ERDF ELECTRICAL NETWORK SUBSTATIONS CONTROL COMMAND SYSTEM : AGEING AND STRATEGIES OF RENEWAL

Mbaye SARR
EDF R&D - France
mbaye.sarr@edf.fr

Francis GALLON
ERDF – France
francis.gallon@erdfdistribution.fr

ABSTRACT

This paper presents a methodology for determining an optimal rate of refurbishment of the instrumentation and control (I&C) systems used in ERDF's 2200 substations. The article first describes how substation reliability is characterized through a combined use of statistical methods and expert knowledge. In this way the substations can be ranked according to the risk posed by the use of legacy components in the I&C systems. The second part of the work describes the determination of the optimal rates of refurbishment. The outcome is a reasoned tradeoff between maintenance and renewal, taking into account both economic cost factors and contractual issues of quality and continuity of supply.

INTRODUCTION

The majority of control and command systems or instrumentation and control (I&C) system in ERDF's 2200 substations were installed in the 1970's (conventional series) and 1980's (1986 series). These systems use mainly electromechanical relays and/or analog relay technology. Currently, digital relays are being placed in either new or some refurbished substations (at a rate of about 40 substations per year). Consequently, there are now three different technologies of devices being used across the 2200 ERDF substations. These different types of I&C systems used in ERDF's substations are detailed in [2].

As the annual rate of substation refurbishment is limited, a decision must be made as to which sub-stations should be refurbished first. This article will first present the way we have classified the substations according to their reliability determined using statistical methods and expert knowledge. This ranking includes the risk posed by the use of the "legacy" components in the control and command systems, taking into account the unavailability of the "legacy" components due to obsolescence and the impact of their failure.

The second part of the work will explain a process used to determine the optimal rate of substations to refurbish with digital relays per year. Through examination of an extensive database (Computer Maintenance Management System) of maintenance activities it was possible to create potential I&C renewal scenarios based on parameters like expected lifetime, failures, cost and stock/number of spares. This calculation also included several factors such as; the benefits of the renewal of the old I&C equipments due to the end of Through-Life Support (TLS) contracts after 20 years and increase in I&C maintainability resulting from a process of cannibalization (where spare parts are used to maintain electromechanical or analogical relays in operating condition before their renewal).

The purpose of these scenarios is to arbitrate between maintenance and renewal while taking into account economics factors like costs and contractual ones like quality and continuity of supply.

HV/MV SUBSTATIONS RANKING

The aim of this first part of the paper is to elaborate on the method used for ranking of HV/MV substation based on their Criticality.

Intrinsic HV/MV substation criticality

The criticality captures the probability of occurrence and the gravity of events involving the mal- functioning of the substation I&C – and the protective devices in particular- is involved.

Substation criticality is determined based on the state of the protection components which make up its control command system. The system of protection insures a set of functions on the parts of the substation such as Busbar, Transformer, Automatism, Remote Tariff Changing, Supervision. The consequences of the non-execution of these functions (constituting a "Functional Dreaded Event" -FDE) can have grave effects on the safety of personnel, equipment and on the quality and continuity of electrical supply.

The criticality of substations is obtained as follows:

- For each Functional Dreaded Event (i.e. a long cut), the failure models of each relevant protective devices at issue is listed (using Failure Mode Effect Criticality Analysis (FMECA).)
- Each type of protective device adds its contribution to a given FDE
- The sum of all contributions for each FDE is multiplied by the severity factor of the FDE
- The sum of over all FDE constitutes the Criticality of the HV/MV substation.

A mathematical expression for the criticality of a substation is then:

$$Criticity(Sub) = \sum_{k \subset FDE} G_k \left[\sum_{\substack{p \subset sub \\ p \subset k}} R(p) \right]$$

where

- **Sub** is a given substation
- ***k*** is one Functional Dreaded Event (FDE)
- $\boldsymbol{G_k}$ is the gravity of the FDE_k.
- ***p*** is a protection device involved in the FDE_k

Functional Dreaded Events

The make-up of the FDE and the list of protective devices involved in each of them are determined using FMECA.

Functional Dreaded Event	gravity
Functional failure of substation's MV material without impacting continuity of supply	1
Disturbance to quality of supply in outgoing feeder due to MV equipment failure	2
Brief outage of an outgoing feeder due to a MV equipment failure	3
Long outage of an outgoing feeder due to a MV equipment failure	3
Long outage of several outgoing feeder (as a result of incoming circuit-breaker tripping) due to a MV equipment failure	4
Remote Tariff Changing order disturbance	4
Malfunction involving risks of damage to equipment	5
Malfunction involving safety risks to EDF agent or third person	6

Table 1 : Functional Dreaded Event

Risk value of a protective device

In the process of determining substation critically, evaluating the risk due to the protections is very important. The risk of a model of protection depends on its failure rate and on its obsolescence factor. Risk is given by the expression:

$$R = \lambda \times F$$

where λ is the failure rate of the device and F its obsolescence factor. In the following lines, the determination of these parameters is presented.

- **Failure rate calculation**

The failure rate of each model of protection is evaluated from the operational feedback. Over several years, a description of control command system equipments and failures observed have been collected and stored in a Computer Maintenance Management System (CMS). It is felt that the reliability of the protection can be characterised using a two-parameter form Weibull distribution expressed as:

$$R(t_i) = e^{-\left(\frac{t_i}{\eta}\right)^{\beta}}$$

The failure rate is then given by :

$$\lambda(t_i) = \frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1}$$

where:

- $\mathbf{t_i}$ is the device age;
- **η** is the scale parameter (with the same dimension as $\mathbf{t_i}$**);**
- **β** is the (dimensionless) shape parameter.

With β and η, it is possible to predict the evolution of the reliability (rate of failure) of the protection devices with their age and, as a result; the substations' critically.

We have used a Maximum Likelihood Estimation process to calculate the Parameters of the Weibull Distribution on right censored data [1]. We get a system of two equations in the two variables $\hat{\mu}$ et $\hat{\sigma}$:

$$\begin{cases} \hat{\mu} = \hat{\sigma} \ln\left(\frac{1}{r}\sum_{i=1}^{n} \exp\left(\frac{x_i}{\hat{\sigma}}\right)\right) \\ \frac{1}{r}\sum_{défaillances} x_i + \hat{\sigma} - \frac{\sum_{i=1}^{n} x_i \exp\left(\frac{x_i}{\hat{\sigma}}\right)}{\sum_{i=1}^{n} \exp\left(\frac{x_i}{\hat{\sigma}}\right)} = 0 \end{cases}$$

where **n** observations where done in times $t_1, t_2, \ldots, t_n$ from which:

- **r** observations are not censored (failures)
- **n-r** observations are right censored
- $x_i = \ln t_i$

$\hat{\mu}$ et $\hat{\sigma}$ are linked to the estimated weibull parameters $\hat{\beta}$ and $\hat{\eta}$ as below :

$$\begin{cases} \hat{\beta} = \frac{1}{\hat{\sigma}} \\ \hat{\eta} = \exp(\hat{\mu}) \end{cases}$$

Determining the values of $\hat{\mu}$ et $\hat{\sigma}$ by resolving the system of two equations leads to the weibull parameters . The software Scilab was used to resolve numerically this system and then get to the Weibull parameters for each type of protection device for which enough information was collected .

- **Obsolescence factor calculation**

In addition to the failure of each protection, the obsolescence factor is necessary to calculate its risk. Obsolescence captures the scarcity of the protection device model by considering their stocks and the end of their Through-Life Support contracts after 20 years. It is given by the expression below:

$$F = \left(K - \frac{nb\ in\ stock}{nb\ in\ use}\right)$$

where:

- *K* is a scale parameter and is dimensionless.
- *"nb in use"* refers to the number of devices of the model in use in all the ERDF's substations.
- *"nb in stock"* refers to the number of devices of the model in stock.

The number in stock also includes the spare devices from the process of "cannibalization". The process of "cannibalization" is used to keep conventional series relays and 1986 series relays in operational conditions while awaiting replacement by Digital I&C. Legacy protection devices taken out of service in a refurbishment of I&C are kept and constitute the "cold" stock. These "cannibalised" devices are selected and tested before becoming part of the "hot" stock (spare devices) and available for reuse as introduced in [2].

At this point, the risk associated with a protective device can be calculated. Associating the protective devices and their risk with the FDE's leads to the criticality of the substation.

Example of application

The methodology described is implemented in a tool developed at EDF R&D to facilitate the rankings of substations. The example is based on assets in the west of France. This allows us to keep homogeneity (climatic, organizational…). The ranking, taking into account all the FDE criticality, is as below:

Team	Substations	Type of I&C	Critically
LE_MANS	Substation 1	Conventional series	192
BREST	Substation 2	Conventional series	123
ALENCON	Substation 5	COHABITATION 1986 series/ digital	57
CHARTRES	Substation 6	1986 series	56
CAEN	Substation 3	Conventional series	55
BLOIS	Substation 4	Conventional series	54
RENNES	Substation 8	1986 series	52
RENNES	Substation 7	1986 series	41

The ranking takes into account all of enumerated FDE's. It is also possible to rank substations using a particular FDE by only considering the relevant protective devices.

I&C RENEWAL SCENARIOS

The previous results act as a base to consider the renewing of I&C. In addition, the asset manager have to take into account further parameters, like the number of customers powered, and/or the priority of some costumers. Given this;, we present a more general approach used to find an optimal rate of substations to refurbish with digital relays per year.

Presentation of the methodology

Our goal is to refurbish all substations by digital I&C. These new relays have a predetermined lifetime-A years- given by the manufacturers After A years of use, digital I&C have to be replaced. Then it is important to determine a constant rate of refurbishment which will allows us to finish the renewal of all old I&C before starting to renewal the first installed digital I&C. That specific rate, denoted by N, is obtained as follows:

$$N = \frac{Total\ Number\ of\ \ I\ \&\ C}{A}$$

Under the rate of N substations per years, old relays will exist in some substations. The way to get that rate between the first year of the process and the end of the simulation constitutes the profile of renewal. The profile of renewal is a set of transition(s) from renewal rate at the beginning (R substations per year) to N. The rate N is reached after T years.

The profile of renewal can be represented by the following diagram. The replacement of Conventional series and 1986 series I&C system is represented by the pink area and the replacement of digital I&C is shown by the blue area.

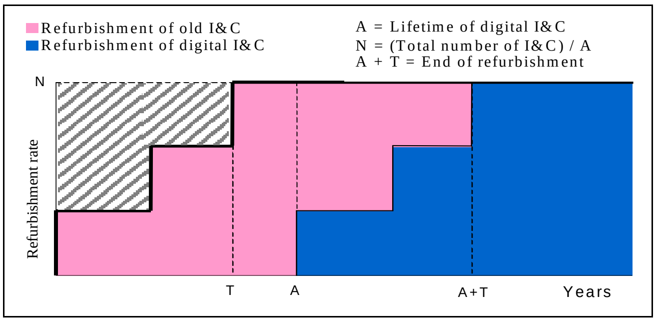

Figure 1 : Renewing I&C profile

It is shown that the renewal of the old I&C is finished at the date T + A. Indeed, the total number of old I&C to be renewed is N x A by definition of N. It is the area of the rectangle of length A and of height N on the graph. If the profile of renewal does not cover this area between year 0 and year A, the missing (Gray area) is compensated for between years A and A+T.

If T is greater than A, no old I&C will be replaced between the years A and T because the totality of the replacement credit serves to renew digital I&C :

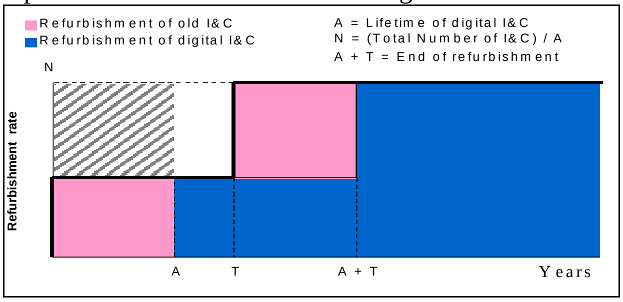

figure 2 : Renewing I&C profile

When the limit rate N is exceeded to accelerate the renewal, this effort will have to be repeated every "A" years.

Definition of scenario

The method described is implemented in order to simulate and compare various scenarios easily. Several parameters and data groups define a renewal scenario.

Data

Assets data:

An initial distribution of I&C, in term of type and age, is needed. An example is shown in Figure 3

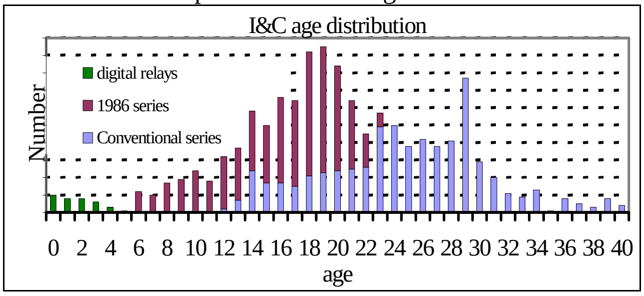

figure 3 : I&C age distribution

Reliability data :
The annual average number of failures per I&C type and a distribution of these failures per I&C equipments is required. The average failure rate is calculated as below:

$$\lambda_{average} = \frac{Number \quad of \quad I\,\&\,C \quad faults \quad during \quad T}{T * Assets \quad Data}$$

Specific values are determined based on data collected and stored in our database.

Cost Data :
Cost data required includes: installation cost of a digital I&C; repair cost for a device available in stocks (the "cannibalization process" is cheaper than the repair cost for a device not available in stocks); and discount rate.

Parameters
The parameters needed for each scenario include renewing strategy parameters and storage strategy parameters. The renewing strategy parameters consist of Renewal profile, Priority groups of I&C by type and age; and Life time of digital I&C. Examples of storage parameters include: Initial stock of spare parts, and Annual loss of spare parts (devices out of order, damaged etc…).
Each scenario can be analyzed through four different indicators.

Scenario results

To illustrate the methodology, two scenarios A and B were simulated. The rate of renewal for these scenarios are respectively Ra and Rb with Ra = 2*Rb for each year. The results below focus on the scenario with a lower rate of renewal applied to a sample of ERDF substations.

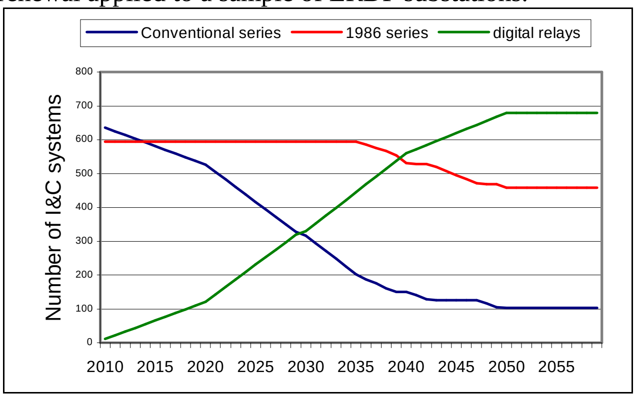

figure 4 : distribution of I&C

Figure 4 shows the evolution of the numbers of the different I&C technologies units in the assets for that particular rate of refurbishment. In this case, rate of refurbishment was not high enough to achieve total replacement of existing I&C systems. This approach; although less expensive; would leave the system exposed to risk from the legacy I&C systems.

Proportion of failures repairable by cannibalization
Figure 5 shows how the probability of a repair by cannibalization evolves. This indicates the availability of spare I&C equipment. The low rate of renewal impacts on the availability of spares, which also impacts the risks to the quality of supply.

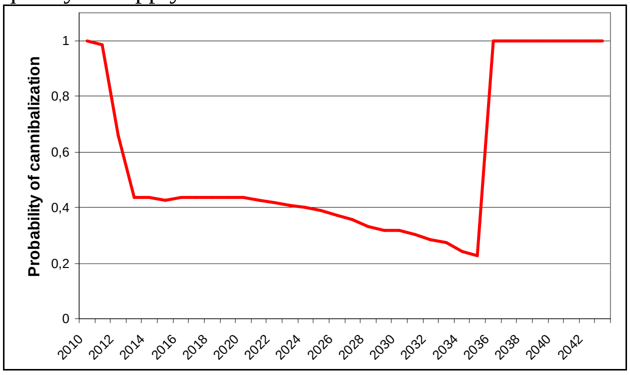

Figure 5: probability of repair by cannibalization

Comparison of cost of installation and renewal rate
The final figure presents the evolving cost of installation for scenario A and scenario B.

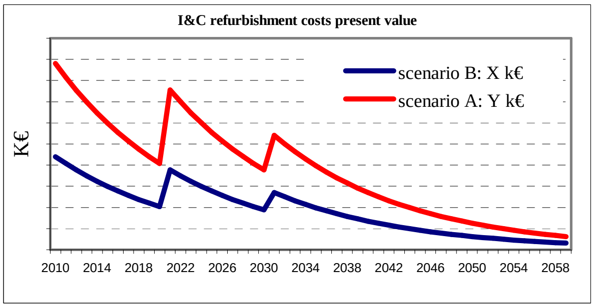

Figure 6: present value installation cost comparison

Scenario A is more expensive than scenario B where old I&C are not completely refurbished. However, the risk to quality of supply is reduced if renewal rate is higher.

CONCLUSION

The methodologies presented in this paper allow to an asset manager to get a rank of his substations based on their criticality while knowing the most risked models of protective devices. As demonstrated in the results, the method described also allows a quantitative comparison of renewal scenarios. This allows the selection of the best scenario according to the investment policy of the company and the need for maintaining quality of supply.

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[2] M. ODDI, F. LUCET, 2007, "Aging of the Control System of the EDF Primary substations",*19th International Conference on Electricity Distribution*, Vienna, CIRED, Paper 0299