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A risk measurement tool for an underground electricity distribution system considering the consequences and uncertainties of manhole events

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ABSTRACT

This paper explores a risk measure of underground vaults that considers the consequences of arc faults. The increasing use of underground systems, together with the aging of networks, the lack of maintenance and interference from other (third party) underground systems nearby have caused many accidents in urban areas, thus endangering human life. The involvement of a large number (hundreds or thousands) of underground vaults with different characteristics, the lack of historical data on modes of failure, the rarity of the occurrence of some faults, the magnitude of their consequences and the involvement of a complex environment surrounding the hazard zone make risk management even more complex and uncertain. Furthermore, given that the (monetary, time, staff, etc.) resources of an electrical power company are limited and scarce, it is necessary to use decision-making tools that aggregate the consequences and the uncertainties to assess the risks jointly with the preference structure of the company, thus solving the problem more realistically. Therefore, this paper puts forward the use of an additional risk analysis for manhole events in underground electrical distribution networks with a view to its being used as a decision aid tool in risk management. As an illustration of the use of the risk measurement tool proposed, a numerical application is presented. The result rather than showing a ranking of underground vaults, gives a measure of the risk used that can show the decision-maker (DM) how much better one group of alternatives (formed by alternatives with quite similar risk values) is than other groups, based on the DM's attitude to risk and grounded on the axiomatic structure of utility theory.

1. Introduction

An electric power distribution network is a segment of the electricity system, consisting of primary and secondary electrical networks. These networks can be both overhead and underground, the latter being more complex, since they require greater investment and incur higher costs which are associated with their operation and maintenance. Thus, underground networks are only feasible in urban medium and high density networks, or when the use of an overhead network becomes technically unfeasible, or when they must be used for regulatory reasons. On the other hand, an underground system is safer for the population and has less impact on the esthetics of the landscape.

The increasing use of this type of underground distribution, together with the aging of the network, the lack of maintenance and interference from other nearby underground systems, for example, a sewage system and a natural gas distribution network, has caused many accidents in urban areas, thus endangering human life [1–3].

In the city of Manhattan, there are hundreds of manhole events every year. These events include manhole fires, manhole explosions and manholes which emit smoke [4,5]. An arc flash, which is a dangerous condition associated with the release of energy caused by an electric arc, is believed to have been the cause of several manhole fires and explosions in the secondary distribution system operated by Consolidated Edison of New York [6].

Koch and Carpentier [1] observe that even in low voltage, secondary networks, where arc failures are usually considered self-extinguishing, several arc flashes occurred which caused explosions in the underground system of Hydro-Québec's secondary network in downtown Montreal. Also, Hamel et al. [7] observe that, despite a protection system having been installed, considerable damage, even explosions, occurred in manhole events in a 600/347V system.

The involvement of a large number (hundreds or thousands) of underground vaults with different characteristics, the lack of historical data on failure modes, the rarity of the occurrence of these faults, the magnitude of their consequences and the

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involvement of a complex environment surrounding the hazard zone makes risk management even more complex and uncertain.

In general, various studies have been conducted to evaluate such infrastructure systems, and they do so by evaluating the interdependencies and vulnerability of critical systems [8–13]. There are several studies in the context of underground systems [14–19]. For example, Cagno et al. [19] propose a risk analysis methodology, which integrates vulnerability and resilience analysis. Also, the papers by [14,15] focus on the underground network of natural gas pipelines, and [16,17] focus on an underground hydrogen pipeline system. More specifically, studies on manhole events in underground electric power systems are recent and small in number, but there has been an increase in the number of publications in the area because those systems are becoming larger, more complex and older, and are causing accidents with significant consequences in several cities [1–5,18–21]. Therefore, this study is one more important step forward in risk assessment in this context.

In underground electric power systems context, several questions arise such as What underground vault is considered to have the highest risk? What is the intensity level of consequences that really is important to the decision-maker (DM)? What underground vaults or set of vaults should be considered when allocating hazard prevention or mitigation actions?

However, first, it is extremely important to identify correctly who the DM is because the decision making process can involve social, operational and economic impacts. Therefore, the DM must have knowledge and experience about the behavior of the power distribution system, such as possible failures, hazard scenarios, the dimensions of the consequences caused by accidents, and preventive and mitigation measures.

The DM must also have knowledge of the risks inherent in the context of an underground power distribution grid and also of the needs of the various stakeholders involved in the decision process, such as the vicinity of the areas affected by possible accidents, consumers and the requirements as to safety and the availability of the system which are regulated by public bodies. However, when necessary, the decision maker can be supported by experts.

Furthermore, the DM´s preferences should reflect the interests and goals of the company, as well as of the managers responsible for any consequence arising from the decision.

As the decision model is intended to be a tool to assist in risk management, we can regard some managers in key roles within the company as being DMs. Among other functions, we emphasize those in which the result of risk management serves as input information. In other words, this information helps, for example, the maintenance manager, the safety manager, or even the operational or planning manager to perform their duties. In some particular situations, the DM can be a public official who regulates and supervises the distribution network in order to ensure acceptable levels of safety and an acceptable level of availability of the network.

As to major and complex systems, Apostolakis and Lemon [22] prioritize infrastructure vulnerabilities to terrorism, using Multiattribute Utility Theory to elicit DM's preferences, and conducted a consequence-based risk analysis. Furthermore, other papers have used decision-makers' preferences to determine the extent of the impact of different types of accidents [14–18]. In contrast, Lambert and Turley [23] and Lambert and Farrington [24,25] determine a method for the allocation of localized hazard protection based on cost–benefit analysis under uncertainty, without asking a DM to precisely quantify his/her preferences.

Given that the power distribution system in operation meets all the minimum safety requirements required by regulatory and inspection safety agencies, in various situations DMs are faced with problems that are about needing to allocate or assign additional (financial, safety, time, staff, technology, etc.) resources of electric power companies to a given set of alternatives, when these resources are scarce and limited and may not have been distributed equitably. Hence, the DM faces a problem of choosing or prioritizing of alternatives to determine which alternative will be chosen (prioritized) from the perspectives of the company's needs.

In other words, decision making tools must be used that aggregate the consequences and uncertainties so that the risks are assessed jointly with the company´s preference structure, thus solving the problem more realistically. Therefore, this paper puts forward the use of an additional tool that will aid risk management for manhole events in underground electrical distribution networks.

The rest of the paper is organized as follows. Section 2 describes the risk measurement tool, under the concepts of decision theory. Section 3 differentiates the proposed methodology from a traditional risk analysis. Section 4 defines the context of the problem and the hazard scenario, and presents an event tree analysis for the arc fault. Section 5 formulates the consequence function on humans. Section 6 presents an application of the proposed model. Finally, Section 7 concludes the paper and outlines some perspectives.

2. Risk measurement

There are several definitions of the concept of risk [26–29]. Aven [27] draws up a classification system of risk definition, under a temporal analysis, in nine categories. According to Aven [27], the most appropriate definition of risk involves setting out what the consequences and uncertainties are. Therefore, what is required is to identify a set of events of interest which characterize consequences, c, and measures of uncertainty.

The uncertainties come from different sources in the model. In this context, under decision theory, the uncertainties considered are those (i) arising from the occurrence of a hazard scenario (because it is not known what hazard scenario actually will occur), (ii) arising from the consequence of hazard scenario that has occurred (because there are probabilistic mechanisms that interfere in the magnitude of the consequences).

The first uncertainty can be dealt with by using a probability distribution that represents the expert's *a priori* knowledge and/or data gathered from accidents that have occurred. The second uncertainty is modeled by a probability distribution that defines the range of possible consequences that may result from an accident.

In decision theory [30,31], the loss function can be defined as the negative of the utility function of the expected consequence [$L(c) = -u(c)$]. We can consider that consequences are the outcomes in a given dimension of the impact of an accident, and that they can be estimated by a probability distribution function $P(c|\theta, V_q)$, where θ are states of nature (hazard scenarios), and V_q is the underground vault analyzed. The utility function is defined in an interval scale between the extremes [0,1], where "0" is associated with the "least preferred" consequence and the extreme "1" is associated with the "most preferred" consequence, which is estimated in accordance with the domain of the consequences [31].

The states of nature, θ, are the possible hazard scenarios that can occur due to a failure mode having occurred. These hazard scenarios are the result of the interaction of several factors that in the end can generate an accident and, consequently, some negative impacts. This can be determined by using the event tree method, as seen in Section 4.

Thus, the utility function can be calculated by

$$u(\theta, V_q) = \int_c u(c) P(c|\theta, V_q) dc \quad (1)$$