Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P281-cd

Multicriteria optimal maintenance planning for industrial electrical installations

Jhonatan Albertini

Analysis, Evaluation and Risk Management Laboratory (LabRisco), University of Sao Paulo, Brazil. E-mail: Jhonatan.albertini@gmail.com

Marcelo Ramos Martins

Analysis, Evaluation and Risk Management Laboratory (LabRisco), University of Sao Paulo, Brazil. E-mail: mrmartin@usp.br

This study proposes a practical method for developing maintenance plans for industrial electrical systems that minimize the cost of failures and maintenance using a model capable of quantifying the risk of an electrical system failure considering (a) its configuration, (b) current condition of the components, and (c) uncertainties in the current condition of the components. The system reliability is obtained through simulation based on the survival signature, and the action plan is defined based on a set of actions that can be performed on the system components: retain, replace, refurbish, or acquire spare parts. The options are evaluated with a multi-objective optimization algorithm, NSGA-II, to find maintenance plans on the Pareto front, minimizing the loss of production due to unavailability and maintenance costs. A case study is presented with a process plant with more than 20 years of operation, receiving a new expansion that will use the existing electrical system.

Keywords: Reliability optimization; Electrical installations; Maintenance optimization; Survival Signature.

1. Introduction

The infrastructure of electric power systems is ageing worldwide. The decommissioning of existing plants threatens the reliability margins of electrical systems, and methods to keep existing installations reliable at the lowest cost are being encouraged. Similar challenges can also be found in large industries, where failure of electrical systems causes downtime and loss of production that might extend to a long period of time, as lead times for large or special equipment can take more than a year.

Despite the abundant literature on the reliability of electrical equipment, the task of analyzing the risk of failure of a system composed of many components, multiple modes of operation, and subjected to the wear and tear of years of operation, is complex.

This study proposes a practical method for developing maintenance plans for electrical systems that minimize the impact of failures and maintenance costs using a model capable of quantifying the risk of electrical system failure.

The analysis employs a bottom-up approach, based on the work developed by Propst and Griffin (2000), and is divided into the following phases:

(i) Initial considerations
(ii) Equipment reliability parameter assessment
(iii) Intervention assessment
(iv) System assessment
(v) Optimization

2. Initial considerations

It is key at the beginning of the study to define the concepts of failure, the effects of unavailability, and how the associated costs will be measured. Some processes are more resilient than others to power supply interruptions, while others may suffer losses that are not proportional to the time out of service, as in services with start-up and shut-down times or which require products to be purged. It is also important to understand how much the owner values the production of each area due to a higher margin on the production or because the product is an input to other process areas.

At the end of this phase, it is expected to have an explicit definition of how the cost of unavailability must be measured, the number of future overhauls to be analyzed, and the expected time for these overhauls.

3. Equipment reliability parameter assessment

The equipment reliability parameter assessment phase goal is to model the expected and lower bounds for the reliability and maintainability of the electrical components, such as transformers, switchgears, circuit breakers, cables, motor control centers (MCC), and auxiliary systems required for safe operation, such as uninterruptible power sources (UPS) and protection systems.

The degradation of electrical equipment is better explained by the combination of stresses it must endure, which are usually divided into electrical, thermal, and mechanical stresses. Based on historical data of failures and the failure mode, Zhang and Gockenbach (2007) proposed a model that connects the physical parameters of equipment to the statistical process of failure. This model allows for the incorporation of use and environmental data into the failure model. Advanced asset assessment strategies for the main equipment based on inspection and tests may also be used on the most critical equipment, such as power transformers. Ibrahim et al (2022), Abu-Elanien and Salama (2009). To address this uncertainty, the failure distribution parameters were estimated in bounds.

Beyond failure statistic modelling, it is also important to model the maintenance process, as often a spare part is not readily available and/or specialized workers can take days to arrive at the plant, factors that can greatly increase unavailability.

At the end of this phase, the following information must be available for each component:

- Failure distribution and parameters
- Maintenance distribution and parameters
- Cost of a corrective maintenance

4. Intervention assessment

The maintenance action cost and effect on the component reliability and maintainability parameters are defined in this phase. Standard actions and effects are listed in Table 1. It is expected that interventions will occur at a plant's planned stops or overhauls in a planned setting, not contributing to plant unavailability.

Table 1. Intervention effect on equipment parameters.

Action	Reliability	Time to repair	Initial Cost
Retain	No change	No change	None
Refurbish	Increases	No change	Low/Avg.
Spare	No change	Reduces	High
Replace	Greatly increases	No change	High

Other actions may be evaluated based on the criticality of the equipment; for example, periodic inspections of transformer oil may be foreseen as an option to reduce uncertainty in the transformer condition, or more than one action can be implemented, with the equipment being replaced and spared.

At the end of this phase, the following information must be available for each intervention:

- Updated failure distribution and parameters
- Updated maintenance distribution and parameters
- Implementation cost

5. System reliability assessment

System reliability quantification is performed using the algorithm to calculate the survival signature by Reed (2017) and the third simulation method based on the survival signature proposed by Patelli et al. (2017), which proved to be an efficient method for obtaining system reliability.

A key characteristic of the survival signature is the separation of the system structure from the failure distribution of components. The survival signature only must be computed once, reducing the computational effort at the optimization phase.

The method for computing production starts by computing the survival signature of the system. The survival signature of a certain system state is equivalent to the expected production level of the system state. The next step is the Monte Carlo simulation, in which the transition times for each component are sampled. When a transition occurs the survival signature for the current system state stored for the duration the system was in that state, then the component status is updated, and the next transition is sampled until the mission time is completed. When the number of simulations is reached the average production and corrective maintenance cost for that system is computed.

The interventions are transitions programmed into the simulation, where the parameters used to sample the transition times are changed according to the schedule, and only components with changed parameters transition times are resampled.

At the end of this phase, the system under analysis will be separated into subsystems, if needed, and each subsystem will have its own adjacency matrix, defining how the components are interconnected. This input is used to generate the survival signature of the system.

6. Reliability and costs multicriteria optimization

In the optimization phase, the possible options for intervention plans are evaluated using a genetic algorithm, which is a population-based algorithm that uses operators such as crossover and mutation to search for solutions with improved fitness. Among the available multi-objective algorithms, NSGA-II (Deb et al., 2002) was chosen because it has proven results in other reliability optimization problems and because it provides a wide diversity of non-dominated solutions at the Pareto front. The framework “pymoo” presented by Blank and Deb (2020) was used for the optimization phase.

Beyond the choice of the combination of interventions, when the intervention takes place is also an optimization parameter, as the electrical system can go through improvements during scheduled overhauls that occur at a certain frequency.

6.1. *Chromosome format*

Figure 1 shows the chromosome format for a system with *n* components.

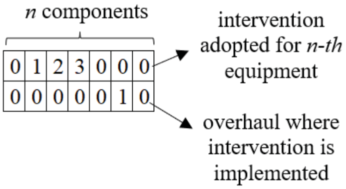

Fig. 1. Chromosome format

When an intervention is adopted, the parameters of the components are updated and the cost of implementing the intervention is added to the maintenance cost. An example codification of intervention and implementation genes is shown below for a component with four intervention options and four implementation possibilities.

Table 4. Example genes codification

Gene	Intervention	Implementation
0	Retain	t=0
1	Refurbish	t=5 years
2	Spare	t=10 years
3	Replace	t=15 years

6.2. *Results presentation*

The goal of the optimization phase is to provide the decision maker with a set of solutions on the Pareto front.

7. Case study

The case study is based on an energy-intensive chemical plant installed 30 years ago, considering the scenario of old process equipment being replaced with new and more efficient models, but relying on using the current electrical power system. The details were adapted from the real projects that the authors were involved in.

7.1. *Case study initial considerations*

The proposed system was connected to two completely redundant high-voltage power lines through two step-down transformers (PTR-100 and PTR-200). These transformers supply power to the medium-voltage switchgear (MVP-100 and MVP-200), which feeds all the loads of the plant according to the following simplified single-line diagram:

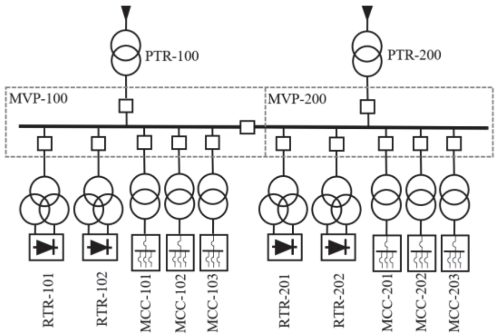

Fig. 2. Case study simplified single line diagram

Each rectifier transformer (RTR) is responsible for 25% of the plant production and shares a redundant auxiliary power supply; that is, units RTR-101 and RTR-201 require MCC-101 or MCC-201 to work. The MCCs require the associated transformer to be functional. The plant utilities common to all process trains are fed from redundant medium-voltage MCC-103 and MCC-203, but the plant comes to a complete halt if both are unavailable.

Another peculiarity of the plant is that the step-down transformers are not completely redundant because the plant can only operate at 50% of the nominal capacity if PTR-100 or PTR-200 become unavailable. The high-voltage switchyard, up to the power transformer, is maintained by the utility company; for this reason, it is not included in the scope of the analysis.

After the installation of the updated units, the plant is expected to go through an overhaul every five years, and it is desirable to know when interventions in the electrical equipment will be optimal. The plant is expected to run for at least 20 years.

7.2. *Case study – Equipment reliability parameter assessment*

The equipment reliability parameter was estimated based on the condition and stress level of each piece of equipment. A brief abstract of the considerations made for each type of equipment is as follows:

The failure rates for the equipment will be obtained from studies previously cited, based on the analysis of historical data, and will be adjusted to the condition of equipment, based on operation history and inspections. The repair time and cost are based on historical data from IEEE 3006 and the authors' experience in similar projects.

7.2.1. *Power transformers PTR-100/200*

Thermal aging influences the aging process of power transformers. The transformers PTR-100 and PTR-200 operate with a spare capacity of 10%. These transformer ratios and rated powers are usual, so no major issues are expected to replace or repair these units. The major point of concern for these transformers is the on-load tap changers (OLTC), which are responsible for more than one-third of power transformer failures and are operated multiple times a day on this plant owing to voltage fluctuations on the supply side. (Jürgensen et al., (2016), (Zhang and Gockenbach (2007)

7.2.2. *Medium Voltage Switchgears MVP-100/200*

Medium-voltage switchgears were not frequently operated and replaced 10 years ago to withstand the available short-circuit. They were equipped with SF6 circuit breakers and numerical relays. The switchgear counts with spare columns; therefore, in the case of failure, the service can be fixed quickly.

7.2.3. *Rectifier transformers RTR-101/102/201/202*

Rectifier transformers are special transformers with unusual transformation ratios that are designed to provide a 12-pulse voltage source for the rectifier. These transformers operate very close to their rated power and are under a high harmonic current from the rectifier to which they are connected. Transformers RTR-101 and RTR-201 already show signs of solid insulation degradation, as identified by dissolved gas analysis (DGA). Owing to their special construction, with secondary windings rated for several kiloamperes, the repair is very costly and can take a long time, as a new unit cannot be obtained in less than 6 months.

7.2.4. *Auxiliary power transformers PTR-103/104/105/203/204/205*

These transformers are expected to be in a better condition, as they are completely redundant, and in normal conditions, operate at approximately 40% of their rated capacity. They are smaller in size than the other transformers in the plant and are much easier to replace because of their conventional ratings.

7.2.4. ***Low voltage motor control centers MCC-103/203***

The original MCCs have been replaced over the years and are in operation for less than 10 years. They are frequently operated owing to process requirements, and incoming and tie-circuit breakers are protected with numerical relays. The power and available short-circuit nominal are below the MCC ratings, and spare feeders are mostly available. No major issues are to be expected on these MCCs.

7.2.5. ***Medium voltage motor control centers MCC-104/105/204/205***

These MCCs have been in operation for more than 30 years, with the only improvement being to the controls to enable remote control of circuit breakers. They are currently on the limit of their ratings regarding the demanded load and short-circuit withstand. Access to this switchgear room is restricted when the bus is alive, so any maintenance/inspection activity requires the entire bus to be deenergized.

7.2.6. ***Reliability parameters for base scenario***

The equipment is assumed to have a constant failure rate, and the repair times are assumed to be uniformly distributed between the minimum and maximum values according to the following table:

Table 2. Failure rates for base scenario

TAG	Failure rate (h^{-1})
PTR-100	5,6E-05
MVP-100	1,4E-05
RTR-101	5,1E-05
RTR-102	2,6E-05
PTR-103	4,1E-05
MCC-103	6,8E-06
PTR-104	4,1E-05
MCC-104	6,8E-06
PTR-105	4,1E-05
MCC-105	1,0E-05
PTR-200	5,6E-05
MVP-200	1,4E-05
RTR-201	5,1E-05
RTR-202	2,6E-05
PTR-203	4,1E-05
MCC-203	6,8E-06
PTR-204	4,1E-05
MCC-204	6,8E-06
PTR-205	4,1E-05
MCC-205	1,0E-05

7.3. ***Case study – Intervention assessment***

The proposed interventions are to refurbish, replace, or purchase spare parts.

Each intervention changes the parameters of the component and includes a predetermined cost for its implementation.

Table 3. Time to repair upper and lower bounds for base scenario

TAG	Lower bound (h)	Upper bound (h)
PTR-100	3,8E+02	4,8E+02
MVP-100	5,3E+01	6,6E+01
RTR-101	3,5E+03	4,3E+03
RTR-102	3,5E+03	4,3E+03
PTR-103	3,8E+02	4,8E+02
MCC-103	1,3E+02	1,7E+02
PTR-104	3,8E+02	4,8E+02
MCC-104	1,3E+02	1,7E+02
PTR-105	3,8E+02	4,8E+02
MCC-105	1,3E+02	1,7E+02
PTR-200	3,8E+02	4,8E+02
MVP-200	5,3E+01	6,6E+01
RTR-201	3,5E+03	4,3E+03
RTR-202	3,5E+03	4,3E+03
PTR-203	3,8E+02	4,8E+02
MCC-203	1,3E+02	1,7E+02
PTR-204	3,8E+02	4,8E+02
MCC-204	1,3E+02	1,7E+02
PTR-205	3,8E+02	4,8E+02
MCC-205	1,3E+02	1,7E+02

7.4. *Case study – System modelling*

The components were divided into nine subsystems to satisfy the previously informed description. The modelling is validated using deterministic data for components, assuming some components are perfect, never fails, and others are obsolete, fail instantly, and never repair, and verifying if the production level is what is expected.

The expected production for the base scenario is 84,9% at a cost of 5270, which is a very low production level, as only failures in the electrical system are considered. All the results of the case study were evaluated using 50 simulations.

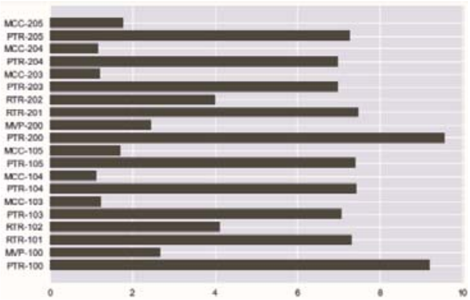

Fig. 3 Expected number of failures for each equipment at base scenario

7.5. *Case study Optimization*

This problem consists of 20 components: the chromosome will have 20 genes to define which type of intervention will take place and more than 20 to define at which overhaul it will be implemented. Gene codification for the case study problem is described below.

Preliminary tests were performed to define the parameters of the genetic algorithms aiming to improve the solution quality, convergence, and diversity. The final parameter adopted was a population of 100 individuals for 500 generations. Gene codification followed the previously described example. The evolution of the objective space can be seen in Figure 4, which confirms that the algorithm was able to navigate the solution space towards better solutions and that the solution converged, owing to the very little improvement in the latter generations.

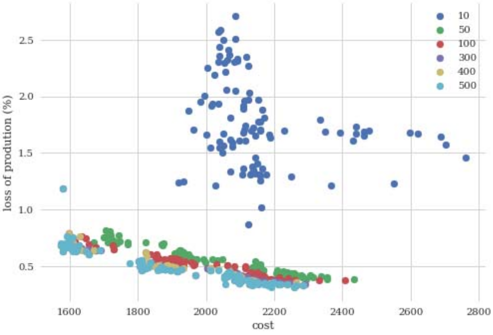

Fig. 4 Genetic Algorithm population evolution through generations

It is assumed that the decision maker values the production at different rates, and we will search for the best maintenance plan among the non-dominated solutions for this scenario, which will be discussed.

The final set of nondominated solutions and the best solution for each scenario are shown in Fig. 6. The actual genes are shown in Table 6, from which we can observe some patterns. The first is that for an aged installation as the base scenario, there is a huge upside for intervening, with almost every piece of equipment being at least refurbished during the mission time of the plant. However, there are some unexpected solutions, such as MCC-103 and 203, in which only one unit of a redundant set is replaced. Regarding the implementation date, most interventions were planned for the first two overhauls, immediately and in five years, with most exceptions being the refurbishment of those units.

Table 5. Decision making scenarios

Scenario	Value of one hour of production
A	1,45
B	1
C	0,65

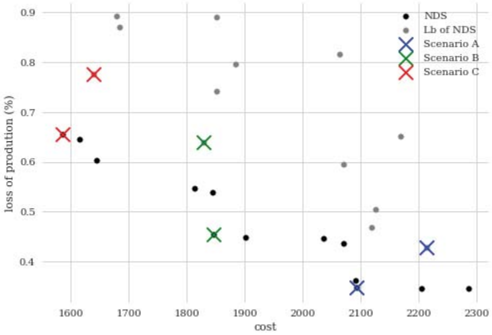

Fig. 6 Non-dominated solutions (NDS) and lower bound (LB) of NDS with indication of optimal solution for each scenario

Table 6. Best solution for each scenario

	Action			Implementation time		
Equipment	A	B	C	A	B	C
PTR-100	3	3	2	0	0	0
MVP-100	3	3	3	1	0	2
RTR-101	2	2	2	0	0	0
RTR-102	2	2	2	0	0	0
PTR-103	1	1	1	0	0	0
MCC-103	3	3	1	0	0	2
PTR-104	1	1	2	0	0	0
MCC-104	1	1	1	3	2	2
PTR-105	2	2	2	0	0	0
MCC-105	2	0	1	2	2	2
PTR-200	3	2	2	0	0	0
MVP-200	1	1	1	3	1	0
RTR-201	2	2	2	0	0	0
RTR-202	2	2	2	0	0	0
PTR-203	1	1	1	0	0	0
MCC-203	0	0	0	1	0	1
PTR-204	2	2	2	0	0	0
MCC-204	3	3	3	2	0	3
PTR-205	2	2	2	1	0	0
MCC-205	0	0	1	2	1	1

8. *Conclusion*

The presented procedure provides a quantitative approach to planning the overhauls of industrial electrical installations. This method has practical applications in real installations and can be used in systems with many components. The optimization phase effectively improved the quality of solutions from the initial populations and provided the decision maker with several plans from which to base their choice.

Further improvements could include the inclusion of restraints to force some interventions to occur at the same time, or from the other side, including incentives to have multiple interventions occurring simultaneously. Common cause failures also often cause the unavailability of electrical power systems, and including their impact on the model would improve the accuracy of the model.

The case study used the result from an inspection of transformers to evaluate the current degradation level; it would also be fruitful to include the planning of these inspections in the model.

Acknowledgement

Prof. Marcelo Martins wish to acknowledge the support by the Brazilian National Council for Scientific and Technological Development/Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) by grant 303908/2022-0.

References

Abu-Elanien, A. E. and M. Salama (2010). Asset management techniques for transformers. Electric Power Systems Research 80(4), 456–464.

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan(2002). A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6(2), 182–197.

Ibrahim, K., R. Sharkawy, H. Temraz, and M. Salama (2022). Reliability calculations based on an enhanced transformer life expectancy model. Ain Shams Engineering Journal 13(4), 101661.

IEEE (2012). Historical reliability data for IEEE 3006 standards: Power systems reliability. 3006HistoricalData-2012 Historical Reliability Data for IEEE 3006 Standards,1–303.

Jürgensen, J., L. Nordström, and P. Hilber (2016, 12). Individual failure rates for transformers within a population based on diagnostic measures. Electric Power Systems Research 141, 354–362.

Patelli, E., G. Feng, F. Coolen, and T. Maturi (2017). Simulation methods for system reliability using the survival signature. Reliability Engineering System Safety 167.

Propst, J. and P. Griffin (2000). Evaluating aging electrical systems and equipment. In Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129), Volume 4, pp. 2790–2797 vol.4.

Reed, S. (2017). An efficient algorithm for exact computation of system and survival signatures using binary decision diagrams. Reliability Engineering System Safety 165.

Zhang, X. and E. Gockenbach (2007). Component reliability modelling of distribution systems based on the evaluation of failure statistics. IEEE Transactions on Dielectrics and Electrical Insulation 14(5), 1183–1191. r IEEE 3006 Standards: Power Systems Reliability