CIGRE-138 **2019 CIGRE Canada Conference**
Montréal, Québec, September 16-19, 2019

Risk-Informed Decision-Making in Asset Management of Electrical Utilities

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SUMMARY

Modern electrical power utilities are capital-intensive organizations that are fairly complex in terms of their internal structure, operations and deployed technologies. They also act in an increasingly complex business and operational environment characterized by significant uncertainties (evolution of markets/customers, changing regulatory framework, new technologies, malicious human actions, climate change, etc.). Globalization, market deregulation and tough competition are part of their typical operational and business environment. Furthermore, electrical utilities must deal with the replacement of large parts of their assets as they reach the end of their useful life or become obsolete due to technological changes. Major upgrades are also necessary due to the need to grow capacity. High-impact, low-frequency (HILF) events such as extreme weather/natural disasters, major geomagnetic disturbances and cyberattacks have become significant factors. Meanwhile, few studies have thoroughly examined the associated risks and their effects on the overall performance and vulnerabilities of electrical utilities exposed to them.

In recent decades, asset management (AsM) has become a favored strategy among successful organizations as an effective approach that delivers value from assets and ensures the sustainability of the business and operations. In practice, AsM is sometimes narrowly viewed as being essentially related to maintenance and reliability, but it actually covers much more: ISO 55000 defines it as a coordinated activity of an organization to realize the value of its assets. Asset management is composed of an array of interdependent activities and parts within a multilevel structure (people, technologies, organizational unities, processes, management, etc.). As per best practices, it is closely linked to an enterprise's strategic planning, which translates organizational objectives into AsM policy, strategy and objectives.

In such a context, decision-making as an essential AsM activity is quite challenging. A comprehensive AsM approach is vital for electrical utilities that aim to maximize the value of their assets throughout their life cycle. There are various types of decisions made in AsM: (a) capital investment, (b) operation, maintenance and replacement, (c) shutdown and outage strategies, (d) life cycle value realization, (e) resourcing strategy and so on.

In the decision-making process, it is essential to strike the right balance between numerous competing factors, such as performance, risks, benefits, costs, opportunities, short-term vs. long-term goals and sustainability. New concepts and approaches in modeling AsM and the related decision-making are needed to systematically take into account the overall complexity of the business and operating environment discussed above. A holistic, risk-informed decision-making (RIDM) methodology has been proposed for AsM of electrical utilities, in which it is considered as a complex adaptive system of systems. The models and their limits, the complexity and uncertainties, as well as the strength of knowledge of analysts, experts and decision makers, are taken into consideration. The methodology is applied and validated in a case study analyzing possible design modification strategies to a strategic transmission substation to achieve the required performance.

KEYWORDS: Asset management, electrical utilities, complex adaptive system of systems, uncertainties, risk-informed decision-making, transmission substation

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1. Introduction

Electrical power grids (transmission and distribution) are large-scale critical infrastructure, like telecommunication networks, transportation systems, and water and gas distribution systems. All these types of critical infrastructure should be considered as complex systems composed of numerous interacting components/subsystems designed to provide optimal performance and safe, reliable operations [2],[9],[11],[19]. Power grids have to deliver electricity and maintain their service level for long periods of time (several decades), going through maintenance, updating and integration of complex new technologies and increased capacity. This situation creates a dynamic operating and business environment with deep uncertainties and emerging systemic risks [1],[6],[7],[11],[13],[16],[17],[19]. It requires flexibility and adaptability to respond to new contexts (technology, society, economy, legislation, politics, climate change, etc.), which define service demand and expected performance [19].

Those conditions initiated the development of new concepts like resilience and AsM [3],[4],[5],[8],[9],[11],[14],[17],[18],[19]. AsM has become an effective approach for delivering value from assets and ensuring business sustainability. The decision-making in AsM is quite complex and requires the development of new methods and tools to adequately support it.

The paper proposes an RIDM methodology in AsM for electrical utilities, considering it as a complex adaptive system of systems. The case study assesses design modifications and impacts on performance for a strategic transmission substation at Hydro-Québec TransÉnergie.

2. Risk-Informed Decision-Making in Asset Management

Modern electrical utilities attempt to address the above-mentioned challenges using various models and tools that help decrease uncertainties and better quantify risks within their AsM decision-making processes. It is worth pointing out that assessing risks also involves seizing opportunities, given that risk should be viewed as not just negative, but as positive (opportunity) [7]. Those models and tools are typically based on traditional methods that have been revealed to be limited in effectively dealing with complexities and uncertainties [1],[2],[11],[19].

Very little work has been published on how to actually link information and insights obtained from various and sometimes very sophisticated quantitative models in AsM analyses to the decision maker’s qualitative needs. Furthermore, the impact of other barely quantifiable or intangible factors (e.g., public perception, political influence, company’s reputation) may occasionally become dominant in final decisions, yet they are quite difficult to adequately account for. So, future challenges require new ways of thinking about the complex, interconnected and rapidly changing world.

This paper presents a holistic RIDM approach for AsM in the context of operational and business complexity, with a view to addressing the challenges mentioned earlier.

The original RIDM concept was developed by the U.S. nuclear power industry with respect to nuclear safety issues in the late 1990s [15]. Since then, RIDM has been adapted to other industries, such as aerospace and dam safety [10],[11],[12]. RIDM involves considering, appropriately weighting, and integrating a range of often complex inputs and insights into decision-making that includes risks. Inputs and insights considered may come from traditional engineering analyses, deterministic and probabilistic risk analyses, operational experience, cost-benefit considerations, regulatory requirements, allowable “time at risk” (risk exposure) and any other relevant quantitative, qualitative and/or intangible influence factors and considerations. This concept is opposed to a risk-based approach in which decision-making is based solely on the numerical results of quantitative assessments [10],[11],[12].

Our proposed methodology is a three-step process: (1) establish the decision-making framework, (2) perform detailed analyses, and (3) deliberate and make final decisions (Figure 1) [10]. It should be emphasized that this process is more suitable for large projects addressing strategic concerns, such as long-term performance and sustainability. It is considered a poor fit and impractical for daily decision-making. Although important, risk assessment is only a part of the whole RIDM process, which includes a broader range of analyses (engineering, risk, economic, societal, environment, regulatory, etc.) in order to be effective. Figure 1 presents the participants involved—namely decision maker, management, stakeholders, and subject matter experts (SMEs)—and their functional roles in each step.

The overall AsM decision-making process involves control/decision steps. They are represented by a decision diamond that has three potential outcomes: Back, End, or Continue (Figure 1). A "Back" decision requires the repetition of one (or more) previous steps in order to improve assumptions, accuracy, and completeness of information/data or to perform supplementary analyses. It is iterative and enables the continuous improvement of the whole process. An "End" decision specifies the termination of the AsM decision-making process. It is vital that the decision to end the process and the rationale behind it be duly documented. A "Continue" decision involves proceeding to the next stage of the process.

Step 1 serves to adequately define the issue, the context, alternatives to be considered, the decision to be made, and suggested technical and scientific analytical methods to be used. This phase should not be underestimated and may be time consuming.

Step 2 involves performing the required detailed engineering, risk and economic analyses, along with any others that may be relevant. It is mainly carried out by SMEs and analysts using the appropriate methods, models and tools suggested in the previous step. This phase is intended to produce results, inputs and insights, as well as formulate recommendations for the decision-maker. These analyses have to be technically and scientifically sound. A more comprehensive model is necessary to perform all the required in-depth analyses, characterize uncertainties and assess the impact of relevant influence factors. Figure 2 shows more details regarding the model that is referred to as Step 2 in Figure 1. The model consists of seven submodels and is presented on the left side in Figure 2 [10],[11]. The submodels and their internal parts interact in a complex manner that leads to an emergent behavior of the whole process. Risk assessment (right side in Figure 2) is carried out in accordance with the generic ISO 31000 approach [7]. Before and during the detailed analyses in Step 2, it is highly important that participants evaluate the strength of their background knowledge of the subject. Given their opacity, this is particularly important when analyzing complex systems. Background knowledge also includes undocumented data, information and beliefs, with the latter articulated as assumptions. Weaker knowledge introduces more uncertainties into the analyses and results in lower confidence in their outcomes [10].

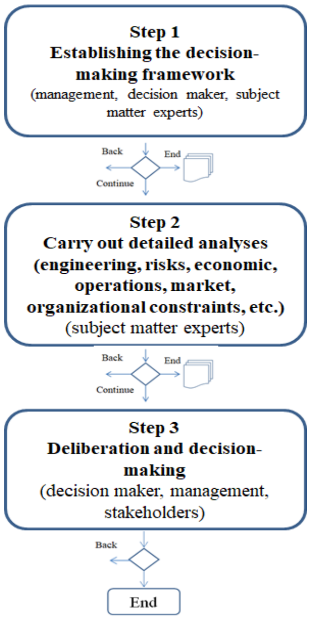

Figure 1: Global RIDM process in AsM

Step 3 of RIDM in AsM is mainly performed by the decision maker, supported by SMEs, analysts and stakeholders. The aim of this qualitative and quantitative step is to gather all relevant insights for satisfactory decision-making. Through the RIDM process, an organization gives the decision maker the authority and responsibility to make critical decisions. While the ultimate responsibility for selecting from among the alternatives belongs to the decision maker, the evaluation can be performed within a number of deliberation forums that may be held before the final selection is made. The final AsM decision should be made only after deliberations have taken place. (This is one of the differences between a risk-*informed* as opposed to a risk-*based* process.)

Deliberations are necessary because there may be aspects of a particular decision that cannot be considered formally or through the use of models. It is important to understand that deliberations do not delegitimize the use of either scientific understanding or detailed quantitative analyses. Both are important. The insights gained from Step 2 may eventually lead to the formulation of additional decision alternatives, in which case it is necessary to go back to Step 1, as indicated by the feedback loop (decision diamond in Figure 1). Without good analyses from Step 2, deliberative processes can lead to agreements that might be unwise, misleading or unfeasible.

Once deliberations are complete, the final decision is made and documented. The organization has to provide the necessary resources to implement it. This may be done as part of regular activities or as a specific distinct project, using internal or external resources. It will depend on the scale and size of activities to be carried out, as well as on the internal governing rules of the enterprise. Key stakeholders have to be informed.

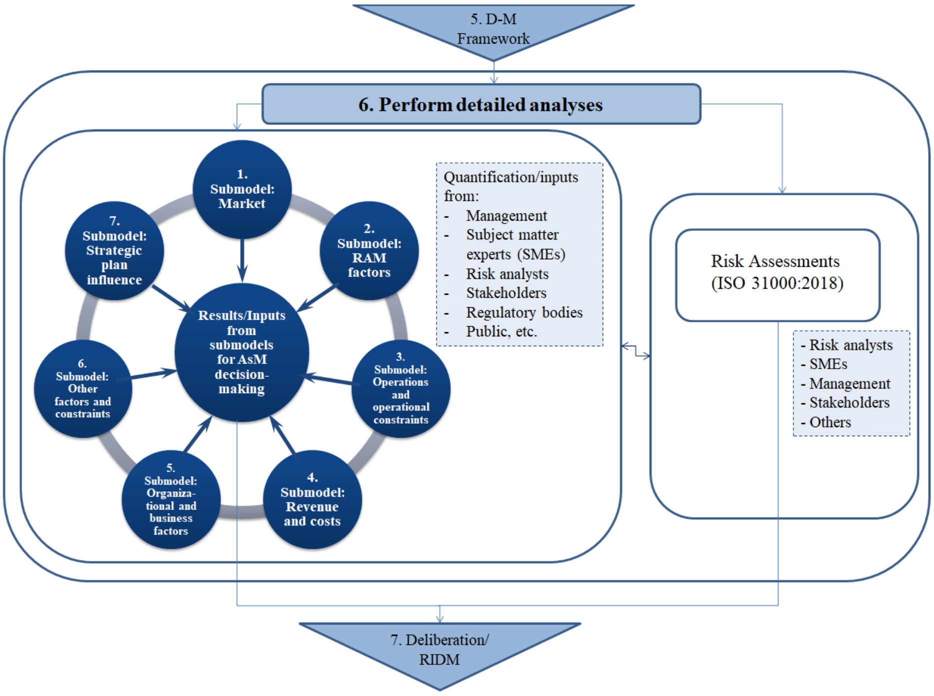

Figure 2: Model for detailed analyses in RIDM in AsM (Step 2)

3. Case Study

This case study illustrates the application of the methodology described above. Such a case study was possible thanks to the organization's maturity level and knowledge acquired in the fields of innovation, reliability, power grid engineering and asset management. It relies on models developed and improved over the last decade within the asset management team. The study introduces, for the first time, quantitative risk modeling to a transmission substation at Hydro-Québec TransÉnergie, in order to assess the impact of design modifications on performance. It follows the three-step RIDM process illustrated in Figure 1.

- Step 1. Establishing the framework

The study concerns a strategic 735/315 kV substation with two 100% redundant 1650 MVA power transformers and other equipment in the primary power path (circuit breakers, measurement transformers, disconnect switches, etc.). The entire load can be powered by a single power transformer, but normal operation uses both. There is a perception that the current substation design and an N-1 contingency are not enough to prevent loss of power to the region for a period of several days. Such a hypothetical situation could have serious societal and economic consequences, including potential loss of export earnings. It is therefore necessary to study both different substation design alternatives and risk mitigation measures. The analysis has to consider the failure patterns of physical assets, as well as human error. A sensitivity analysis has also to be performed.

The following permanent design measures are envisaged:

1. Status quo
2. Install a double high-voltage circuit breaker (HVCB) with its accompanying auxiliary equipment for each power path
3. Add another unit for the three-phase unit transformer in the substation (measures 1 and 3 have been analyzed together)
4. Install a third power path (third power transformer and other equipment)

Temporary mitigating measures include applying temporary configurations during planned extended outages and reorganizing work schedules in order to reduce the exposure duration (“time-at-risk”) in the N-1 topology. Based on discussions between SMEs, the development of reliability/risk simulation models with a multilevel method combining the dynamic block diagram (system level) and dynamic fault trees (component level) was recommended. The Monte Carlo simulation integrates the overall model by using the discrete events approach. The BlockSim® software was used to develop the models.

- Step 2. Detailed engineering analyses and results

Following the recommended approach regarding detailed analyses, two sets of models were developed. The purpose of the first set was to analyze the average performance of various nominal topologies of permanent mitigating measures over a 40-year period using both availability and the expected number of system failures as metrics (Figure 3). The simulation was performed with a one-month step. A total of 10E+05 simulations were carried out for each topology. There were no constraints regarding power flow requirements, given that the topology is almost radial. Sensitivity analyses were done for a number of component reliability characteristics, including various frequencies of human errors.

Each component/equipment behavior was modeled through different failure modes and maintenance strategies using simulated fault trees: lethal failure, reparable failure, unavailability due to maintenance (systematic, conditional, refurbishment, etc.). For each power path, the contribution of common cause failures was also considered. In the case of an N-1 topology (second set of models), availability due to maintenance was omitted, given procedural restrictions. No common cause failure (CCF) was considered in this topology. Figure 4 illustrates the dynamic fault tree of the power transformer: (a) normal topology and (b) N-1 topology. Table 1 presents summary results.

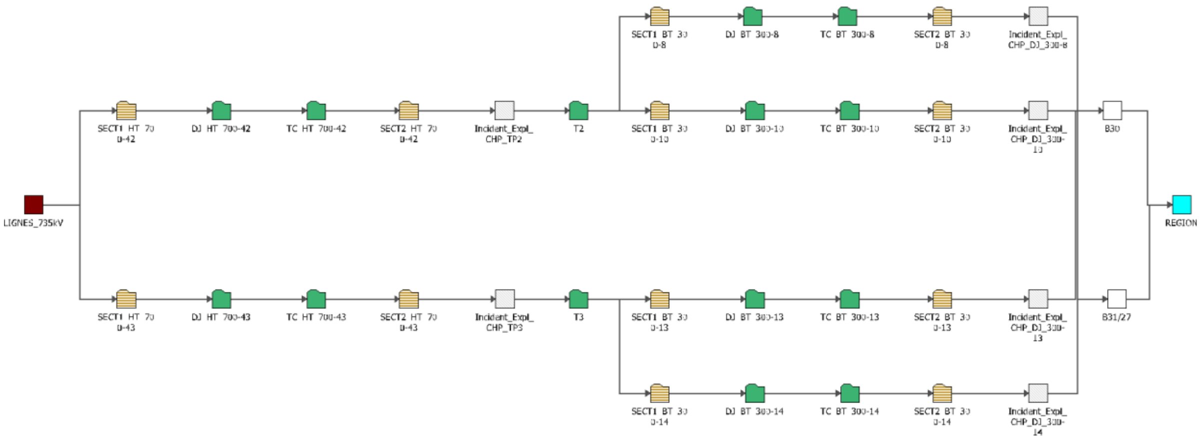

Figure 3 : System model of current topology based on dynamic reliability diagram

The component/equipment reliability characteristics (failure and repair rates) and corresponding statistical distributions were calculated using survival analysis and Bayesian approaches [5] based on enterprise historical data.

Table 1: Results for substation only

Topology	Total unavailability over 40 years due to failures (h)	Availability (all events)	Reduction of unavailability hours over 40 years (h)	Expected number of system failures over 40 years
A	B	C	$D_i = B_i - B_{(i-1)}$	E
Status quo	78.2	0.999024	0.0	0.7
Three power transformers	40.4	0.999131	-37.8	0.045
Two power transformers and two HVCBs	42.9	0.999124	-35.3	0.17

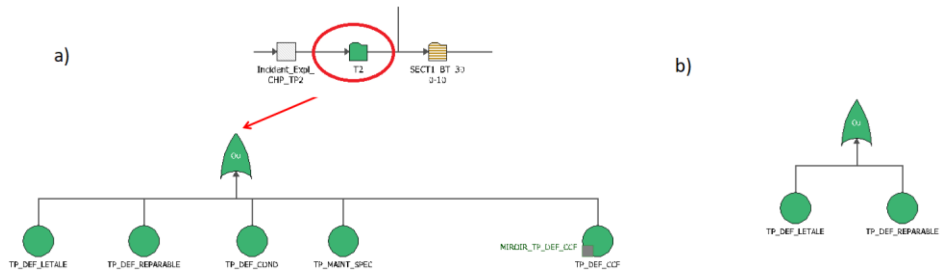

Figure 4: Dynamic fault tree of power transformer

The second set of models is designed to study degraded (N-1) topologies. A period of 9 months was considered, with reliability and the expected number of failures as corresponding metrics. A total of 10E+06 simulations were carried out for each topology, with a 12-hour step. A large number of simulations were necessary because of the low frequencies of lethal failures and the short interval of analyses. The obtained unreliability (1 – reliability) represents the level of risk of losing the substation. Since some failure rates are time-dependent (Weibull distribution), the calculations were performed for various ages of equipment/components without planned maintenance activities: new, 25 and 42 years. Table 2 shows the main results for the analyzed topologies.

Table 2: Levels of risk for different substation topologies analyzed

Model/Scenario	**Risk (Unreliability) F(t)**				**Exposure time to reach risk level of 1% (hours)**
	3 days (72 h)	**4 days (96 h)**	**1 week (168 h)**	**2 weeks (336 h)**	
TP1-DH1-IE30-LS-M09-D20_New	3.170E-03	4.050E-03	6.960E-03	1.406E-02	228
TP1-DH1-IE30-LS-M09-D20_25years	3.489E-03	4.672E-03	8.203E-03	1.640E-02	204
TP1-DH1-IE30-LS-M09-D20_42years	4.382E-03	5.849E-03	1.012E-02	2.030E-02	156
TP1-DH2-IE30-LS-M09-D20_New	2.000E-03	2.610E-03	4.840E-03	9.450E-03	348
TP1-DH2-IE30-LS-M09-D20_25years	2.161E-03	2.878E-03	5.032E-03	1.004E-02	324
TP1-DH2-IE30-LS-M09-D20_42years	2.241E-03	2.997E-03	5.273E-03	1.055E-02	312
TP2-DH1-IE30-LS-M09-D20_New	8.000E-05	1.200E-04	2.400E-04	4.300E-04	6570
TP2-DH1-IE30-LS-M09-D20_25years	8.800E-05	1.380E-04	3.090E-04	7.910E-04	2676
TP2-DH1-IE30-LS-M09-D20_42years	1.540E-04	2.360E-04	5.150E-04	1.367E-03	1440

In order to provide a better understanding of the respective influence of each type of failure (F), Figure 5 illustrates the breakdown of failure causes. It shows the proportions of major (Ma) and minor (Mi) failures of the most important pieces of equipment—circuit breaker (HVCB), transformer (Tr) and current transformer (HVCT)—and operating errors, which together account for more than 95% of all causes. Two permanent design measures, the status quo (1 HVCB) and addition of a second circuit breaker (2 HVCB) for the two sets of models (N-1 and N-2), are presented. For 2 HVCB N-1 and N-2, only the transformer failures are significant, because the path of the second HVCB provides very effective redundancy. In the case of 1 HVCB, the percentage is very similar for the N-1 and the N-2 simulations.

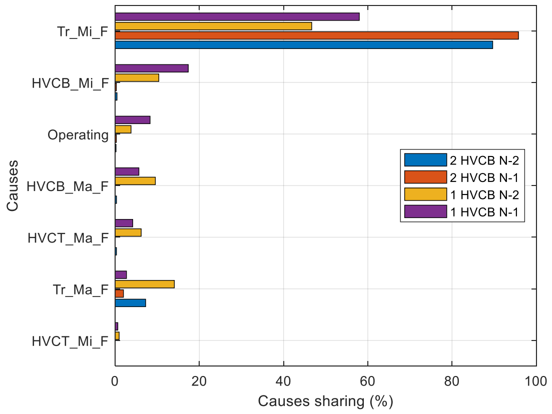

Figure 5: Proportion of incidents (%)

Focusing on the status quo permanent design measure (1 HVCB), the most frequent cause is minor transformer failure; major transformer failure is less frequent. A minor failure can be repaired rapidly in a few days, but it takes two months to replace the transformer. Figure 6 represents all the combinations of N-1 and N-2 causes, with an arbitrary acceptable level of risk of once per 100 years serving as the reference.

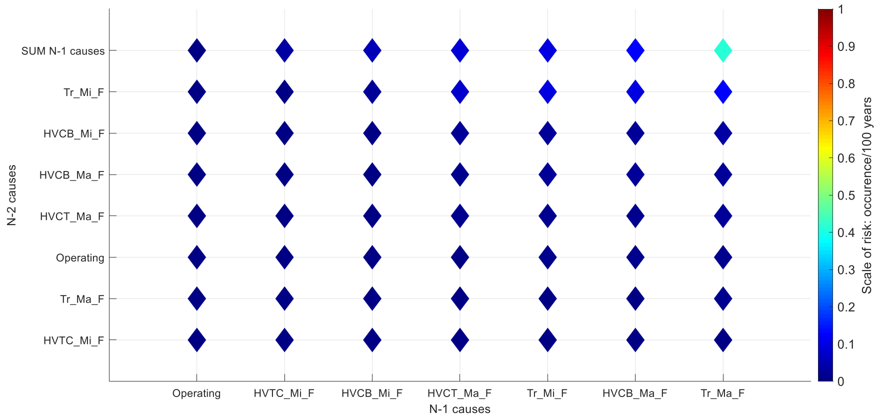

Figure 6: Combinations of N-1 and N-2 causes of a loss of load

Major transformer failure (Tr_Ma_F) is the most significant N-1 cause, representing a risk of ~ 0.4 occurrences/100 years. The total risk, the sum of the N-1 causes, is ~ 0.8 occurrences/100 years. In other words, after a major transformer failure, half of the risk comes from minor failures of the second transformer and the other half from all other failure causes.

Repair time for minor failures (RTM) and replacement time (RTT) for transformers are important parameters. Figure 7 shows the risk dependence for these parameters, where *1 HVCB RTM 2 d* means a repair time of two days and *1 HVCB RTT 60 d* means a transformer replacement time of 60 days These values are used in the original (*ori*) studies. The small variation in risk with respect to transformer replacement time can be explained by the low frequency of major transformer failures (see Figure 5).

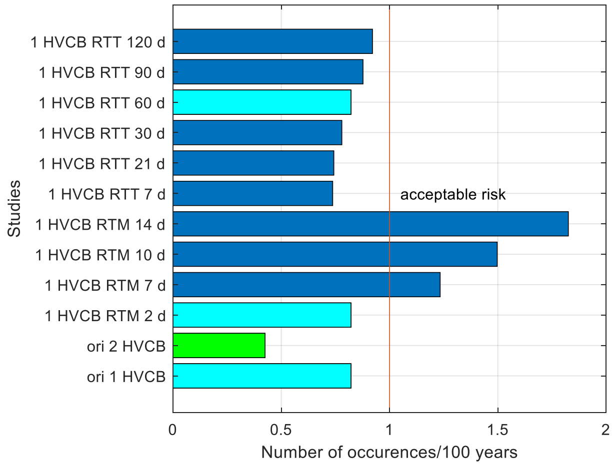

Figure 7: Risk dependence versus repair time and transformer replacement time

In order to reach the target risk of 1 occurrence per 100 years, the repair time should be between 2 and 7 days, with a target value of 5, which seems to be a good value. The effort of reducing transformer replacement time has less influence. In comparison, adding a second HVCB seems to be a good approach to reducing risk, as half of the target value is reached (Figure 7, green bar).

In accordance with the Hydro-Québec TransÉnergie risk matrix in use, the calculated levels of risk are referred to as low (under control with no need for further mitigating measures; monitoring only). The types of risk considered relevant here are level of power loss, financial risks and negative media/public perception. However, there are no clearly identified quantitative levels of acceptable risks that would help in the final decision-making process.

- Step 3: Deliberation and decision-making

This step involves final deliberation and decision-making. The above-mentioned risks are used as decision-making criteria in RIDM, to which cost figures are also added (benefit-cost ratio). Figure 8 shows the structure of the decision-making process.

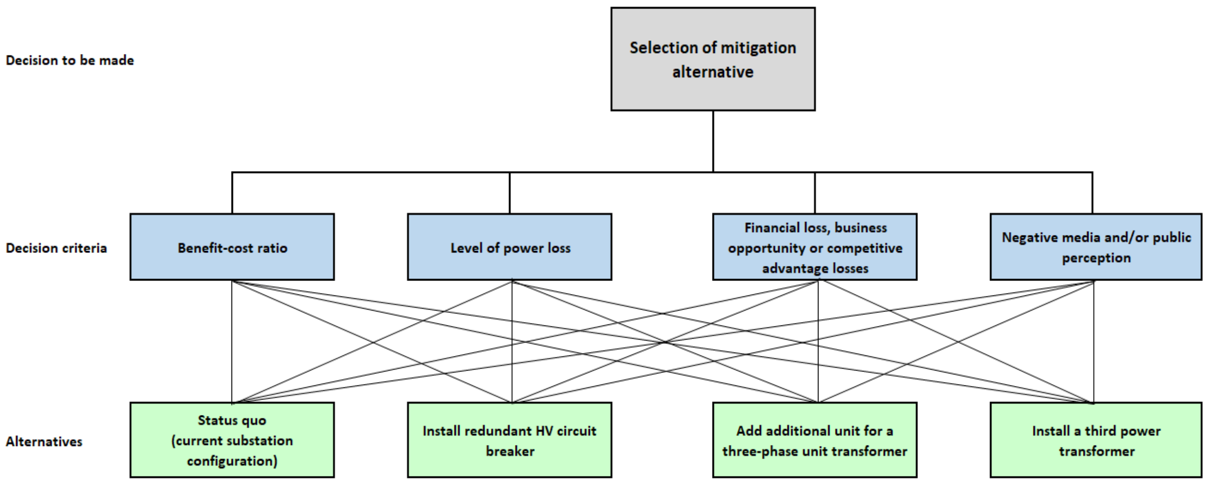

Figure 8: Decision-making criteria in RIDM

The benefit-cost ratio (BCR) has been calculated by using the traditional approach for such studies. The results obtained show that the measures analyzed have a BCR < 1.0. As of the time of writing, the deliberation process was not finished and the final decision had yet to be made.

4. Conclusions

This paper presents an integrated framework for a comprehensive decision-making process in asset management, considering it as a complex adaptive system based on RIDM. This approach is proposed to ensure a better characterization of the complex operational and business environment of modern electrical utilities.

A case study related to potential design changes at a strategic substation at Hydro-Québec TransÉnergie demonstrated the applicability of the proposed methodology. The study has shown among other things that it is necessary to define quantitative levels of acceptable risks by type in order to support efficient decision-making in asset management.

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