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Systemic modelling and integrated assessment of asset management strategies and staff constraints on distribution network reliability

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ABSTRACT

Aging assets, tighter and tighter budget constraints, and Smart Grid technologies will have profound implications on the reliability of electricity distribution networks. The aim of this paper is to study the impact of changing network characteristics on its reliability in a system-of-systems ("systemic") way. A key reason for attempting this is to capture the compounding effects of interdependencies due to degrading asset reliability (for instance due to aging), different asset management strategies (including condition monitoring and automation options), and staff resource constraints when performing maintenance and repairs. A Monte Carlo based simulation tool that uses OpenDSS as a load flow engine has been specifically developed to address these issues. The model is demonstrated on an 11 kV test distribution network. The studies clearly demonstrate the need to represent the finite number of staff available for maintenance and repair activities. This limitation allows better capturing unexpected dynamics such as frequent failures reducing maintenance activities, or multiple simultaneous faults having a higher impact than randomly distributed repair times would suggest. Overall, the results thus show how a sequence of planning decisions can compound to degrade network performance much more than might be anticipated. This clearly demonstrates the case for advanced integrated network-staff modelling that needs to be carried out, as proposed in the paper.

1. Introduction

Electrical distribution reliability has been much studied over the last 50 years. However, recently the underlying network issues have become significantly more complex. This is in part due to the advent of various new technologies associated with the "Smart Grid" paradigm. These new smart grid technologies are expected to appear in large numbers over the coming decades [1]. At the same time, many assets on distribution networks are ageing, and becoming progressively less reliable [2]. Without large scale renewal, there could be a substantial increase in failure rates across all asset classes.

In order to better predict network performance, it is increasingly necessary to consider how multiple changes combine, along with network operations to form a system of systems. Due to computational constraints, historically many studies have focused on one type of system component [3] at a time. Focusing in this way delivers considerable value but can miss crucial interactions and effects that only occur on a larger system.

2. State of the art and contribution

Historically, direct (analytical) calculation approaches have been the most common way [4,5] to forecast network reliability. However, recently stochastic approaches have been used more frequently [6]. One reason for this is that stochastic approaches allow the capture of complex network behaviour, that cannot be easily described mathematically.

Often any work involving substation equipment tends to focus on just the substation [3], rather than considering the wider system. Some extremely detailed studies have focused on individual asset classes, for example transformers [7]. The advantage of this type of study is that it allows a detailed understanding of the underlying causes of asset failure. The disadvantage is that without understanding the failure rate of nearby assets, and the interactions among different assets, the overall system risk is hard to quantify, particularly in meshed systems. Nevertheless, the paper [7] demonstrates the importance of not looking at single assets when evaluating network risk, but looking at the wider network. While

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some of the phenomena demonstrated are perhaps intuitive, being able to quantify the phenomena allows a better justification of any changes to stakeholders.

The impact maintenance has on asset reliability over time has seen significant study, for which Markov states approaches [8] are typically used. Typically, these have multiple "operational" states, each representing a different stage of degradation [9–11]. In each of the states, maintenance has different effects, and the transition to full failure of the asset has different probabilities from each state. These studies are typically used for asset maintenance analysis rather than integrated into a network model. The effect of different circuit breakers facing different demands is not studied, nor is the impact of other asset failures deferring maintenance activities. Hidden failures, whereby an asset enters a state where it will fail on demand are rarely considered explicitly. Such analysis often fails to account for changes in the network around the component studied [12].

Frequently in risk studies, repair times are randomly generated and are not affected by other failures occurring on a network [13,14]. However, in reality there is a fixed amount of resource available for fixing faulted equipment. Beyond a certain number of failures, repair times increase as more failures occur. Staff constraints cannot be properly captured by adjusting average repair times, and the distribution of repair times. Firstly, it is not always possible to increase repair times by committing more staff to a repair: there is for example, a limit to how many people can excavate a cable fault, or add a new cable joint at any given time. Secondly, if the number of simultaneous repairs are limited, repair times will not increase randomly. Increased repair times due to staff unavailability will have the largest impact when the network is most under stress. Repair times will be unaffected when only one fault is present on the system. However, if multiple faults are present on the network the chance of two faults combining to keep customers off supply until repairs increases, and it is then that the increased repair times will have an effect, slowing system recovery.

Some work has been done on the effect of having limited resources for repairing faults on distribution networks [15]. However, this does not consider hidden failures, which will normally become apparent when the system is already in a degraded state. It also does not capture knock-on effects from reduced breaker maintenance. Therefore, the study misses how systems can go into a downward spiral where increased fault rates lead to reduced maintenance, in turn leading to further increased failure rates.

Many studies exist on how individual asset performance is affected by aging [16,17]. However, few studies have attempted to understand this on a system level. How average asset age could affect the severity of faults, and a network operator's ability to carry out normal maintenance activities is poorly understood.

Hidden failures in protection schemes (or circuit breakers) have been analysed in Ref. [18]. However, this study does not consider the impact when restoration resources are constrained. Nor does it demonstrate how the impact of a change in hidden failures could change, as other system parameters change.

Some have considered how changing maintenance could affect network reliability. Optimising maintenance to minimise the total cost of maintenance and outages [19–22]. These studies however, did not consider that staff carrying out repairs could lead to maintenance being deferred. Therefore, there was no consideration of the potential of a vicious cycle forming, where lower maintenance leads to more failures, which in turn leads to less maintenance.

The previously discussed papers do not capture interactions between increased failure rates, limited staff numbers and infrequent maintenance. This paper proposes a comprehensive methodology for predicting in a holistic system-of-systems ("systemic") way the reliability performance of distribution networks. The work presented in this paper predicts network reliability in the presence of staff constraints; in particular, staff constraints affect not only fault repairs but also maintenance, thus adding a new "human" dimension to traditional network studies.

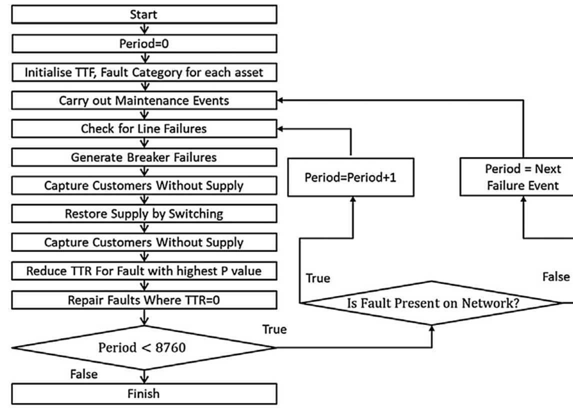

Fig. 1. Overall flow chart of the model.

The overall model used in the study is a sequential Monte Carlo simulation. The primary aim of this paper is to study the changes in risk profile when changing the reliability of several types of assets concurrently. Given that finite resources are available to repair faults, and hidden failures can cause multiple faults to occur simultaneously.

The key contribution is to show how to represent network operators having limited resources for both preventing and resolving faults. This study is expanded to demonstrate that the effect of resource constraints is most significant when different asset classes (lines, circuit breakers and transformers) degrade and fail more frequently.

This paper is organized as follows. Section 3 is a methodological section describing how each part of the model operates; this includes modelling of asset failures and repairs, maintenance, condition monitoring, and network switching. Section 4 contains several case studies. These studies highlight the implications of different asset failure rates, in the presence of resource constraints. Section 5 contains final remarks.

3. Methodology for network reliability analysis

This paper describes a sequential Monte Carlo simulation implemented in C# using OpenDSS [23] to provide load flow solutions. OpenDSS was used to identify which circuit breakers would operate to clear a fault, and which loads would be without supply as a result of that operation. Furthermore, when reconfiguring the network, OpenDSS was used to ensure that all current constraints were satisfied, and to identify which loads were without supply.

The model simulates the effect of having finite staff available to carry out work on the network, capturing the impact of staff constraints on both maintenance and repairs. The aim of the model is to enable better prediction of network reliability when multiple changes to network operations occur. The methodology is based on sequential Monte Carlo simulation. A three-state failure model is used for circuit breakers, to represent hidden failures, and a two-state failure model for other equipment. A flow chart summarizing the overall process is shown in Fig. 1.

The model initially starts by generating a time to fail (*TTF*) for each asset. The model also generates a fault category for each fault determining how maintenance may affect that potential fault, which is explained in Section 3.1.

In each simulated period, the model first evaluates maintenance events. If a maintenance event is to occur, the next selected asset undergoes maintenance, potentially avoiding asset failure.