HARDWARE DEPENDABILITY STUDY OF AN AUTOMATIC CIRCUIT RECLOSER

Jaroslav SNAJDR
Schneider Electric – Germany
jaroslav.snajdr@se.com

Marc FERRAZZI
Schneider Electric – France
marc.ferrrazzi@se.com

Pavel NOVAK
Schneider Electric – Germany
pavel.novak@se.com

Laurence AMIGUES
Schneider Electric – France
laurence.amigues@se.com

ABSTRACT

At present the rate of digitalization in the world of energy is increasing and the effort aims product development as well. The need of more efficient processes utilizes numerical modeling and simulations to their limits to provide quick and reliable results often unattainable by testing. One of such examples is the assessment of mean time to failure (MTTF) of switchgear components.
An automatic circuit recloser with expected operating life of 25 years in 24/7 regime and 10 years warranty period is investigated. The critical component within the auto recloser design is an electronic controller board.
MTTF analysis, considering a temperature rise near the electronic assembly is performed in this paper. Effective utilization of top analysis methods, including numerical simulation, is demonstrated for smooth implementation of the digital components.

AUTO RECLOSERS AND SMART GRID STRATEGY

Ensuring a quick response to faults and keeping outages to a minimum is key for utilities who operate power transmission and distribution networks. When a fault occurs, minimizing its impact is what an auto recloser will do.
Auto reclosers are usually installed on overhead networks. For such networks, a very few percentage of faults are permanent ones. The majority are transient or semi-permanents, caused by events like lightning strokes, animals or branches bridging the power lines. Therefore, they clear in a relatively short time.
Considering this, a protection scheme that would simply isolate the network section where the fault has occurred would contribute to unnecessary increase of the downtime. This is exactly what auto reclosers help to prevent, by isolating the affected part of the network and then re-energizing it after a short delay to determine whether the fault has cleared. If all is correct, that's the end of the sequence, but if the fault persists the breaker trips again and, after a further delay, the digital controller recloses it for a second time and checks again for the continuing presence of the fault. If the fault is still present after this second reclose, the breaker will trip again.
Digital controllers are designed to lock out after a certain number of trip/reclose cycles. Usually two, three or four cycles, depending on the application.
Major benefit of the product is that it can improve electric power utility reliability indices, SAIDI (system average interruption duration index) and SAIFI (system average interruption frequency index), by automatically reducing outages.
It can as well defer capital works by offering features that reduce network stresses and are easily integrated into smart grid applications with advanced capabilities such as 'loop automation' and 'automatic changeover'.
Therefore, auto reclosers are part of the connected products proposed by Schneider Electric to utilities in order to adopt the right digital grid strategy, based on EcoStruxure™ Grid.

MTTF OF ELECTRONIC CONTROLLER

The electronic controller board is located in the metallic box, at the bottom of the three recloser poles as shown in Figure 1. The box is designed to be air tight to withstand harsh conditions of excess dust, heat and high humidity. For this reason, no ventilation opening can be installed and the electronic board is exposed to elevated temperature due to solar radiation.
To perform the MTTF analysis, a temperature rise study had to be finished first. Due to the combination of ambient temperature and solar radiation, several locations in the world were studied to estimate the worst-case conditions.
The temperature rise estimated by the 3D model, considering the worst case for environmental conditions around the tank, has been used to run a preliminary reliability study of the electronic board.
The failure rate calculations for each of the components referred to the IEC/TR 62380 [1], including models taking directly into account the influence of the environment. Component failure rates were considered as constant over operating life. Finally, based on a maximum ambient temperature around the electronic board, we could calculate a MTTF.
This gave us a preliminary vision of the board reliability, even though quite conservative one, as we considered the electronic board to be permanently exposed to the maximum temperature.
We'll fine tune our MTTF point of estimate in a second step of that study, considering the temperature variation during night, day and the four seasons.

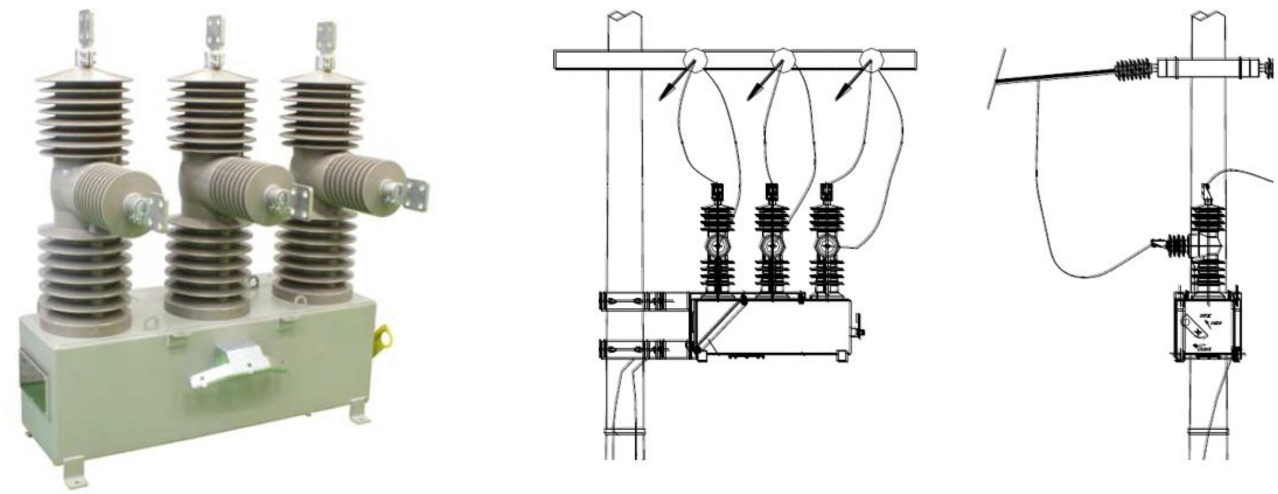

Figure 1. The studied recloser with an outline of its typical installation.

TEMPERATURE RISE SIMULATION

Validation of a design's criteria often represents difficulties, especially in cases when random input elements affect results. Dealing with temperature rise of outdoor equipment is one of them. According to [2] the defined maximum limit of solar radiation is 1000 W/m², but the extreme values lie beyond. Assessment of true maximum values was then possible only by time and material expensive testing, or by utilizing numerical simulations. Due to 3 geographical locations needed to be assessed, the latter was chosen. In Table 1 a list of the locations is shown with maximum values of ambient temperature, direct and diffuse solar radiation.

To minimize influence of errors on results, the following methodology was selected. Only sun radiation was considered due to 2 facts - the circuit board is in a closed box without any additional heat sources and the current path of the recloser is located far enough from the box. Though the main outer shape of the recloser was retained to simulate outer air flow. Then the numerical model itself was build using thermal network method and computational fluid dynamics (CFD) to cross-check the performance [3].

Table 1. Overview of weather conditions.

Location	T ambient [°C]	I direct [W/m²]	I diffuse [W/m²]
Dubai	45	884	118
Novi Sad	35.8	872	117
Alice Springs	43.3	1068	61

Thermal network model

Thermal network method is based on mathematical analogy between heat transfer and electric flow physics. Therefore, a model can be split into series of equations involving thermal resistances, sources and flows and solve it as a regular electric circuit. Although model discretization gets more cumbersome with its complexity, it can provide a decent precision of mean values for given volume, which is essential for checking CFD results. [4]

In Figure 2 an example of a thermal model schematic is shown. It consists of individual branches representing heat transfer through walls of the box. Beside thermal resistors standing for heat transfer by conduction, convection and radiation, the branches also include power sources for solar intake and potential sources to modify ambient temperature.

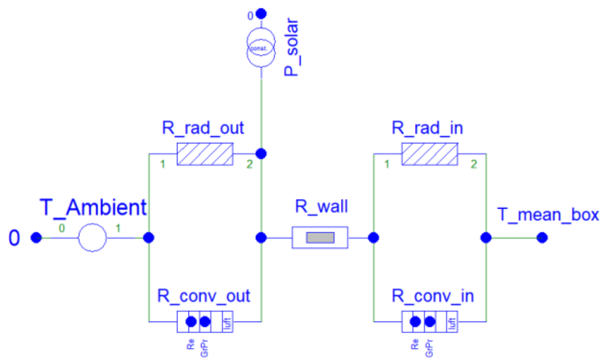

Figure 2. Thermal network model.

Finite volume model

With this methodology, the focus was to get maximum temperature at the exact location of the circuit board. This was not possible to achieve by thermal networks, giving only 1D results. Therefore, a detailed 3D model of the closed box with the simplified model of recloser poles was built together with internal and external air volumes. The model is shown in Figure 3. All the external volume boundaries are open, medium is atmospheric air, the recloser poles are hollow and the box was modelled as shell conduction walls with high emissivity.

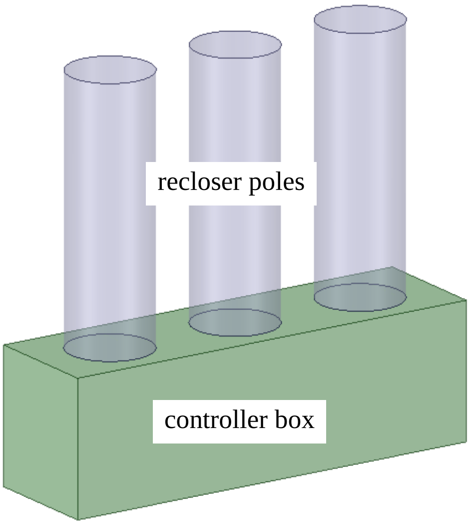

Figure 3. Simplified geometry model – box and poles.

The mentioned simplifications allowed creation of a high-quality mesh, necessary for achieving required results with needed precision. The most important part was to mesh boundary layers correctly while keeping high quality mesh and low element number. In Figure 4 a detailed view on a combination of hexa, prism and tetra elements is shown, covering an edge of the box with the hollow poles.

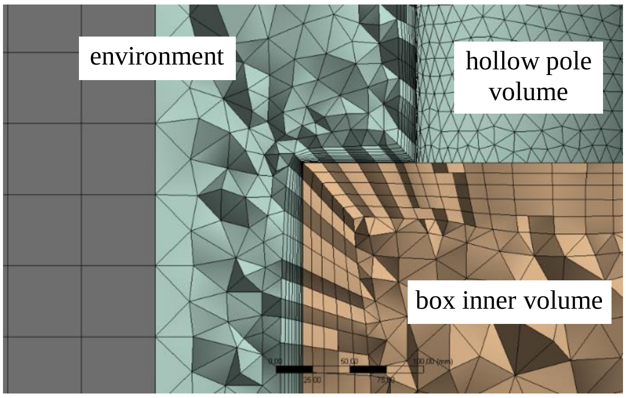

Figure 4. Detailed view on meshing.

Results

The highest absolute temperature was calculated for Dubai weather conditions. Mean temperature in the middle of the box was 64.7 °C by CFD and 62.7 °C by thermal networks. In both cases data from the same solar calculator, based on proprietary software, were used and applied as heat sources. However, thermal network method cannot consider the exact airflow around the box and uses correlations to calculate heat transfer coefficient instead. CFD model calculated maximum temperature at the location of the circuit board to be 63.4 °C, as shown in Figure 5. The temperature differs from the one in the middle of the box, due to inner flow.

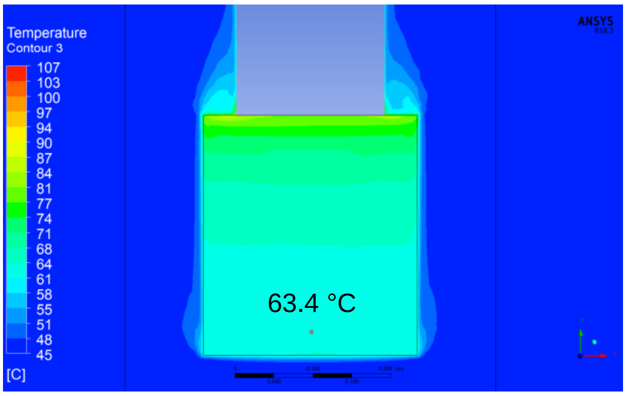

Figure 5. Contours of temperature field – Dubai.

DEPENDABILITY STUDY

A dependability study has three complementary objectives:

- Evaluate system specifications from a dependability point of view
- Prove that the proposed solutions respect architectural and operational (maintenance policy) objectives,
- Detect the weak points.

It covers the following activities:

- A risk analysis
- A reliability calculation
- A design FMEA (Failure Mode and Effects Analysis)

Figure 6 summarizes the different tasks with their associated inputs and outputs.

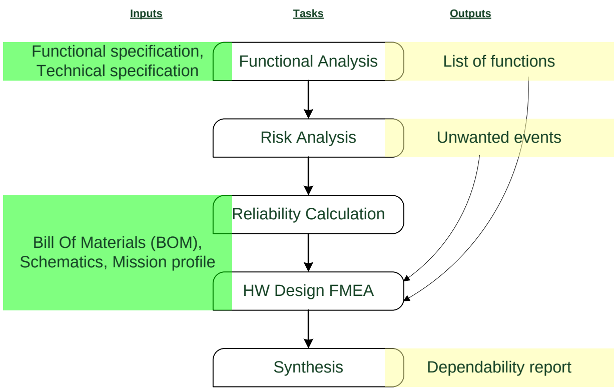

Figure 6. Dependability study.

The first step is to perform a functional analysis to provide a good understanding of the role of the product/system subassemblies in their environment. Once it has been carried out, the following is identified:

- Critical functions that could lead to the occurrence of a feared event,
- Equipment implicated in achieving critical functions

The preliminary risk analysis enables the identification of all the undesired events that are likely to occur. Then the

reliability calculations, based on the detailed Bill of Material and board mission profile, provide the data necessary for the quantification of undesired events in the design FMEA.
Finally, the design FMEA analyses the impact of the failure modes for each electronic component. It provides the probability of occurrence of the undesired event and the list of the riskiest components.

Preliminary risk analysis

Based on the functional analysis, undesired events were defined for the recloser, which are summarized in Table 2 and 3.

Table 2. List of rankings of undesired events.

Undesired event	Severity ranking
electric shock hazard	10
no trip on overvoltage	7
spurious trip	7
no trip on overcurrent	7
no trip on unbalanced current	7
Loss of voltage measurement of controller	5
performance degradation	4
EMC degradation	4
without effect	1

Table 3. List of severity scale levels [5].

Level	Severity scale
1	The effect of the default is indiscernible by the end-user
4	A light decrease of achievements make the end-user embarrassed
5	Lower achievements make the end-user unsatisfied
7	The product is out of order, the end-user is really unsatisfied
10	Potential safety problem

Reliability calculation

The IEC TR 62380 provides reliability prediction models for electronic components using mission profile as a basis for failure rate calculations. It provides a method to handle mission profiles in the failure rate prediction. Component failure is defined in terms of an empirical expression containing a base failure rate that is multiplied by factors influenced by mission profiles for example, for an active component such as a diode or a transistor the failure rate breakdowns as:

$$\lambda_{component} = \lambda_{die} + \lambda_{package} \quad (1)$$

with

$$\lambda_{die} = \lambda_{thermal\ effect} + \lambda_{EOS\ effects} \quad (2)$$

and

$$\lambda_{package} = \lambda_{thermo\ mechanical\ effects} \quad (3)$$

A good knowledge of the use and environmental conditions is mandatory to gain confidence in the calculations results. For example, for a diode the failure rate $\lambda_{thermal\ effect}$ directly depends on a temperature factor π_t:

$$\lambda_{thermal\ effect} = \lambda_0 . \pi_t \quad (4)$$

This temperature factor is determined as follows:

$$\pi_t = e^{4640(\frac{1}{313} - \frac{1}{273+T_{junction}})} \quad (5)$$

With $T_{junction}$ the junction temperature of the diode

$$T_{junction} = T_{ambient} + R_{th} . P \quad (6)$$

With R_{th} = thermal resistance; P = power dissipation

The thermal resistance is provided by the component supplier and the power dissipation is calculated by the electronic designer but the ambient temperature needs to be determined as well. Thermal simulation allows us to get accurate values without having to perform testing. Therefore, the results of the thermal simulation are a good way to justify the calculation is done considering realistic conditions.
The analyzed board contains active and passive electronic components which are mounted on a printed circuit board. The reliability assessment assumes that all components are equally necessary to perform the system function, which means that any component failure is assumed to result in functional failure of the board.
If an element failure rate is constant over time, the reliability for a single series element can be expressed as the following exponential distribution [6]:

$$R(t)_i = e^{-\lambda_i \cdot t} \quad (7)$$

where:
$R(t)_i$ = the probability of survival for a single series element for a given operating time t
λ_i = a constant representing the ith element failure rate
t = the element operating time

If each element is independent, it can be shown that the failure rate for an exponential distribution series system is the sum of the failure rates of the individual elements:

$$\lambda_{series} = \sum_{i=1}^{n} \lambda_i = \lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_n \quad (8)$$

where:
λ_{series} = a constant representing a series system failure rate
λ_i = a constant representing the ith element failure rate
λ_n = a constant representing the last element failure rate

The mean time to failures (MTTF, [6]) for an exponentially distributed series system can be determined from the reliability function or directly from the failure rate:

$$MTTF_i = \int_0^\infty R(t)_i dt \quad (9)$$

$$MTTF_i = \int_0^\infty e^{-\lambda_i t} dt = \frac{1}{\lambda_i} \quad (10)$$

where:
$MTTF_i$= the mean time to failures of single series element
λ_i = the constant failure rate of the ith element

For a series system with exponentially distributed elements the $MTTF_{series}$ can be expressed as shown below:

$$MTTF_{series} = \frac{1}{\lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_n} \quad (11)$$

where:
$MTTF_{series}$= the mean time to failures for a series system
λ_n = the constant failure rate of the n^{th} element

The results for the electronic controller board are given in Table 4. To complete the analysis the relationship between the reliability indicators and the undesired events severity is performed using Failure Modes and Effect Analysis.

Table 4. Board reliability indicators.

Failure rate (FIT, $10^{-9}h^{-1}$)	MTTF (years)
1509	75.6

Occurence probabilities of undesired events

The calculation of the occurrence probabilities is made using an exponential law at constant rate:

$$P_{UE\ i\ (25\ years)} \leq 1 - e^{-25\ years\ .\lambda_{UE\ i}} \quad (12)$$

Failure modes and effects analysis

The design FMEA analyses the impact of the failure modes for each electronic component. It provides the probability of occurrence of the undesired event. The results are shown in Table 5.

Table 5. Probability of failure occurrence over the lifetime.

Undesired event	Severity	Failure rate (FIT, $10^{-9}h^{-1}$)	Probability over 25 years
electric shock hazard	10	26	0.6%
no trip on overvoltage	7	1415	26.6%
spurious trip	7	1	0.0%
no trip on overcurrent	7	16	0.4%
no trip on unbalanced current	7	41	0.9%
without effect	1	11	0.2%

The probability of “no trip on overvoltage” over the lifetime is high due to the high failure rate of the surge arresters. Indeed, in IEC 62380 the failure rate models for interface circuits include a failure rate considered to be constant, due to external influences. This failure rate depends on the electrical environment of the equipment and lead to high failure rate of protection devices such as surge arrester and varistors.
Nevertheless, the probability of “no trip on overvoltage” is seen as acceptable as in case of overvoltage the system will trip elsewhere. The probabilities for the other undesired events are less than 1% which is acceptable. Furthermore, the reliability calculations were done with the worst-case mission profile so the results are conservative.

CONCLUSION

In this paper, the reliability analysis of an automatic circuit recloser was presented. The failure rates were calculated using the IEC 62380 procedure, so the prediction was performed considering the mission profile. To determine the mission profile and in particular the temperature conditions related to the different possible locations and consider the worst case, thermal simulation was used.
To analyze the results the study was completed with a Failure Mode and Effect Analysis to get a repartition of the failure rate by undesired events. It allows us to conclude that the probability of critical failures is very low over the complete lifetime.

REFERENCES

[1] IEC/TR 62380 Ed. 1.0, 2004, “Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment”.
[2] IEC 62271-1 Ed. 2.0, 2017, “High-voltage switchgear and controlgear”.
[3] S. Singh, R. Summer, U. Kaltenborn, 2011, “A novel approach for the thermal analysis of air insulated switchgear”, *CIRED 21th International conference on electricity distribution*, paper 492.
[4] C. Gramsch, A. Blaszczyk, H. Löbl, S. Grossmann, 2006, "*Thermal network method in the design of power equipment*", Scientific computing in electrical engineering, SCEE, 213-219.
[5] IEC 60812 Ed. 3.0, 2018, “Failure modes and effects analysis (FMEA and FMECA)”.
[6] IEC 60050-192, Ed. 1.0, 2015, “International electrotechnical vocabulary – Part 192: Dependability.