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Reliability-Based Preventive Maintenance of Oil Circuit Breaker subject to Competing Failure Processes

FAIROUZ IBERRAKEN[1], RAFIK MEDJOUDJ[1], RABAH MEDJOUDJ[1]*, DJAMIL AISSANI[2] and KLAUS DIETER HAIM[3]

[1]*Lamos Laboratory, Electrical Engineering Department, University of Bejaia, Algeria*

[2]*Lamos Laboratory, Operational Research Department, University of Bejaia, Algeria*

[3]*Applied Science of Technology, University of Zittau, Germany*

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Abstract: This paper investigates technical and organizational tools to improve performances of a multi-state degraded system subject to multiple competing failure processes. The competing failure processes treated in this paper are oil insulating aging and electrical contacts wear out of high voltage oil circuit breaker. To degradation processes, is associated random shocks process highlighted by the stresses due to short-circuit solicitations. To keep a high level of circuit breaker reliability, two policies are developed and cover reliability increasing of the downstream feeder and reliability based preventive maintenance of the item. The first policy is developed using technical and organizational measures, while the second policy is based on improvement factors method optimizing availability under threshold reliability and a maximum benefit. The results obtained using a case study allow the decision maker to reach better information, to target the equipment that reduces the performances of the system, and to practice suitable maintenance actions.

Keywords: *Shocks process, degradation modeling, reliability, preventive maintenance, electrical components*

1. Introduction

The use of degradation measures to assess reliability has seen some important findings in the literature and the binary assumption used to analyze, to model and to compute system reliability is relaxed [1]. The oil circuit breaker (OCB) is highly efficient and there is a significant number installed in today's electrical power grid, unless the preferred technology is the one developed following SF6 and vacuum breakers. Regarding its design and its function, it offers the possibility of implementing both degradation and shocks processes. The replacement of the OCB is considered unrealistic and prohibitive looking to the large life duration of the component (about 40 years) and its cost. To ensure a safety behavior until the end life of this item, energy utilities should perform maintenance. Therefore, in practice, before recording a maintenance action, it is useful to ensure its applicability which is the resultant of ease of implementation and effectiveness of its results. The novelty introduced in this paper is the adaptation of some maintenance policies often restricted to less complex than electrical systems, in the case of competing failure processes, such as: maintenance cost optimization based on equipment conditions under

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*corresponding author email: r.medjoudj66@gmail.com reliability threshold and, or maximum benefit constraints. The earliest theoretical investigations on competing failure processes were developed by Li and Pham [2]. The degradation modelling constitutes an efficient way to estimate full and residual lifetime distributions [3]. The case of oil circuit breaker reliability assessment considering both insulating oil aging and contacts wear out is studied in the present paper. It deals with degradation processes due to the use of the equipment and shocks process when it is triggered on the fault.

Shocks occur randomly in time as a stochastic process and cause a certain amount of damage to a system. This damage accumulates and gradually weakens the system. A system fails when the total damage has exceeded a failure level. For application, shocks data, corresponding to OCB operations were collected from 1999 to 2007, corresponding to 17 years of system a continuous operation at the national company of electricity and gas of Bejaia city district (Algeria). Reliability modelling and data analysis for the state probabilities assessment were introduced and discussed by Medjoudj *et al.* [4]. The authors have introduced two types of shocks which occur on the OCB when it is triggered from a defect, such as: cumulative and extreme shocks. The shocks arrive according to a counting process $\{N(t), t \geq 0\}$, and it is assumed that the random variable X , representing the annual number of shocks, follows either exponential $E(\lambda)$ or Weibull $W(\beta, \eta)$ distributions. The values of λ, β and η were determined by probability plotting and maximum likelihood estimation [5].

Following Li and Pham [2] theoretical investigations on the competing failure processes, we have developed two degradation processes for the OCB, corresponding to the aging of oil insulation and the wear out of electrical contacts. Both degradation processes have finite number of states and the transitions between states are governed by threshold values. For each process, we have defined degrading states where the system has a decreasing effectiveness and a degraded failure state where the system fails and need repair. The rest of the paper is organized as follows: A brief overview of failure mechanisms of electrical components under study is given in section 2. The reliability data analysis of a degraded system using experience feedback data is presented in section 3. The section 4 is concerned by reliability improvement aspects based on extrinsic and intrinsic reliability characteristics of the studied system. A particular interest is given to the application of a based-conditions maintenance policy to electrical system. Finally, the discussions and the conclusion of the research are dressed in section 5.

2. A Brief Overview of Failure Mechanisms in Electrical System under Study

A comprehensive failure mechanism development is needed and can allow to a practitioner of the considered system to understand the notion of competing failure processes and highlight their correlation with the operational reliability aspects. It is about the random shocks highlighted by short-circuits appearance (frequency and magnitudes) and the degradation phenomena (aging, wear out and sudden break) expressed by the behaviour of the components.

2.1 Bus Bar Insulated Supports Sudden Break

The term bus bar commonly replaces the term bus on heavy current circuits. Bus bars are used as distribution points for electrical power. There are two problems which are common to all types of bus bars, thermal and magnetic.

***Thermal*:** As ambient temperature and load current varies, a bus bar will heat up or cool down. This will cause considerable expansion and contraction. Sufficient stress may be placed on the support insulators to cause them to break. Any joints in a bus bar system, which become loose, will give rise to localized heating. In extreme cases, this heating can result in arcing and cause the bus bar to fail.

Magnetic**:** When current flows in a conductor, a magnetic flux is produced around the conductor. When current flows in two adjacent conductors the magnetic fluxes interact and produce attractive or repulsive forces. With normal load currents, these forces are small but under short-circuit conditions the forces can be very high and reach tones per meter length. Clearly, forces of this magnitude can distort conductors and break insulators [6].

2.2 Circuit Breaker Oil Aging

Circuit breakers are used to connect and disconnect transmission lines under normal conditions. They are also used to clear sections of a transmission grid should a short -circuit occur in the system, isolating the fault. Circuit breaker failures resulting in a fire or explosion are rare events, but have occurred frequently enough in the past to warrant concern. Fires in mineral oil typically occur due to the breakdown of liquid insulation within the equipment (caused by switching, lightning surges, or by gradual deterioration), low insulating oil level, moisture intrusion in the insulating oil, or by failure of an insulating bushing.

2.3 Electrical Contacts Wear

The electrical contact function plays a main and critical role in the breaker's proper operation. The high voltage circuit breaker has three major components:

a) Interrupting chamber, where the current conduction and interruption in the power circuit occurs. It is usually a closed volume containing the make-break contacts and an interrupting medium (compressed air, oil, SF6, vacuum, *etc*.) used for insulation and arc benching.

b) Operating mechanism, where the needed energy to close or to open the contacts and to quench the arc is initiated.

c) Control, where the orders to operate the breaker are generated and its status is monitored.

As mentioned earlier, the power current passes through the conducting material in the interrupting chamber. Various parts that are joined together form the conducting material and the different junctions form the electrical contacts. For an increasing temperature of the contacts, the material of the contacts may soften to the point where it will reduce the contact force, leading to a quick increase of the contact resistance. It has been proved that oxidation; wear, fretting, force and temperature directly affect the resistance value (in micro ohms) of the contacts.

In a recent publication [7], two failure types are distinguished and subdivided as dielectric and interruptions ones. Dielectric type of failures is internal bushing deterioration by oil leakage, moisture/tracking; water leakage into main tank; tracking or related deterioration of operating rod; loose and splitting joints and carbonization of the oil. However, Interruption type of failure is deteriorated arcing contacts or baffles chambers; evolving fault; binding mechanism; inoperative tank heaters; control malfunction including interlocks; operating without a full close cycle and pumping or related pilot valve failures.

It is well known that for every failure, the circuit breaker trips and the fault research is initiated and done manually. In some cases, the fault is not isolated and the circuit breaker is closed negatively, therefore it is subject to additional electrodynamics efforts. For the statistical considerations, the number of shocks is defined as the total number of operations. Failure research procedure is largely developed in reference [8], where the number of operations in fault tracking procedure is exposed associated with time of each stage.

3. Reliability Modelling and Data Analysis

Traditionally, electrical system reliability is perceived as a set of objectives to attempt, fixed a priori and could be expressed as follows: reliability parameters (failure rate, repair rate and maintenance rate), mean durations (MUT, MDT and MTBF) and mean frequencies of scheduled or forced outages. To highlight the reliability indices improvement, it is useful to assess them for the current state of the system and then propose tools. By exploiting results gathered in table 1 showing the indices cited above, it is stated that the circuit breaker minimal tripping (shocks) corresponds to the failure frequency FF (1/year) = 10.995 of the downstream feeder.

Table 1: Components and Sub-system Reliability Indices for the Current State

Component or sub-system	MUT (hours)	MDT (hours)	MTBF (hours)	A	FF (1/year)
MV/LV Transformer	4256.08	5.49	4261.57	0.9987	2.0527
Underground cable	5226.30	19.84	5246.10	0.9962	1.6656
Overhead line	1177.28	3.64	1182.06	0.9969	7.2770
Feeder	792.05	5.08	796.75	0.9873	10.995

To improve system performances, technical and organizational measures are considered during system planning and operation phases, such as:

- Intensification of maintenance operations to reduce the number of failures;
- Addition of remote control switches on outgoing MV lines to restore quickly power supply and to limit the geographical area affected by failures;
- Automation of failure research using faults detectors;
- Undergrounding overhead circuits and aging equipment replacement.

As shown in Table 1, the great part of failures appears in overhead circuits. At this stage of the investigation, the results comforts the decisions of undergrounding the overhead circuits and the removing out of the oldest sections by taking into account the economic balance between the desired reliability level and its cost [9]. For the case studied, the implementation of the above actions has reduced the occurrence frequency of shocks for about 50%. The reliability indices are improved and a special attention is given to the failure frequency of the feeder which becomes FF=6.1372 (1/year).

4. Oil Circuit Breaker Preventive Maintenance

4.1 Expert Judgments Review

Oil circuit breakers perform the same function in switchgear assemblies as air circuit breakers; they are quite different in appearance and mechanical construction. The principal insulating medium is oil rather than air. The oil, in addition to providing insulation, acts as an arc extinguishing medium in current interrupters. In this process, it absorbs arc products and experiences some decomposition in the process. Thus, maintenance of the oil is of great importance. Oil maintenance involves detection and correction of any condition that would lower its quality. The principal contaminants are moisture, carbon, and sludge. Moisture will appear as droplets on horizontal members, while free water will accumulate in the bottom of the tank. Sludge caused by oxidation will appear as a milky translucent substance. Carbon initially appears as a black trace.

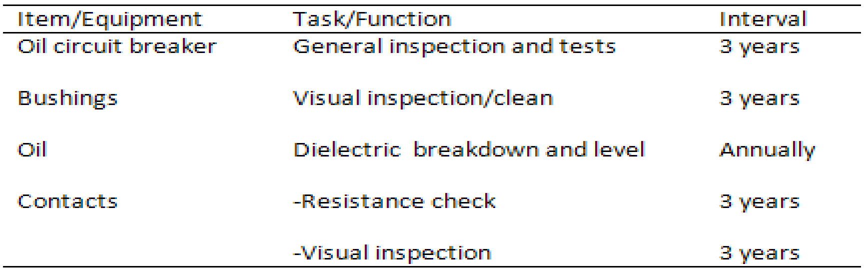
It eventually will disperse and go into suspension, causing the oil to darken. A dielectric breakdown test is a positive method of determining the insulating value of the oil. Samples can be taken and tested as covered in ASTM D 877, Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes. Oil that tests too low should be immediately reconditioned and retested or replaced with new oil. Oil should be tested periodically or following a fault interruption. In replacing the oil, only the oil recommended by the manufacturer should be used and it should have been stored in sealed containers. In addition, the oil should be given a dielectric breakdown test immediately prior to use. An oil pump or other means should be used to avoid aeration. In the event entrapment of air cannot be avoided, the entrapped air should be removed by application of vacuum or the equipment should be allowed to stand for 8 to 12 hours prior to being energized.

The main contacts of an oil circuit breaker are not readily accessible for routine inspection. Contact resistance should be measured. Contact engagement can be measured by measuring the travel of the lift rod from the start of contact opening to the point where contacts separate as indicated by an ohmmeter. More extensive maintenance on main contacts might require removal of the oil and lowering the tank and should therefore be performed less frequently than routine maintenance. The frequency should be determined by the severity of the breaker duty such as the number of operations and operating current levels.

Any time the breaker has interrupted a fault current at or near its maximum rating, this type of maintenance should be performed. The contacts should be inspected for erosion or pitting. Contact pressures and alignment should be checked. All bolted connections and contact springs should be inspected for looseness.

Arc-quenching assemblies should be inspected for carbon deposits or other surface contamination in the areas of arc interruption. If cleaning of these surfaces is necessary, manufacturers' instructions should be followed. The committee on electrical equipment maintenance suggested the following the plan dressed in Table 2.

Table 2: Initial Guidelines for Maintenance Actions



Item/Equipment	Task/Function	Interval
Oil circuit breaker	General inspection and tests	3 years
Bushings	Visual inspection/clean	3 years
Oil	Dielectric breakdown and level	Annually
Contacts	-Resistance check	3 years
	-Visual inspection	3 years

Maintenance of the operating mechanism, auxiliary devices and other accessories, such as oil level gauges, sight glasses, valves, gaskets, breathers, oil lines, and tank lifters should be inspected following the manufacturer recommendations [10].

4.2 Reliability-based Preventive Maintenance

For the identification of the deterioration stages, the need for preventive maintenance (PM) is established through periodic or continuous inspection. The improvement of maintenance to reliability is developed using two factors and the selection of the action to do for the components on every PM stage is decided by maximizing system benefit in maintenance. Depending on the percent of the survival parts of the system when it is maintained, the reliability function giving the probability that the system is always working on the time interval $[t_{j-1}, t_j]$ is $R_j(t) = R_{0,j}.R_{v,j}(t)$ where $R_{0,j}$ is the initial reliability of the j^{th} stage and $R_{v,j}(t)$ is the reliability degradation of surviving parts on this stage. Considering periodical PM which interval is t_m, the reliability of surviving parts is defined by:

$$R_{v,j}(t) = R\left(\frac{1}{m_1}\left(t-(j-1)t_m\right)\right) \tag{1}$$

with: R being the reliability function, $(j-1)t_m \le t \le jt_m$ and m_1 $(0 < m_1 \le 1)$ the improvement factor of PM action $(1a)$. This PM action $(1a)$ is defined as a mechanical service which emphasizes on maintaining a system on normal operating condition. It usually involves less techniques and tools and just improves the extrinsic state. To model the reliability of systems following PM, the effects of various actions on $R_{0,j}$ and R_j must be evaluated using $R_{0,j} = R_{f,j-1} = R_{0,j-1}R(t_m)$, where $R_{0,j-1}$, $R_{f,j\text{-}1}$ are the initial and the final reliability values of the system on the $(j-1)^{th}$ stage.

PM action $(1b)$ can improve the surviving parts of the system and also recover the failed parts. Generally, the impact of this action on the failed parts can be measured by an improvement factor m_2, which is also set between 0 and 1 representing the restored level except the surviving parts. It will be noted that the improvement factors were already developed by Tsai *et al.* [11]. According to the definition, the initial reliability on the action $(1b)$ can be expressed as:

$$R_{0,j} = R_{f,j-1} + m_2\left(R_0 - R_{f,j-1}\right) \tag{2}$$

where R_0 denotes the initial reliability of the new system. When both improvement factors m_1 and m_2 are equal to 1, we define the PM action (2P) corresponding to a replacement. Using the development of the survival function given bellow, the system reliability is expressed in a developed form of the expression 1, where is associated the cumulative distribution function of random shocks designated by $F_x^{(j)}(S)$ as:

$$R_j(t) = R_{0,j}\exp\left(-\left(\frac{(t-(j-1)t_m)}{m_1\eta}\right)^{\beta}\right)\times e^{-\lambda(\frac{1}{m_1}(t-(j-1)t_m))}\sum_{j=0}^{\infty}\left(\frac{\left(\lambda(\frac{1}{m_1}(t-(j-1)t_m))\right)^{j}}{j!}\right)F_x^{(j)}(S) \tag{3}$$

The benefit of the component maintenance on the j^{th} stage is defined as:

$$B_{i,k} = \frac{\int_{t_j}^{\infty} R_{i,j+1}(t)dt - \int_{t_j}^{\infty} R_{i,j}(t)dt}{C_{i,k}} \tag{4}$$

where: i, k, $C_{i,k}$ denote respectively the i^{th} sub-system or component under consideration, the k^{th} maintenance action been considered and the action cost. The advantageous maintenance action will correspond to the maximum of the benefit, *i.e.*, $B_i^* = Max(B_{i,k})$.

Once the action of maintenance is defined and retained, the availability of the system at any stage is processed as:

$$A_{s,j} = \frac{T - t_{b,m}\sum_{i=1}^{n}\int_{t_{j-1}}^{t_j} h_{i,j}(t)dt}{T + \sum_{i}^{n} t_{i,k,a}} \tag{5}$$

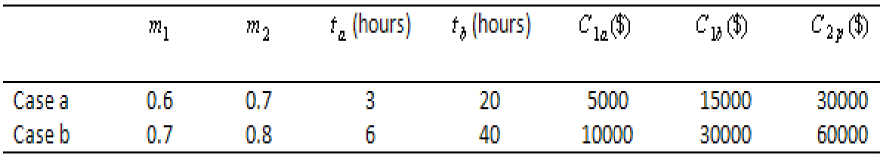
where: n, $t_{i,k,a}$, T denote respectively the number of components or sub-systems, the time of the k^{th} preventive maintenance action and the cycle time. In the following, we discuss the methodology allowing the assessment of reliability under preventive maintenance.

Let's consider T_m the minimal value of preventive maintenance intervals of the system's components, $T_m = min\{t_{m,i}\}$. At every maintenance stage j, verify for the system, if its reliability $R((j+1)T_m)$ for the coming stage $(j+1)$ is greater or equal to the threshold reliability value fixed a priori R_{th}, using equation (3). If the condition is realized, the decision is do nothing. If no, compute the benefit given by equation (4) for each action proposed and choose the maximum value. For the case study application, the maintenance actions are defined as follows:

- Action $(1a)$ corresponds to visual inspection, optical and radiography inspection,
- Action $(1b)$ corresponds to oil replacement,
- However, the action $(2p)$ is gathering the following operations: checking components for wear examination, cleaning, repainting, correcting any identified problems, calibrating to meet original manufacture's specifications and certifying the condition of reconditioned circuit breaker.

For reliability, benefit and availability assessments, maintenance characteristics are dressed in Table 3 and consist on estimated improvement factors (m_1 ,m_2), preventive and curative maintenance durations (t_a ,t_b) and their costs in US Dollars, respectively.

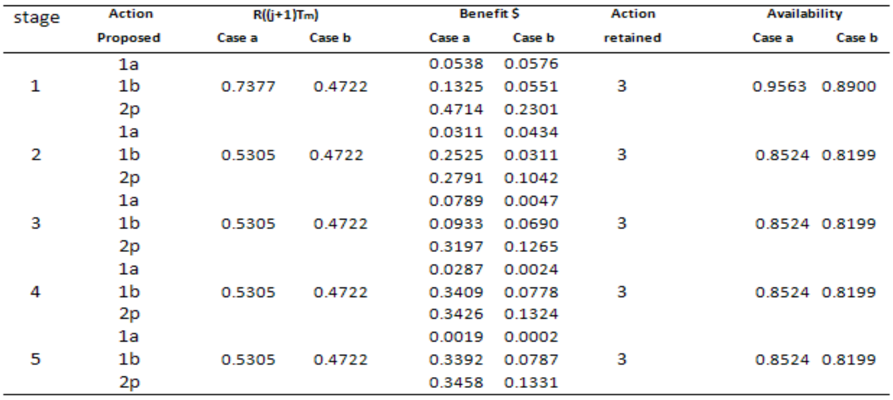
Table 3: Maintenance Actions Characteristics



	m_1	m_2	t_a (hours)	t_b (hours)	C_{1a}($)	C_{1b}($)	C_{2p}($)
Case a	0.6	0.7	3	20	5000	15000	30000
Case b	0.7	0.8	6	40	10000	30000	60000

The results of the assessments of rreliability, benefit and availability were obtained, using equations (3), (4) and (5), respectively. They are gathered in table 4, providing a maintenance plan which illustrates the influence of maintenance actions on failure processes cited above. It will be noted that the maintenance interval is $t_m = 2\ years$. The case (a) denote the consideration of oil insulation degradation process, however the case (b), corresponds to the consideration of both oil insulation degradation and contacts wear out degradation processes.

Table 4: Circuit Breaker Maintenance Actions Plan



stage	Action	R((j+1)Tm)		Benefit $		Action	Availability	
	Proposed	Case a	Case b	Case a	Case b	retained	Case a	Case b
1	1a	0.7377	0.4722	0.0538	0.0576	3	0.9563	0.8900
	1b			0.1325	0.0551			
	2p			0.4714	0.2301			
2	1a	0.5305	0.4722	0.0311	0.0434	3	0.8524	0.8199
	1b			0.2525	0.0311			
	2p			0.2791	0.1042			
3	1a	0.5305	0.4722	0.0789	0.0047	3	0.8524	0.8199
	1b			0.0933	0.0690			
	2p			0.3197	0.1265			
4	1a	0.5305	0.4722	0.0287	0.0024	3	0.8524	0.8199
	1b			0.3409	0.0778			
	2p			0.3426	0.1324			
5	1a	0.5305	0.4722	0.0019	0.0002	3	0.8524	0.8199
	1b			0.3392	0.0787			
	2p			0.3458	0.1331			

The improvement due to technical and organizational mesures taken on the downstream feeder influences directly the effects of schoks, while, the improvement of circuit breaker performances is more significant when these mesures are simultaneously taken with mainteance actions.

5. Conclusion

In this article the main idea was driven by new theoretical developments on competing failure process initiated by Pham. This concept seems more robust and realistic than the one modelling the behaviour of equipment in binary system. The objective attended was the stochastic modelling with application to a multi-state and multi-degraded system considering multiple causes of failures. Those treated were: failures due to the use of the equipment (aging and wear out) and failures due to sudden break (shocks). The study was based on statistical analysis of real data issued from the experience feedback. Degradations were modelled using increasing functions based on Weibull, exponential and uniform distributions; however shocks were modelled using non homogeneous Poisson process. Three types of shocks were illustrated considering state probabilities and reliability changing. It was observed that the random shock process governs the behaviour of the reliability function.

Both reliability improvements of the downstream feeder and the effects of intrinsic preventive maintenance actions were discussed and treated for the improvement of the oil circuit breaker performances. Investigations conducted by Pham in a theoretical framework have been applied successfully to complex system such as electrical one. The models applied on simple numerical examples have been validated by application to a real case of engineering area. In practical operation, the results analysis of the current state of the network allows to the decision maker to reach better information and target the equipment that reduces the performances of the system and practicing suitable maintenance actions. This work has shown that it is possible to maintain equipment using other than the traditional methods (systematic maintenance). By following the methodology explained and applied, this work encourages the introduction of multi-stage degraded system practice in power system reliability modelling.

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Fairouz IBERRAKEN is a Ph.D. student in Electrical Engineering at the University of Bejaia, Algeria. Her areas of interest are smart grids projects development and renewable energy. She worked on the failure mechanisms and degradation models of photovoltaic systems. She is also interested in maintenance policies of electrical equipment.

Rafik MEDJOUDJ is a Ph.D. student in Electrical Engineering at the University of Bejaia, Algeria. His area of interest is stochastic models applied to electrical equipment. A particular interest is made for competing failure processes and state probabilities assessment of sub-station components. He also works on costs evaluation of photovoltaic systems installations.

Rabah MEDJOUDJ is a Doctor of sciences from the polytechnic high school of Algiers; he is associate professor in Electrical Engineering at University of Bejaia, Algeria. He worked for almost 20 years on the reliability aspects, namely: modelling, simulation, technical and economic calculation. Currently he is working on multi-criteria decision making methods in the field of electrical systems and sustainable electricity projects. He is also a consultant to industrial and economic organizations in the areas of networking.

Djamil AISSANI is a professor, director of research at University of Bejaia, Algeria. He is also president of the association GEHIMAB, and has published hundreds of articles relating to queues, the reliability of systems, and the history of mathematics in Bejaia in the middle Ages. He has contributed to the publication of several books. He activated several times as curated exhibitions and as advisor to the Algerians Ministry of Culture and Ministry of Higher Education.

Klaus Dieter HAIM is a professor and director of research at University of Zittau, Germany. His area of interest is MV network design and optimization. His career covered a diverse range of assignments, from a research project for EDF to serving as a Professor in Algeria. Between 1994 and 2005, he worked as Head of Production for medium voltage cable accessories at Cellpack before assuming his current position. He is a Senior Fellow for electrical power systems and networks.