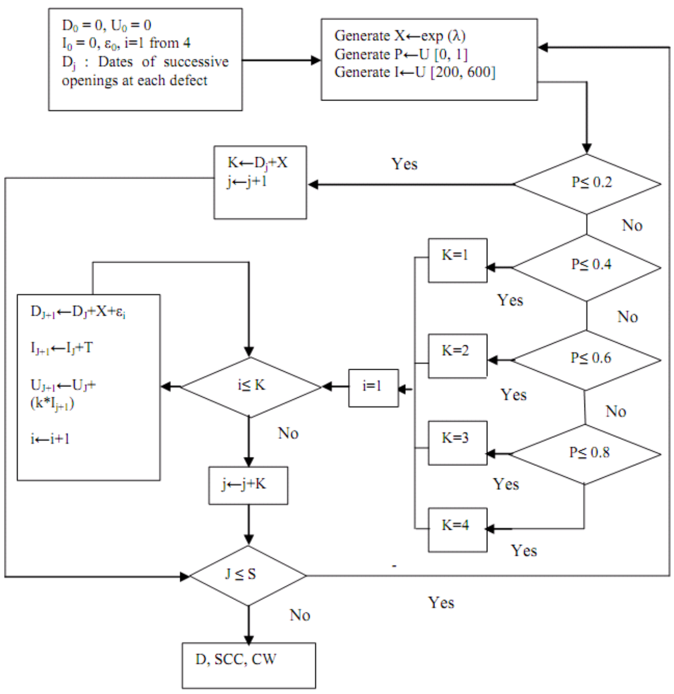


Fig. 1. Simulation program

$$U_r(N) = \begin{cases} U_r(N) & N \geq S \\ 0 & else, \end{cases}$$

The function represents the failure probability with N open-close sequences (shocks).

4-3 *Failure function*

The probability of failure before time (t) defined by the expression $D_T(t) = P(T \leq t)$ representing a composite function of $U_r(N)$ and $N(t)$;

$$D_T(t) = U_r \circ N(t) \tag{12}$$

$$U_r \circ N(t) = U_r(N(t))$$

With:

$$D_T(t) = \begin{cases} D_T(t) & t \geq 0 \\ 0 & else, \end{cases}$$

According to the failure function, we easily determine the reliability by applying the following formula:

$$R(t) = 1 - D_T(t) = P(T > t) \tag{13}$$

*5) Case Study Practice:* The application of the function `polyfit` on both $N$ and $T$ samples give a polynomial of degree "1" which corresponds to:

$$N(t) = a_1 t^1 + a_0 \tag{14}$$

Where the estimator gives the following values:

$$N(t) = \frac{4}{39} t$$

$$With \begin{cases} a_1 = \dfrac{4}{39} \\ a_0 \simeq 0 \end{cases}$$

The order of the polynomial wear function based on the number of operations $U(N)$ is "2" the form with the values of the coefficients given by:

$$\begin{cases} a_2 = 0.002 \\ a_1 \simeq 40.43 \\ a_0 \simeq 0 \end{cases}$$

Therefore:

$$U(N) = 0.002N^2 + 40.43N \tag{15}$$

The graph of the wear evolution with the number of openings is clarified through the figure (2).

*-Specific value $U'$*

$U'$ is the value of the wear for $N = S$ and we write: $U' = U(S)$.

$S$ is the threshold number of cycles at rated current $I_n$, is a data retrieved from the data sheet on the life of the MV circuit breaker studied. This is a threshold open-close sequences leading to mechanical wear of the VCB.

We have $S$ = 30000 operation cycles and thus:

$U'$=$U(S)$=3.013$\times$ $10^6$

It will therefore:

$$U_r(N) = \frac{U(N)}{U(S)} = \frac{0.002N^2 + 40.43N}{3.013 \times 10^6} \tag{16}$$

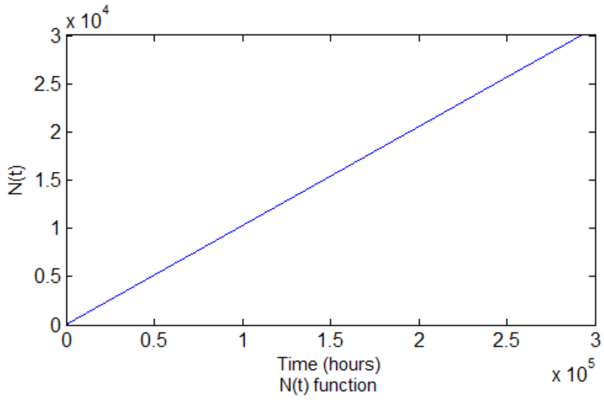


Fig. 2. Number of open-close sequences.

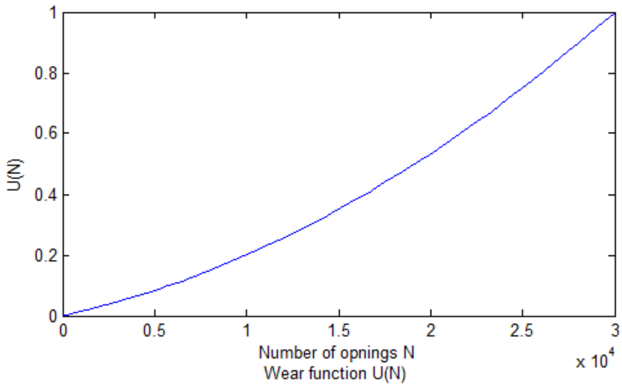


Fig. 3. wear contacts based on the number of openings.

The failure function in our case is equal:

$$D_T(t) = \frac{0.002(\frac{4}{39}t)^2 + 40.43(\frac{4}{39}t)}{3.013 \times 10^6} \tag{17}$$

The reliability function is:

$$R(t) = 1 - D_T(t) = 1 - (\frac{0.002(\frac{4}{39}t)^2 + 40.43(\frac{4}{39}t)}{3.013 \times 10^6}) \tag{18}$$

The failure and reliability functions are illustrated in the figures (4) and (5).

The figure (5) illustrates the simulation result of MV circuit-breaker of bejaia departure, and it fails from time t = 293480 hours, or lasting about 34 years.

- Results of Amizour MV departure:

Using the same methodology for the case of departure Amizour, we obtained the following results:

$$D_T(t) = \frac{39.1N(0.07t)}{1.173 \times 10^6} \tag{19}$$

And

$$R(t) = 1 - D_T(t) = 1 - (\frac{39.1N(0.07t)}{1.173 \times 10^6}) \tag{20}$$

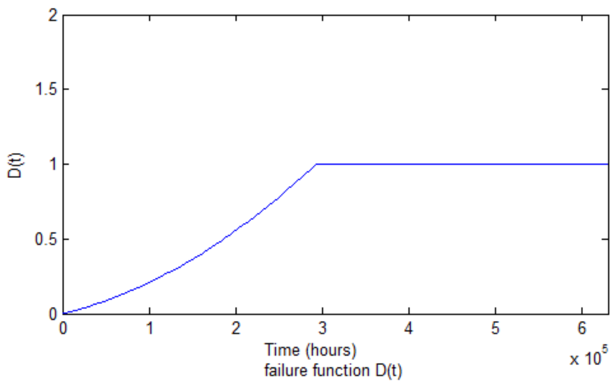


Fig. 4. Failure function.

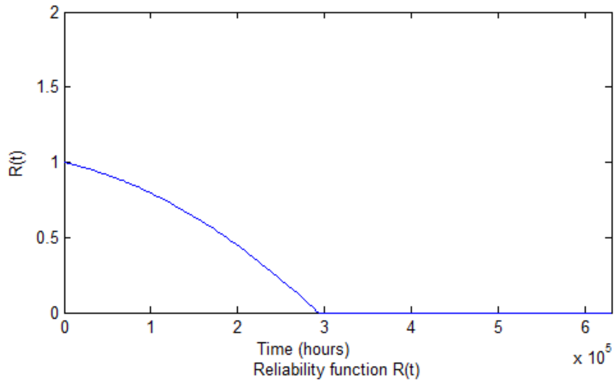


Fig. 5. Reliability function

The curves of the failure and reliability functions are respectively given in Figures (6) and (7):

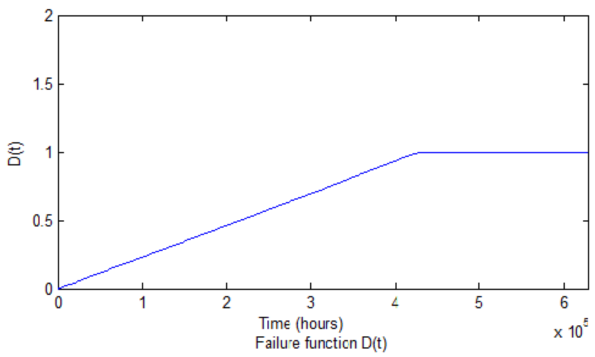


Fig. 6. Failure function.

The figure (7) illustrates the simulation result of MV circuit-breaker of Amizour's departure, and it fails from time t = 423360 hours, or lasting about 49 years.

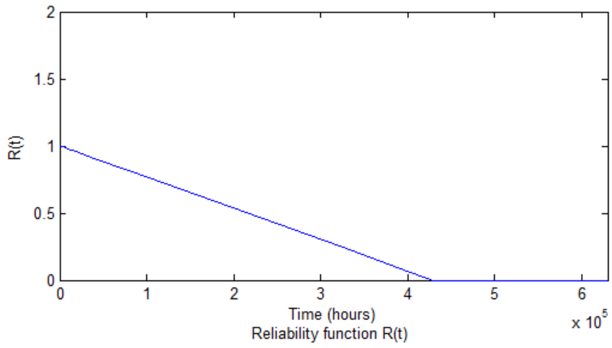


Fig. 7. Reliability function

## II. Conclusion

This paper has presented the reliability modeling of electrical degraded system regarding substation components. A special attention is made for vacuum circuit breaker behavior under shock processes. The contact is a crucial component in power circuit breakers and an increase in its Wear can cause the failure of the breaker. This work has followed this logic, and deals exhaustively with using mathematical tools related to the reliability of electrical systems, and knowing the classical degradation model of equipment subject to a cumulative impact, a new model of shock based on the statistical treatment of data collected in El-Kseur (Bejaia, Algeria) substation has been established. This model is difficult to solve in a theoretical way; the simulation has been an excellent alternative to solve the problem. The simulation results were discussed and demonstrated, where the reliability of the equipment and its residual lifetime have been determined in real functioning conditions.

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