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Risk-based planning of the distribution network structure considering uncertainties in demand and cost of energy

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ABSTRACT

Technical and financial uncertainties may put distribution system planning at risk. In this paper, a new risk-based planning method is proposed which pays more attention to low-probability and high consequences events in energy supplying systems. The proposed approach is adopted for determining the optimal structure of a Medium Voltage network where risk-based determination of the radial network structures is implemented through an uncertainty model of the system's variables based on discrete states, called scenarios. The cost of distribution system planning consists of investment cost, maintenance cost, power losses cost, reliability cost, and technical risk cost. In this paper, appropriate models are proposed to consider the monetary effects of technical risks. The proposed approach is applied to a test system consisting of 52 electric load points and two substations. It is observed that the proposed risk-based method for planning the optimal network structure can properly reduce the cost of extreme events, therefore reducing the concerns of distribution system operators about these possible situations.

1. Introduction

Distribution system planning and the economic and reliable design of distribution networks are important challenges for electrical distribution companies. In an electrical distribution network, a feeder is the group of electrical lines (overhead lines or cables) starting from the supply point (an electrical substation) and connecting a group of loads. Each feeder has a radial topology, and in general multiple feeders start from an electrical substation. For an electrical distribution system, the number of lines existing in the system is larger than the number of loads, in such a way to have a number of redundant lines maintained open in each radial configuration of the network. The lines to maintain open are chosen during the definition of the paths (or routes) with which the loads are served, in such a way to serve all the loads and to maintain the network radial. This selection is indicated as *feeder routing* in the technical literature.

The planning of distribution networks can be divided into two sub-problems including substation location and feeder routing. Substation location, size and its services are determined in the first problem, while the size of the feeders and their routes are indicated in the second one. In this paper it is assumed that the substations are already positioned, and the optimal feeder routing is discussed.

Different approaches for feeder routing have been presented during past years. There are large numbers of discrete variables in distribution system planning and various mathematical programming techniques, such as mixed integer programming [1], branch and bound methods [2], and transportation [3] have been used to solve the problem of feeder routing optimization. However, by using these models, the solution time increases and it is difficult to achieve the optimal solution. In recent years, metaheuristic methods such as particle swarm optimization (PSO) [4], genetic algorithm [5], and teaching learning optimization [6] have been extensively used in distribution network planning. Using these optimization techniques, the nonlinearity of the cost function and constraints can be easily incorporated in the formulation. However, the solution of these methods may be a local optimum. A different approach based on branch-exchange techniques has been applied in deterministic planning of distribution system [7] and in long

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Nomenclature

C_{Tot}^{s}	Total cost of planning in Scenario s ($)
C_{Ex}	Expected planning cost over a set of scenarios ($)
C_{Inv}	Investment cost ($)
C_{Int}^{s}	Interruption cost in Scenario s ($)
C_{L}^{s}	Power losses cost in Scenario s ($)
C_{OM}^{s}	Maintenance cost during in Scenario s ($)
C_{TR}^{s}	Technical risk cost in Scenario s ($)
$C_{OC}^{b,s}$	Cost of overcurrent risk in feeder b in Scenario s ($)
$C_{UOV}^{n,s}$	Cost of undervoltage/overvoltage risk at node n in Scenario s ($)
$C_{ODT}^{\tau,s}$	Cost of distribution transformer overload risk for transformer τ in Scenario s
CVaR_{α}	Conditional VaR with probability level α percent
OF	Objective function
VaR_{α}	Value at risk with the probability level α percent
D_{n}^{s}	Energy demand of node n in Scenario s (kVA)
FIC_{b}	Feeder installation cost ($/km)
FMC_{b}	Feeder maintenance cost ($/km)
$FP(.)$	Penalty function of voltage quality (pu)
I_{b}^{rated}	Thermal rating of feeder b (A)
I_{b}^{s}	Current of feeder b in Scenario s (A)
K_{el}^{s}	Electricity price in Scenario s ($/kWh)
K_{pl}^{s}	Economic savings per active power reduction in the peak power for Scenario s ($/kW)
L_{b}	Length of feeder b (km)
$LL_{b}(.)$	Loss of feeder b life in Scenario s as a function of feeder current (pu.$)
LOL_{τ}^{s}	Loss of life transformer τ in scenario s (year)
oc_{n}	Outage cost for load point n ($/kWh)
PNL^{max}	Maximum damage cost to a customer due to undervoltage or overvoltage ($/kW)
r_{b}	Resistance of the branch b (kΩ/km)
TIC_{τ}	Transformer τ installation cost ($)
V_{n}^{s}	Node voltage in Scenario s (kV)
$V_{\min}$	Minimum allowed voltage (kV)
acf	Annual cost factor
$cos\phi$	Loads' Power factor
DN_{b}	Downstream nodes of branch b
LF	Load factor
LSF	Load loss factor
N_{b}	Number of branches
N_{n}	Number of load points
N_{s}	Number of scenarios
N_{τ}	Number of distribution transformers
r_{d}	Discount rate
ρ^{s}	Probability of Scenario s
$\psi_{Rf}, \psi_{Df}, \psi_{Ep}, \psi_{Dl}$	Sets of discrete distributions of failure rate, failure duration, energy price, and load, respectively

term planning considering uncertainties [8]. This approach is a mathematical method which finds a pseudo-optimal solution in an admissible computational time also for large-scale real distribution networks.

The problem of power systems' planning has been traditionally developed using deterministic models. However, in recent decades, new probabilistic models have been introduced to consider uncertainties in power systems. In this approach, the goodness of a solution can be measured through a particular set of scenarios, each one with a given probability. The expected cost over the set of considered scenarios is calculated and the optimal solution is chosen to minimize this expected value. However, this planning approach has encountered several challenges in its generalized adoption [9].

Furthermore, in recent years, a risk analysis approach has been suggested for power system planning and has been well developed in some literature contributions to assess [10] and manage [11] the operational risk of power system. This approach chooses the preferred scheme while considering its cost in extreme events and is well understood by planners who have experienced real and practical problems. The word *risk* considers both the probability of occurrence of an event that harms or damages people or equipment, and its consequences generally assessed in economic terms. The important issue that should be considered in power system planning is that it is not possible to have a plan without risk. But the risk should be managed and a certain level of risk should be accepted when it is technically and economically admissible. The risk-based planning mainly concentrates on the decision about the admissible level of risk.

In electrical distribution networks, the sources of risks are some parameters having probabilistic behaviors. In order to manage these risks, the risk-based planning of distribution networks is used which pays more attention to low-probability and high consequences events. A risk-based allocation of distribution system maintenance resources is presented in Ref. [12], where a method to allocate maintenance resources to various distribution system assets is proposed. To determine the effects of maintenance, a predictive reliability assessment tool is developed. A risk management method is introduced in Ref. [13] to reduce the negative electrical vehicles (EVs) effects, where stochastic models of EVs, renewable resources, and availability of devices are proposed to evaluate the system reliability comprehensively. It is assumed that the system is at risk when the energy demand is more than the generation capacity. By using the managed charging of EVs, the risk level of smart grid and its adequacy have been improved.

In distribution planning, most of papers are not considering the risk concept and its monetary consequences. In this paper, the consequent impacts of risk and probabilistic events on the distribution network are modeled as a monetary term called *cost of technical risks*. A risk-based method for optimal routing of MV feeders is proposed and the effect of technical risks on the distribution network is investigated. In the presented approach, the probable events, including overcurrent of MV feeders and variations of node voltages more than acceptable values, are considered as technical risks. The feeder routing problem is solved using a customized version of the branch exchange method where the optimal configuration of distribution network is determined in accordance to a predefined objective function including costs of installation, maintenance, power losses, reliability, and technical risks.

The novelty of this contribution is the exploitation of the risk-based concept called Conditional Value at Risk (CVaR), used in financial analysis, for optimal planning of a distribution network structure, based on modeling the consequence impacts of probable events (including overcurrents and variations of node voltages beyond acceptable values) by using costs of technical risks.

This paper is organized as follows: Section II introduces the proposed feeder routing method. Section III describes the proposed