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Assessing survivability to support power grid investment decisions

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ABSTRACT

The reliability of power grids has been subject of study for the past few decades. Traditionally, detailed models are used to assess how the system behaves after failures. Such models, based on power flow analysis and detailed simulations, yield accurate characterizations of the system under study. However, they fall short on scalability.

In this paper, we propose an efficient and scalable approach to assess the survivability of power systems. Our approach takes into account the phased-recovery of the system after a failure occurs. The proposed phased-recovery model yields metrics such as the expected accumulated energy not supplied between failure and full recovery. Leveraging the predictive power of the model, we use it as part of an optimization framework to assist in investment decisions. Given a budget and an initial circuit to be upgraded, we propose heuristics to sample the solution space in a principled way accounting for survivability-related metrics. We have evaluated the feasibility of this approach by applying it to the design of a benchmark distribution automation circuit. Our empirical results indicate that the combination of survivability and power flow analysis can provide meaningful investment decision support for power systems engineers.

1. Introduction

The reliability of power distribution systems has been widely studied for decades [1–5]. The fundamental problem consists of determining how the system behaves when faced with disruptions, and is generally tackled using detailed simulations and power flow analysis [6–8]. Different system characteristics, such as the workload and the availability of backup sources, are taken into account.

The result of detailed power flow analysis and simulations of power systems is an accurate assessment of how the system will behave under the considered configurations. Although the assessment is very precise, it falls short on scalability. The high computational costs preclude the analysis of a large number of configurations, and practitioners have to focus on the most likely or promising setups. Our goal is to propose metrics, models and heuristics to explore the state space in a principled, scalable and effective way that can guide equipment upgrades. The outcome of our analysis is a set of promising circuits, which should then be subject to more detailed investigation.

In this paper, we focus on survivability-related metrics and models to address the challenge of determining promising upgrades. Survivability-related metrics are computed assuming that the system starts in a failure state. They account for the phased-recovery of the system, i.e., how the system behaves since failure up to full recovery. By assuming that the system starts in a failure state, survivability-related metrics do not need to account for failure rates, which are typically orders of magnitude smaller than repair rates. This way, the proposed models to compute survivability-related metrics are amenable to easy solution, as we do not deal with stiff problems. In addition, the proposed survivability models do not need to capture the detailed state of all the system components. To increase scalability, we aggregate the sections of the power system in groups, depending on whether they are connected to a power source, and show how this simplifies analysis.

The proposed survivability-related models allow us to predict how the system behaves after changes. Such changes might be due to failures or due to investments. Consider a power utility company which has a given budget to invest in its circuits. The investments must account for equipment costs, as well as for the gains in terms of reliability and stability. To this end, we suggest heuristics which make use of survivability-related models and metrics to issue recommendations for investments.

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This paper extends [9] by providing (1) a combined availability and survivability model that covers the whole failure and recovery behavior of the studied systems (Sections 3 and 4), (2) a formalization of the optimization problem under consideration (Sections 6.1–6.3), and (3) a detailed description of the heuristics used to solve the optimization problem (Section 6.4).

This work is based on our previous work on survivability assessment of power grids. In [10] we presented an analytical model to assess the survivability of distributed automation power grids. Then, we investigated the application of such model to scenarios with multiple failures [11], using historical data to parametrize the proposed model [12], and studied algorithmic aspects related to the network upgrade optimization problem [13]. Compared to our previous work, the focus of [9] and of the paper at hand is on the *combination of power flow analysis and survivability modeling* to achieve the optimal design of distribution automation grids. The main contributions of the paper are summarized in two groups as follows.

Survivability model: We propose survivability-related metrics and models to capture the phased-recovery of the system from failure up to recovery. Power flow algorithms are used to parameterize the model. The model allows us to predict how the system will behave after failures and investments.

Survivability improvement: We leverage the predictive power of the proposed survivability model to issue recommendations on investments based on survivability-related metrics. Given a budget, we consider heuristics to sample the solution space in a principled way, accounting for equipment costs and survivability gains. The efficient and scalable exploration of the solution space may be followed by detailed analysis of the most promising circuits.

The outline of this paper is as follows. In Section 2 we motivate the use of survivability metrics for the assessment of distributed automation grids. Then, in Section 3 we present real data on availability and survivability from a Brazilian utility. Section 4 derives a combined availability and survivability model and highlights its limitations, thus motivating the need for the aggregated phased recovery model described in Section 5. We present the optimization model used in this paper in Section 6. The analysis of our empirical results is presented in Section 7. Section 8 presents our conclusions and suggests future research.

2. Design methodology

In this section we introduce an overview of the system and models considered in this paper.

2.1. System overview

The power distribution network comprises a set of substations, renewable resources (e.g., Wind Power, Solar), load management (e.g., Demand Response), and devices associated with power distribution (e.g., lines, tap-changing transformers, capacitor banks, etc). The power distribution network is set up to guarantee that supply will equal demand, and that stability conditions are met. However, demand might go beyond predicted bounds, which might lead to instabilities. This occurs, for instance, due to failures of devices, incorrect load management, intentional attacks, or weather conditions (e.g., disruptions due to hurricane Sandy in the US [14,12]). In this paper our focus is on the latter. Our goal is to issue investment recommendations to mitigate instabilities.

2.2. Terminology

Next, we introduce some basic terminology.

Availability model: captures failure and repair of resources. It accounts for the rate at which different components of the system fail.

Survivability model: phased-recovery model (or simply recovery model) characterizing the time-varying system behavior from failure up to full recovery [15].

Performance model: characterizes the performance of the system at different states. In this paper, performance is measured through the expected energy not supplied per time unit, and is captured through reward rates associated to each state.

Performability model: combination of performance model with availability and/or survivability model.

Power flow model: receives as input a set of load points and a circuit, and generates as output the angles and voltages (active and reactive power) associated to each section.

Violation matrices: matrices indicating for each section and for each load point whether the angle or voltages are beyond expected limits.

2.3. Overview of models

In this section we introduce the different models and optimization methodologies considered throughout this paper. We briefly describe reliability model, survivability model and survivability-based optimization (Fig. 1) and point out the fundamental motivations and goals associated to each of them.

The combined availability and survivability model presented in Fig. 1(a) receives as input historical data about failure rates and recovery times of different system components. It yields steady state and transient reliability metrics, and is flexible to capture the interdependencies between failure and recovery of different system components. However, its solution might involve working with a stiff system as failure rates are typically orders of magnitude smaller than repair rates.

In Fig. 1(b) we consider the survivability model. It characterizes the system from failure up to recovery, and does not involve failure

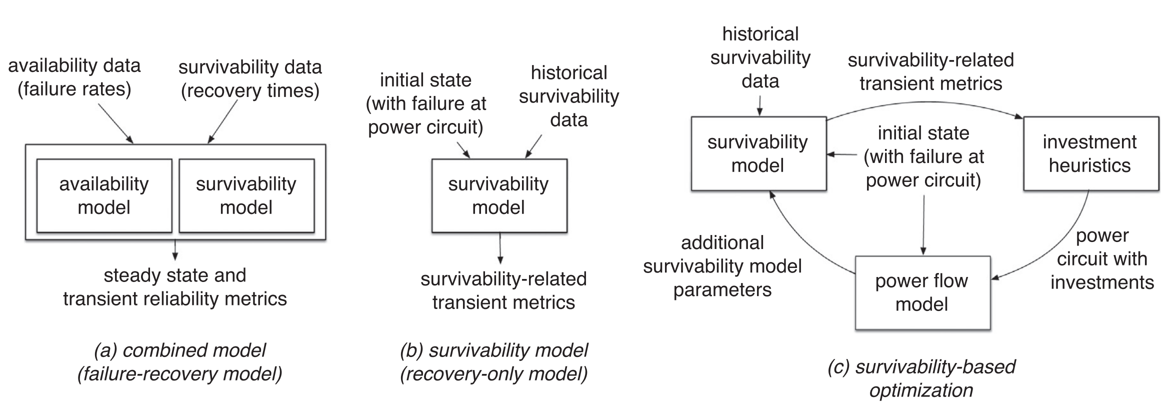

Fig. 1. Methodology overview. In Sections 4, 5 and 6 we discuss the two models and the optimization approach described in (a), (b) and (c), respectively.