Renewable and Sustainable Energy Reviews 37 (2014) 778–793

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A risk-based simulation and multi-objective optimization framework for the integration of distributed renewable generation and storage

Rodrigo Mena [a], Martin Hennebel [b], Yan-Fu Li [a], Carlos Ruiz [c], Enrico Zio [a,d,*]

[a] Chair on Systems Science and the Energetic Challenge, European Foundation for New Energy-Electricité de France, at École Centrale Paris—Supelec, Grande Voie des Vignes, F-92295 Châtenay-Malabry Cedex, France
[b] Supelec, Energy Department, F-91192 Gif-sur-Yvette Cedex, France
[c] Universidad Carlos III de Madrid, Department of Statistics, Avda. de la Universidad 30, 28911 Leganes, Madrid, Spain
[d] Politecnico di Milano, Energy Department, Via Ponzio 34/3, 20133 Milano, Milano, Italy

ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form
15 May 2014
Accepted 17 May 2014

Keywords:
Distributed renewable generation
Uncertainty
Conditional value-at-risk
Simulation
Multi-objective optimization
Genetic algorithm

ABSTRACT

We present a simulation and multi-objective optimization framework for the integration of renewable generators and storage devices into an electrical distribution network. The framework searches for the optimal size and location of the distributed renewable generation units (DG). Uncertainties in renewable resources availability, components failure and repair events, loads and grid power supply are incorporated. A Monte Carlo simulation—optimal power flow (MCS-OPF) computational model is used to generate scenarios of the uncertain variables and evaluate the network electric performance. As a response to the need of monitoring and controlling the risk associated to the performance of the optimal DG-integrated network, we introduce the conditional value-at-risk (CVaR) measure into the framework. Multi-objective optimization (MOO) is done with respect to the minimization of the expectations of the global cost (C_g) and energy not supplied (ENS) combined with their respective CVaR values. The multi-objective optimization is performed by the fast non-dominated sorting genetic algorithm NSGA-II. For exemplification, the framework is applied to a distribution network derived from the IEEE 13 nodes test feeder. The results show that the MOO MCS-OPF framework is effective in finding an optimal DG-integrated network considering multiple sources of uncertainties. In addition, from the perspective of decision making, introducing the CVaR as a measure of risk enables the evaluation of trade-offs between optimal expected performances and risks.

Contents

* Corresponding author. Tel.: +33 1 41131606.
E-mail addresses: rodrigo.mena@ecp.fr (R. Mena), martin.hennebel@supelec.fr (M. Hennebel), yanfu.li@ecp.fr (Y.-F. Li), caruizm@est-econ.uc3m.es (C. Ruiz), enrico.zio@ecp.fr, enrico.zio@polimi.it (E. Zio).

http://dx.doi.org/10.1016/j.rser.2014.05.046
1364-0321/

1. Introduction

Over the last decade, the global energetic situation has been receiving a progressively greater attention. The adverse environmental effects of fossil fuels, the volatility of the energy market, the growing energy demand and the intensive reliance on centralized bulk-power generation have triggered a re/evolution towards cleaner, safer, diversified energy sources for reliable and sustainable electric power systems [1–6]. The challenges involved have stimulated both technological development of new equipment and devices, and efficiency improvements in design, planning, operation strategies and management across generation, transmission and distribution.

In this paper, we focus on distribution networks and the conceptual and operational transition they are facing. Indeed, the traditional passive operation with unidirectional flow supplied by a centralized generation/transmission system, is evolving towards an active operational setting with integration of distributed generation (DG) and possibly bidirectional power flows [7,8].

DG is defined as 'an electric power source connected directly to the distribution network or on the customer site of the meter' [8–10] and in principle offers important technical and economical benefits. Under the assumption that the distribution network operators have control over the dispatching of the DG power, improvement of the reliability of power supply and reduction of the power losses and voltages drops can be achieved. Indeed, DG allocation on areas close to the customers allows the power flowing through shorter paths, and therefore, decreasing the amount of unsatisfied power demand and enhancing the power and voltage profiles. Thus, the eventual intermittence of the centralized power supply can be smoothed [11]. In addition, the modular structure of the DG technologies implies lower financial risks [12,13] and thus the investments on the power system can be deferred [1,3].

Most of the actual DG technologies make use of local renewable energy resources, such as wind power, solar irradiation, hydropower, etc., which makes them even more attractive in view of the requested environmental sustainability (e.g., the Kyoto Protocol [7,14,15]). Given the intermittent character of these energy sources, their implementation needs to be accompanied by efficient energy storage technologies.

Attentive DG planning is needed to seize the potential advantages associated to DG integration, taking into account specific technical, operational and economic constraints, sources and loads forecasts and regulations. If the practice of selection, sizing and allocation of the different available technologies is not performed attentively, the installation of multiple renewable DG units could produce serious operational complications, in fact, counteracting the potential benefits. Degradation of control and protection devices, reduction of power quality and reliability on the supply, increment in the voltage instability and all related negative impacts on the costs, could become impediments for integration of DG [1–3,8,10,14,16–20].

Viewing DG planning as a fundamental baseline of advancement, many efforts have been made to solve the associated problem of DG allocation and sizing. Objective functions considered for the optimization are of economic, operational and technical type. Among the first type, cost-based objective functions have been used considering the costs of energy and fuel for generation, investments, operation and maintenance, energy purchase from the transmission system, energy losses, emissions, taxes, incentives, incomes, etc. [1–3,7,8,11,13,14,16–27]. The second type of operational objective functions mainly revolves around indexes such as the contingency load loss index (CLLI) [23], expected value of non-distributed energy cost (ECOST), system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI) [7,16,28], expected energy not supplied (EENS) [28,29], among others. Regarding the third type of objective functions, technical performance indicators include energy losses [1,30] and total voltage deviation (TVD) [18].

Power Flow (PF) equations are typically solved within the optimization problem to evaluate the objective functions, while respecting constraints and incorporating non-convex and nonlinear conditions. Given the complexity of the optimization problem, heuristic optimization techniques belonging to the class of Evolutionary Algorithms (EAs) have been proposed as a most effective way of solution [10], including particle swarm optimization (PSO) [23,24,27,31,32], differential evolution (DEA) [18] and genetic algorithms (GA) [3,7,11,13,14,16,26,33,34].

An additional difficulty associated to the problem is the proper modeling of the uncertainties inherent to the behavior of primary renewable energy sources and the unexpected operating events (failures or stoppages) that can affect the generation units. These uncertainties come on top of those already present in the network, such as intermittence and fluctuation in the main power supply due to unavailability of the transmission system, overloads and interruptions of the power flow in the feeders, failures in the control and protection devices, variability in the power loads and energy prices, etc. These uncertainties are incorporated into the modeling by generating a random set of scenarios by Monte Carlo simulation (MCS); the optimization is, then, executed to obtain the optimal expected or cumulative value(s) of the objective function (s) under the set of scenarios considered [2,3,7,16,28,32,34,35].

In the search for the optimal DG-integrated network, the use of only mean or cumulative values as objective function(s) of the optimization hinders the possibility of controlling the risk of the optimal solution(s): the optimal DG-integrated network may on average satisfy the performance objectives but be exposed to high-risk scenarios with non-negligible probabilities [1,7,16,24,28,36].

The original contributions of this work reside in: addressing the optimal renewable DG technology selection, sizing and allocation problem within a simulation and multi-objective optimization (MOO) framework that allows for assessing and controlling risk; introducing the conditional value-at-risk (CVaR) as a measure of the risk associated to each objective function of the optimization