Electrical Power and Energy Systems 81 (2016) 184–192

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A fuzzy clustering approach to a demand response model

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ARTICLE INFO

Article history:
Received 18 February 2015
Received in revised form 7 January 2016
Accepted 25 February 2016
Available online 9 March 2016

Keywords:
Demand response
Smart grid
Fuzzy clustering
Load management

ABSTRACT

This paper proposes a novel demand response model using a fuzzy subtractive cluster approach. The model development provides support to domestic consumer decisions on controllable loads management, considering consumers' consumption needs and the appropriate load shape or rescheduling in order to achieve possible economic benefits. The model based on fuzzy subtractive clustering method considers clusters of domestic consumption covering an adequate consumption range. Analysis of different scenarios is presented considering available electric power and electric energy prices. Simulation results are presented and conclusions of the proposed demand response model are discussed.

Introduction

Smart grid concept is at the present time the main motivation for future electricity systems development [1] contributing to an electricity systems convergence, providing further opportunities to distributed generation integration (mainly renewable energy) and allowing consumers to assume proactive actions in demand side management [2]. The success of smart grids depends greatly on the motivation of consumers to play an active role in grid management. Therefore, the consumer's engagement in smart grid first stage initiatives is considered crucial to avoid failing risks [1]. In smart grid context, demand response (DR) is an essential demand side management action for consumers [3]. In fact, the behavior management is of primer importance, namely in what the power consumption shaping is concerned, resorting to time-scheduling or load shedding [4]. The behavior management goal is to reduce or shift electric energy usage from unfavorable to more favorable periods [5]. DR aims to stimulate end-use consumers to change their consumption patterns [6] throughout special designed programs, giving support to domestic consumers' decisions on controllable loads management.

DR is considered a favorable approach for increasing electric energy demand elasticity [7]. The power consumption diagram shaping contributes to a unit commitment reduction, as well as to a reduction on short-time call of power plants, i.e., contributes to the decrease of the necessary spinning reserve secure level but also contributes to the delay of power plants construction, especially of those aimed to accomplish the peak hour energy consumption satisfaction or to satisfy future forecasted increase of consumption [8]. Moreover, if power consumption diagrams shaping allows an air pollutant emissions reduction due to a smaller use of fossil-fuels based power plants, an environmental political payment is performed [9–11].

DR as characterized by [12] can be said as the electric energy consumption reduction from the expected consumption, in response to an increased energy price or to a payment incentive, i.e., is an energy price and also a demand function [13]. Also, DR is an available power function and also a consumption needs function, in a considered time period. These function arguments depend on the generation capacity, the power generation costs and the consumption profiles.

In smart grid perspective, distributed generation must be considered in order to characterize the generation capacity. Assuming that distributed generation is mainly derived from renewable energy [2,14], the resulting generation capacity depends on the resorted renewable energy and its corresponding availability. Additionally, it must be considered that the referred generation capacity should be able to satisfy demand peaks [15]. Consequently, due to the increase of the renewable resources generation in association with its intermittence and variability characteristics,

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http://dx.doi.org/10.1016/j.ijepes.2016.02.032
0142-0615/

the calculation of the generation scheduling, needed to meet demand, is a challenge. However, this renewable resources increasing generation can be conveniently accommodated by DR programs, contributing to an adequate balance between supply and demand [5].

DR is said to be as one of the strategies encompassed on demand side management (DSM) [4] which is characterized as a management action performed on demand side of an electric system, or a more favorable electric system management resulting from consumers' performed actions with cost reduction outcomes [16]. The DSM objective is to achieve an electric energy demand magnitude change or time pattern change, presenting advantages in system reliability and economic performance improvement [17]. Consumer actions are the resulting designed measures to be incorporated on energy control systems, attained by processes such as energy efficiency (EE), time of use (TOU), spinning reserve (SR), besides the referred DR [16].

Also DR, as characterized by [18], is the electric energy consumption pattern change due to a consumer's response to electric energy price (EEP) in a time period. DR gathers all intentional consumer consumption pattern modification used to promote electric energy consumption time changes, in instantaneous demand level or in total electric energy consumption. Additionally, DR contributes to support grid operators in order to ensure the balance between supply and demand, [19] through load management in a time period (i.e. turning off lights or changing air conditioner set points). These strategies can also include, in the future, the electric vehicles charging cycle management [20].

DR classifications

DR programs are classified in accordance with different criteria. Because the majority of DR programs provide solutions to specific scenarios, the comparison between the existing programs is not straightforward [8] and the classification is non uniform. Despite the existence of non uniformities, some similarities can be found in each classification [6,16,18,21–23]. Commonly, the programs are classified into two major types: Time-Based Program (TBP) [6,18,21,22], which is also named as Price-Based Programs (PBP) [6,18], Time-Based Rate program (TBR) [24] and Incentive-Based Program (IBP).

More recently, in [25] these DR programs are divided in three sub-types: Price Options, Incentive- or Event-Based Options, and Demand Reduction Bids.

In TBP, the electric energy price changes in different time periods accordingly to electric energy supply cost [26]. Within TBP the consumption diagram is shaped due to the higher prices offered during peak hours and lower prices during off-peak hours. In power systems scope, the TBP aims to increase competition, to decrease market power, to improve reliability and to allow renewable energy applications [24]. TBP encompasses the following programs [18,22,23,25]: time of use (TOU), critical peak pricing (CPP), real-time pricing (RTP), Extreme Day Pricing (EDP), Extreme Day CPP (ED-CPP), variable peak pricing (VPP) [27] and critical peak rebates (CPR) [27]. A brief description of TBP is here summarized: TOU programs consist on fixed price block rates that differ in one day [25] and reflect the higher supply cost during peak hours and lower costs during the off-peak hours [28]; CPP consists on rates which include a pre–specified extra-high rate, settled by the utility, and that has a limited number of duration hours [25]. CPP seeks to express to consumers the true power generation costs by providing a price signal that more accurately reflects electric energy costs. On the remaining hours consumers generally have discounts and if they are able to move loads from more expensive hours to the less expensive hours, their electric energy bill will decrease [28]; RTP consists on continually changing rates, commonly in a hourly basis, as response to wholesale market price [25]; EDP are similar to CPP because it also has high rates, but these rates have a 24 h duration of that one extreme unknown day, until a day-head [18]. ED-CPP consists on established rates for peak and off-peak periods in extreme days, but a flat rate on the remaining days [18]; VPP consists on a hybrid TOU and RTP, where the different pricing periods are previously defined, but the established price for peak periods differs from utility and market conditions [27]; CPR consists on consumer refund of a predetermined value, for any consumption reduction in relation to the costumer's expected consumption, when the utility anticipates or verifies the existence of high wholesale market price, power system emergency conditions, or critical events during pre-specified time periods [27].

In IBP the electric energy price changes at pre-settled times or in a dynamic way, according to the day, week or year, and to the existing reserve margin [25]. As TBP, IBP programs have higher EEP on peak hours and lower EEP on off-peak hours. The EEP settlement can be established in a day in advance, on an hourly, or daily basis, or even in real-time conditions. The consumer adapts its behavior according to price changes [25]. IBP encompasses the following programs: direct load control (DLC), interruptible/curtailable (IC), demand bidding/buyback (DBB), emergency DR (EMDR), capacity market (CM), ancillary services market (ASM) [18,21,22]. In [18], DLC and IC programs are considered classical IBP and DBB; EMDR and CM are considered market based IBP. A brief description of IBP programs [25] follows: in DLC, consumers receive payment incentives for allowing the utility to have a determined control degree over certain equipment; in IC, programs consumers obtain a price cut rate for agreeing to decrease load by request; in DBB, consumers offer bids to restrain load, when wholesale market prices are high; in EMDR, consumers receive payment incentives for load restrain when they are needed to ensure system reliability; in CM, consumers receive payment incentives for load restrain as a system capacity substitute; and finally, in ASM, consumers receive payment from grid operator for committing to load restrain, when needed, to support the electrical grid operation.

DR advantages and disadvantages

In DR programs, consensus can be found on: (i) energy reduction during peak times; (ii) contribution to facilitate the balance between supply and demand; (iii) and relief of the contingence management conditions, avoiding outages in transmission and distribution system. Additionally, DR allows consumers to reduce electric energy bills. DR programs contribute to adjourn investments in power grid reinforcement and to increase the power grid reliability. DR programs can avoid investments in peaking utilities, reducing reserve capacity requirements and it allows more renewable energy penetration. In electric market scope, DR programs contribute to reduce price volatility and provide wider consumers' price options [25].

It is generally accepted that the main disadvantages of DR programs are related to the potential lack of consumer's knowledge or information to deal with varying EEPs and to analyze the different incentive based programs, offered by the utilities. Nevertheless, the smart grid increasing implementation drives DR programs deployment [29].

DR has been focused mainly on large industrial and commercial sectors. For residential sector the information, communication requirements and assessment methods are not at the same development level [5]. However, it is well accepted that residential demand response contributes significantly to energy reduction [12].