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Reliability assessment in smart distribution networks

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ABSTRACT

The development of the future energy system will be based on planning and management of the distribution system in accordance with the Smart Grid philosophy. This approach involves the extensive use of information and communication technology and innovative control systems in order to enable the realization of smart distribution systems, the active participation of demand, the availability of energy storage, as well as the integration of distributed generation and renewable energy sources and the expected growing number of electric vehicles in distribution networks. The important question that still remains unanswered is how much reliable should be the functioning of the whole future power, information, and communication infrastructures. The increasing complexity of the future distribution system implies to go beyond the classical deterministic contingency analysis with the application of a more correct stochastic approach. Being aware of this, the authors developed a new tool for the reliability assessment of the future distribution network based on a Pseudo-Sequential Monte Carlo simulation. The reliability models of the main power system components, of the renewable generation, and of the communication infrastructure have been considered in the methodology, permitting the simulation of the whole smart distribution system and the estimation of the effects on its reliability performance of the wireless communication system outages.

1. Introduction

Due to the drastically changing nature of the power networks users (less controllable electricity generation and increasingly varied electricity consumption), the architecture and technology used for the transmission and distribution grids and their system interaction will need to change. The challenges of this transformation will grow in the next 20 years as a result of the programmes for energy efficiency in buildings with the increased presence of zero or positive energy buildings, i.e. equipped with their own energy sources for self-consumption or for selling part of their exceeding production to electricity operators, and the full incorporation of renewable energy sources (RES), which by nature exhibit fluctuations in availability and productivity. Energy storage will be required in order to efficiently cover the mismatch between the energy demands and the RES generation, and the use of electric vehicles and their need for both slow and fast charging infrastructures will also need to be considered.

As this scenario approaches, the large majority of power system stakeholders, including governments, are becoming fully aware that the power distribution networks must be cost-optimally re-engineered according to Smart Grids paradigm [1]. Indeed, without involving huge investments, the traditional distribution networks would become less stable and supply interruptions may occur much more frequently. On the contrary, with aimed investments at information and communication technologies, a smart distribution network (SDN) could monitor, control and automate the system for achieving a positive integration of the various distributed energy resources (DER) with an increased exploitation of the existing distribution asset.

This active management of the distribution networks may have a twofold impact on the distribution system reliability. On one hand, it can ameliorate the traditional reliability indexes (SAIDI and SAIFI) for passive loads and the availability of the connection for independent producers by means of specific operation practices, such as: on-line reconfiguration to alleviate load transfer restrictions [2], intentional islanding to improve the reliability of customers supplied with pure radial network schemes [3,4], self-healing and auto-reconfiguring networks to drastically reduce the number of customers that suffer a long interruption [5,6], coordinated Volt/VAR control to limit the occasions of curtailment or complete disconnection of independent producers in case of abnormal operating conditions [7]. On the other hand, there are some concerns, particularly from utilities, that the adoption of new SDN technologies can jeopardize the high level of reliability generally achieved by current distribution systems. Indeed, in contrast with the common practice where technical constraint violations are avoided (or minimized) at the planning stage, the smart control will

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Table 1
Remedial actions against violation of technical constraints.

Contingency	Current passive distribution networks	Future smart distribution networks
Undervoltage	Generally not monitored. Solved with proper network planning.	All contingencies will be potentially solved by the smart management (DERs control, responsive loads, on-line reconfiguration). Need of network monitoring and state estimation.
Overvoltage	Caused by DG. Solved with proper network planning. Maximum voltage relay.	
Overload/thermal constraints	Traditionally solved with the intervention of the breakers installed at the beginning of the feeders. Some utilities have started also the installation of additional coordinate breakers along the feeder.	Deep redesign of the protection system with the full integration of breakers along feeders for on-line reconfiguration and intentional islanding.

be used to solve many contingencies in the operation stage directly when they appear, deferring some network investments dictated by the traditional passive approach as summarized in Table 1.

In an ideal representation of the control system (always available with no errors in the control procedures and in the communication), the SDN clearly improves or at least preserves the reliability of the existing distribution system with less network costs. But, every system can fail, and the reliability of the active management and the ICT system can impair the overall performances of the distribution system.

According to the previous considerations, two kinds of reliability analysis are requested for the SDN. The first category should be focused on the quantification of the benefits introduced by new schemes [2–4]. The second one, instead, should explicitly consider the reliability of the enabling technologies, and particularly of the cyber network (e.g. information and communication infrastructures), needed to implement specific SDN applications in order to evaluate their effect on the reliability of the whole system. Indeed, in the last category, the main interest is addressed to the interdependencies among control, ICT and power systems (cyber-physical reliability analysis), because the future distribution networks will be heavily reliant on communications and control working as intended in [8–11].

The increasing complexity of the SDN requires the resort to modern stochastic methods for reliability evaluation. For this reason, the authors developed a new tool for the SDN reliability assessment based on the Pseudo-Sequential Monte Carlo (PSMC) simulation method. The procedure, presented in its initial form in [11], has been better detailed in this paper and improved to take account of the performance degradation of wireless communication, used to manage the distribution system, due to adverse atmospheric conditions. In particular, a meteorological model has been integrated in the reliability tool to simulate the occurrence probability of transmission impairment caused by rain fade.

2. Distribution system reliability assessment methods

The distribution system reliability assessment methods permit calculating the reliability of distribution system from system configuration, system operation, and component reliability data. This estimation is becoming increasingly important as electric industry becomes more competitive, regulatory agencies regulate reliability, and customers ask for performance guarantees.

Historically, the reliability analysis of the distribution system has been conducted separately from the generation and transmission systems, due to the problem complexity and dimension. Moreover, the absence of generation, the passive network operation and the simple network topology that have typically characterized the distribution system in the past years, have permitted the adoption of the “contingency analysis” (or “N-1”) deterministic criterion for the reliability studies [12]. However, the growing presence of the renewable energy sources, with their inherent intermittency and unpredictability, and the future adoption of the smart management of the network, make the distribution system even more comparable, if not more complex, with the generation and transmission system. Consequently, also the reliability analysis becomes more complicated and should be based on the same techniques adopted for the generation – transmission composite system.

Several approaches have been developed to evaluate power system adequacy, grouped into analytical methods or Monte Carlo simulation. The first category represents the system by mathematical models and evaluates the reliability performance of a power system by using numerical algorithms. They use system topology along with mathematical expressions to determine reliability indices. Monte Carlo simulation, instead, estimates the reliability by simulating the actual process and the random behaviour of the system, and computes indices by simulating the conditions on the system by generating system states of failure and repair randomly. Therefore, by handling the problem as a series of experiments, Monte Carlo simulation can include system effects which may have to be approximated with a direct analytical method, making this approach more flexible when complex operating conditions and system considerations need to be incorporated. Two main Monte Carlo methods are typically used: the non-sequential and the sequential one.

Non-sequential Monte Carlo simulation is a state space based algorithm, where Markov models are usually used for both equipment and load state transitions. Then, with non-sequential Monte Carlo, the states are extracted and evaluated without any chronological dependency determining the systems response to a set of events whose order have no influence or significance. Instead, sequential Monte Carlo simulates the systems operation by generating an artificial history of failure and repair events in time sequences that can reproduce all chronological aspects. This feature is fundamental when complex time correlations have to be taken into account, but, as a drawback, it requires a significant increase of the computational burden. Some variations of these two Monte Carlo simulation techniques have been proposed trying to preserve their advantages and overcome their drawbacks. A promising variation, the Pseudo-Sequential Monte Carlo simulation, was proposed for the first time by Leite da Silva in 1994 [16], by combining the quicker non-sequential selection of the system state with the sequential analysis of the neighbouring states only when the extracted initial state is a failure state. Not being a pure sequential simulation, it cannot provide all the detailed results of the sequential approach (i.e. only the expected value and not the whole probability density function of the reliability indexes). However, by preserving the sequential examination of the failure states, it maintains the chronological description of the system behaviour and the capability to represent complex operating procedures that will be implemented in the future SDN. Therefore, thanks to its flexibility and accuracy, as well as the reduction of computational effort, the pseudo sequential method has been preferred in the paper in place of the sequential Monte Carlo approach.