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Transient performance analysis of smart grid with dynamic power distribution

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ABSTRACT

Transient performance analysis of power distribution network (PDN) after a failure occurrence could facilitate the better design of smart grid. Researchers have proposed analytical models and the numerical solutions to analyze the PDN's transient behaviors by applying homogeneous continuous-time Markov chain (CTMC). However, the PDN system may be time-varying during a failure recovery. Then, the system restoration process evolves as a non-homogeneous CTMC (NHCTMC) on a finite state space. This paper seeks to analyze the transient performance of such a time-varying system from a failure occurrence until the system's full restoration. This restoration process consists of multiple phases which are sequential or in parallel. We apply piecewise constant approximation method to derive the formulas for computing state transient probabilities and then derive the computation formulas for the metrics of interest. A case study is conducted to apply the proposed approach to analyze the transient performance of a simple distribution automation network. This network was derived from a real power distribution network.

1. Introduction

Smart grid is a power grid which utilizes communication systems, and power and energy technology to enhance the efficiency, reliability, economics, and sustainability of electric power systems [3]. With the increasing penetration of demand response (DR) programs [18] and distribution automation (DA) into smart grid, there is a pressing need for the reliability and transient performance analysis of the power distribution network (PDN).

This paper focuses on exploiting the state-space modeling techniques to analyze the transient performance of the PDN system after a failure occurrence to the system. The analysis results could help improve the systems' capability to provide critical services when damage occurs to part of the system or the whole system. However, such analytical analysis is not easy. The reasons are as follows. There are a variety of factors affecting the transient performance, such as current production, demand profile, demand side intelligence and backup power storage. The interplay of these factors brings challenges to the modeling of the PDN's transient performance. Moreover, the PDN is being growing larger and more geographically expansive with many inter-connections between neighboring systems. This feature of large scale further intensifies the complication of the transient performance modeling and the corresponding analytical analysis.

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Table 1
Notations.

Notation	Definition
q_{AR}	Probability that both active and reactive backup power for $i+$ is enough
q_{AnR}	Probability that active backup power for $i+$ is enough but reactive backup power is not enough
q_{nAR}	Probability that active reactive backup power for $i+$ is not enough
$\alpha(t)$	Automatic repair rate at time t
$\beta(t)$	Demand response rate at time t
$\delta(t)$	Manual repair rate at time t
$rR(t)$	Probability that demand response program for reactive power is effective at time t
$rA(t)$	Probability that demand response program for active power is effective at time t

The existing analytical models and the numerical solutions analyzed the PDN behaviors by applying homogeneous continuous-time Markov chain (CTMC) [2,9,14]. However, the PDN system may be time-varying after a failure occurrence. For example, when a PDN component fails, demand response (DR) resources may be scheduled to speed up the power restoration of those parts, which do not fail but their power is affected by the failed component. The fact is that this scheduling in DR market may fail to reduce their loads for DR events. Some external factors, such as DR event duration, natural human inertia and external temperature [31], often make the load reduction fail when requested. It is true that collecting the historical data about customer behaviors may help predict customer actions and then determine system parameters. But customers may change their consumption patterns unexpectedly. Namely, customer behaviors are unstable, changeable and unpredictable. In addition, the utility provider behaviors may not be stable. Therefore, some PDN recovery process parameters may change during a failure recovery, such as α, β, and δ, which are defined in Table 1. The existing models cannot characterize the transient behaviors of such time-varying system.

This paper seeks to use non-homogeneous continuous-time Markov chain (NHCTMC) to characterize the time-varying PDN system restoration process after a part of PDN fails. The time-dependent performance-related metrics are computed under the condition that the system initially is in a failed state. We apply piecewise constant approximation (PCA) [22] technique to carry out the transient performance analysis of our NHCTMC model. PCA divides the recovery time into shorter intervals, in each of which all the system parameters are constant and then the system is a homogeneous CTMC in a small interval.

The main contributions are summarized as follows:

(1) We apply non-homogeneous continuous-time Markov chain model for capturing the time-varying PDN recovery behaviors.
(2) We apply PCA technique to derive the expressions for computing states' transient probabilities. Given these expressions, we further derive the expressions of performance-related metrics of interest.
(3) We present a case study on how the proposed approach analyzes the transient performance of a simple distribution automation network, which was derived from a real power distribution network.

The proposed NHCTMC-based model and the numerical solutions could allow for the accurate assessment of the PDN transient performance by tracking the time-dependent states of the system under study. Meanwhile, they enable the effective investigation of the cost/benefit trade-offs of active and reactive distribution power generation investment. Note that although this paper focuses on the transient performance analysis of smart grid, the proposed approach can be applied to the other systems, such as communication networks and intrusion tolerant database systems.

The rest of the paper is organized as follows. Section 2 presents some background knowledge and related work. Section 3 presents the system model and model solutions. In Section 4, we present evaluation results. The conclusions are drawn in Section 5.

2. Background and related work

This section first introduces some background knowledge, focusing on those related to our recovery model. The presented knowledge forms the basis of the system description of Section 3.1. Then related work is presented.

2.1. Background knowledge

2.1.1. Power distribution network system

The PDN system consists of a set of substations, distributed side generation/load management (e.g., Demand Response) and equipment associated with power distribution (e.g., lines, tap-changing transformers, capacitor banks, etc). In an alternate current (AC) circuit, active power is the power dissipated by the resistive elements of the circuit. Reactive power is the power which is drawn from the source, stored temporarily in the reactive elements and then returned to the source in a later part of each cycle. Power flow is defined as the flow of both active and reactive power from one node of the system to another node through different network buses and branches. Both the loads and the power of distribution generations affect voltage profile in the power distribution network. In a PDN, stability conditions must be satisfied in order to assure that