Applied Energy 217 (2018) 456–466

Contents lists available at ScienceDirect

Applied Energy

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

Analysis of demand response and photovoltaic distributed generation as resources for power utility planning

Matheus Sabino Viana[*], Giovanni Manassero Junior, Miguel E.M. Udaeta

Department of Electrical Energy and Automation Engineering, University of São Paulo, USP, Avenida Professor Luciano Gualberto, travessa 3, no. 158, CEP 05508-010 São Paulo, SP, Brazil

HIGHLIGHTS

- Methodology based on rational use of electricity determined by economic efficiency.
- Power flow analysis and consumers' bill savings evaluation with DR and/or PVDG.
- Evaluation of substation peak demand and energy consumption.
- Verification of voltage limits of loads and power losses in lines and transformers.
- Sensitivity analysis through statistical method is applied to the case study.

ARTICLE INFO

Keywords:
Advanced metering infrastructure
Demand response
OpenDSS
Photovoltaic distributed generation
Power losses analysis
Power utility planning

ABSTRACT

This study aims to analyse the price-based demand response (DR) and photovoltaic distributed generation (PVDG) for developing an approach to model them as energy resources for power utility sustainable planning. The methodology involves a case study based on the IEEE 8500-Node Test Feeder with a distribution substation and 1177 low-voltage consumers, using the open distribution system simulator (OpenDSS). The methodology includes the use of a typical retail pricing practice such as time-of-use (TOU) tariff for residential consumers' DR and net metering for distributed micro-generation provided by rooftop photovoltaic (PV) systems. The highest levels of DR and PVDG on weekday in a group of responsive residential consumers (RRCs), which represents 26.6% of the total load in the feeder, resulted in 6.3% reduction in substation peak demand, 9.3% reduction in substation daily energy consumption, and 13.2% reduction in daily energy losses in lines and transformers compared to the base case with flat tariff, without DR and PVDG. The highest daily average bill savings of RRC samples compared to the base case were 35.2% with the highest levels of DR and PVDG and 36.3% with the highest level of PVDG and without DR, indicating a situation in which regulatory changes are necessary to stimulate DR simultaneously with PVDG, such as in the case of optional TOU tariff, the so-called white tariff, in Brazil. The quantification of DR and PVDG potential contributes to the planning of modern distribution networks in which end users can participate more actively, enhancing the sustainability of electrical energy systems.

1. Introduction

The evaluation of alternative resources to meet the growing electricity demand is an essential aspect in the development planning of developing countries. The electricity sector needs to integrate novel options in the energy planning methodology, considering both supply resources and the use of energy as fundamental elements to achieve sustainable development [1].

According to the vision of UK specialists, smarter grids are necessary from economic and environmental perspectives. Although risks and barriers exist, their implementation can enable meaningful savings in network expansion and facilitate the transition to low-carbon energy systems [2].

Typically, residential consumers billed through a flat tariff based on energy consumption do not have an economic signalling, such as higher prices during peak demand or system contingencies, to which they can respond with demand reduction [3]. Time-of-use (TOU) tariff, critical peak pricing, and real-time pricing (RTP) are time-based programs in which price variations of energy over time produce changes in consumers' demand profile, or price-based demand response (DR) [4–7].

The other type is incentive-based DR, in which users receive a payment for participating in demand reduction programs such as direct

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[*] Corresponding author.
E-mail addresses: matheus.s.viana@usp.br (M.S. Viana), manassero@usp.br (G. Manassero), udaeta@pea.usp.br (M.E.M. Udaeta).

https://doi.org/10.1016/j.apenergy.2018.02.153
Received 24 November 2017; Received in revised form 21 February 2018; Accepted 23 February 2018

load control, curtailable load, and demand-side bidding, as described in [5,6,8,9], or in ancillary services market, as mentioned in [7]. Distributed resources such as physical storage or thermal inertia also provide electricity demand flexibility for consumers [10].

The recent cost reduction of photovoltaic (PV) technology [10] and the need of renewable distributed generation (DG) development [8] bring out the possibility of photovoltaic distributed generation (PVDG) expansion in distribution systems.

From the perspective of alternative resources incorporation to power utility planning, the motivation for this study is the evaluation of DR and PVDG as energy resources for sustainable development of electrical systems.

Advanced metering infrastructure (AMI) is an important element of smart grids to boost DR potential, since it makes possible bidirectional communications, such as acquisition of consumers' demand information by power utilities and signalling to consumers for energy price variations over time [5,8].

Ref. [11] presents studies in the field of smart grids, highlighting the development of plug-in hybrid electric vehicles (PHEVs), distributed energy resources (DERs), DR, and the interaction between smart grids and other types of networks such as gas grid in the broader context of intelligent energy systems.

A strategy to integrate renewable resources with DR and thermal comfort optimization in microgrids was presented in [12]. The integration of DERs and responsive load demand through an energy management system using a stochastic approach was considered in [13], aiming to provide sustainable scheduling for smart microgrids.

DR was identified as an essential aspect of smart grids in [5], where incentive programs to stimulate changes in consumers' consumption patterns and a review of DR modelling were presented. The use of AMI and integrated social approach for individuals' behavioural change and improvement in energy efficiency was explored in [14]. Ref. [9] evaluated the impact of different DR levels on the voltage profile and technical losses of a distribution network in response to day-ahead RTP and highlighted the importance of DR models to achieve implementation of consistent DR contracts between aggregators and utilities.

A review of DR opportunities, challenges, and barriers focusing on the study of production cost and generation aspects was presented in [4]. Ref. [15] compared DR modelling tools from the viewpoint of economic dispatch.

Ref. [16] emphasized DR and DG as important elements for evaluating the efficiency of smart grids. The influence of DR and pricing schemes on the expansion of residential PVDG was discussed in [17]. According to [18], a significant part of opportunities in Germany's PVDG market was not explored by utility companies of that country, but by investors from outside the electric sector. DR, DERs, and demand side management were analysed in [19–22]. Refs. [23–25] investigated DR and DERs in the context of distribution planning.

An active network planning method integrating incentive-based DR tested in a 33 kV 16-bus rural network model was proposed in [26]. Ref. [27] presented a planning model for distribution systems considering DG and demand side response (DSR) resources mainly through interruptible load with the use of an algorithm to obtain the best DSR plan and DG sizing and allocation, analysing examples in a 42-node distribution system model based on real network data. However, Refs. [26,27] did not evaluated neither the potential of price-based DR of residential loads nor random DG allocation based on the economic efficiency pursued by consumers.

Ref. [28] presented an assessment methodology for statistical studies using randomly generated networks with similar characteristics derived from real network data to analyse the impact of low-carbon technologies on electric distribution systems, aiming at the future development of an evaluation tool for large-scale statistical analysis of multi-energy systems.

To the best of our knowledge, few studies have conducted detailed power losses analysis in distribution systems involving DR and renewable DG, frequently using small-scale models. Ref. [29] compared line losses with traditional optimization and a proposed one, which considered DR and maximizeed social welfare using smart grid technology in a modified IEEE 30-bus test case. In [21], a 32-bus distribution system with DERs was used to compare power losses under different supplier electricity prices. Ref. [30] presented the power losses results in a case study with an approximation considering only two distribution feeders, to which a closed-loop linear programming model with DR and variable renewable generation systems was applied. A method for DERs allocation and network optimal reconfiguration considering peak power losses and using the IEEE 33-bus and 69-bus test feeders was presented in [31].

In the context of Brazil, research has been conducted on the application of smart grid technologies to the electric distribution sector [32] and to the integration of end users from this perspective [33].

In Brazil, tariff flags [34] indicate to low-voltage retail-captive consumers the monthly cost of electricity generation without reflecting variations during the day. Consumers of group A, with supply voltage equal to or greater than 2.3 kV, are billed by demand and energy consumption with differentiation of energy price during the day. The white tariff is an optional TOU tariff for consumers billed as group B (low-voltage) to be implemented according to the calendar defined in [35], which starts in 2018.

The access of distributed micro-generation and mini-generation to electric distribution systems in Brazil was defined by [36–38] using the net metering pricing scheme [17].

1.1. Contribution of this study

The contribution of this study is the structuring of a novel approach to evaluating DR and PVDG as energy resources for power utility planning aiming at sustainable development, through rational use of electricity determined by economic efficiency. This approach focuses on the applicability to detailed analysis including power losses, and demand and energy consumption evaluation with large-scale representative models such as the IEEE 8500-Node Test Feeder used for the case study, as defined in Section 3.

The approach proposed in this study can also be used for virtual power players and aggregators [21].

The rest of this paper is organized as follows: Section 2 presents the procedures for a combined analysis of DR and PVDG; Section 3 presents the network model for the case study; Section 4 synthesizes DR and PVDG aspects and Section 5 characterises the analysis of the system. Section 6 presents the results for the case study and for the sensitivity analysis and Section 7 presents the conclusion.

2. Combined analysis of DR and PVDG

This section describes a general approach to achieving the objective of evaluating DR and PVDG as energy resources for power utility planning.

2.1. Modelling of distribution network and typical daily load curves of consumers

The case study identification and its location are considered for selecting a network topology that in conjunction with typical load curves composes the base case. Different penetration levels of DR and PVDG can be defined to evaluate the effects on the distribution system, as presented in Section 2.2.

Defining demand as the load average power for a time interval, the equation for describing a load curve in per unit (p.u.) can be expressed as

$$d_{load\,pu}(t_i) = \frac{\overline{P}_{load}(t_i)}{P_{base\,load}} \tag{1}$$