Electrical Power and Energy Systems 97 (2018) 353–362

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A novel two-stage structure for coordination of energy efficiency and demand response in the smart grid environment

Sobhan Dorahaki[a], Masoud Rashidinejad[a,*], Amir Abdollahi[a], Mojgan Mollahassani-pour[b]

[a] Department of Electrical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[b] Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran

ARTICLE INFO

Keywords:
Demand response
Energy Efficiency Programs (EEPs)
Economic analysis
Unit commitment

ABSTRACT

In recent years, Energy Efficiency Programs (EEPs) have been greatly expanded in multifarious aspects. Here, EEPs is considered as a virtual resource affecting operating expenditures of the power system. On the other hand, under the smart environment, Demand Response (DR) programs are also contemplated as virtual power plants in energy policy decisions ranging from short term to long term. Therefore, in this paper, a novel integrated model of demand in presence of EEPs as well as DR programs has been nominated. The presented model is handled in a Two-Stage Structure to Coordinate the EEPs and DR programs, namely $\text{TSSC}_{\text{DR}}^{\text{EEP}}$. In the first stage, the level of Energy Efficiency Investment (EEI) is determined over the midterm horizon time. In the next stage, regarding the rate of EEI, a unit commitment problem incorporating EEPs as well as DR programs is handled while the interactions between EEPs and DR have been scrutinized. The proposed problem is implemented in GAMS. To evaluate the capability of EEPs and DR programs coordination, several analysis are carried out on the IEEE 10-unit to confirm the capability of the proposed framework from economic aspect.

1. Introduction

In the last decades, the growing energy consumption has increased the operation expenditures in electricity sector which causes to release the large amounts of greenhouse gases into the atmosphere. However, smart grid utilization is considered as an efficient tool to decline the negative impacts of growing electricity demand. Under the smart environment, the economic and environmental as well as technical considerations such as energy efficiency as well as loading improvement, reducing losses and increasing the penetration rate of distributed generations can be observable [1]. In fact, the increasing penetration rate of green energy is considered as one of the interesting advantages of smart grid's implementation [2]. Furthermore, smart grid technologies will enable the grid to better adapt to demand-side behaviors to procure safe, reliable and sustainable electricity for all consumers [3]. In fact, handling the consumers' behavior in smart environment is more simple than conventional generating units due to utilizing advanced communication infrastructures which offer different opportunities to the system operator [4]. Under the smart environment, Demand Response (DR) programs and Energy Efficiency Programs (EEPs) are contemplated as important technologies which affect handling and controlling of power systems over the different horizon time.

EEPs include utility and non-utility energy efficiency programs [5] which improves the operation conditions of the power system. Therefore, the level of investment on EEPs has been extensively increased all over the world [6]. In [5], an energy efficiency model regarding generation expansion planning has been proposed. The transmission expansion planning scheduling is performed in presence of EEPs in [7] while a novel technique of energy efficiency trading to decline the demand has been addressed. The EEPs is handled over a 20-year in [8] while the results show that the energy intensity has been reduced to 25% in 2030 in comparison with 2010. The potential of energy efficiency improvement in the long term power system scheduling has been investigated in [9].

DR is a program that is established to change electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [10]. DR programs can be utilized in smoothening the load profile, as well as deferment of additional investments, reducing the financial burden of the system, reducing the emitted greenhouse gases and improving the line congestion [11]. An MILP formulation of cost-emission based of unit commitment problem associated with DR has been addressed in [12] The economic model of DR has been investigated in [13]. The integrated unit commitment problem in presence of DG and DR programs

* Corresponding author.
E-mail address: mrashidi@uk.ac.ir (M. Rashidinejad).

https://doi.org/10.1016/j.ijepes.2017.11.026
Received 7 May 2017; Received in revised form 10 September 2017; Accepted 19 November 2017
Available online 24 November 2017
0142-0615/

Nomenclature

A	incentive of DR programs in per hour
$A(\cdot)_{min}$	minimum incentive level
$A(\cdot)_{max}$	maximum incentive level
$AS_m(\cdot)$	slope of mth segment in linearized total incentive curve
$a(\cdot)$,$b(\cdot)$,$C(\cdot)$	fuel cost coefficient
b_m	slope of mth segment in linearized fuel cost
$CSC(\cdot)$	cold start-up cost of a unit
$CST(\cdot)$	cold start-up time of a unit
d	number of hours in per week
$D(\cdot)$	demand in a period
$E(\cdot)$	price elasticity of demand
EEI	final energy efficiency investment
EEI_0	initial energy efficiency investment
$F(\cdot)$	fuel cost function
$\underline{F}(.)$	lower limit on the fuel cost of a unit
$HSC(\cdot)$	hot start-up cost
i	index of units
$invcost$	investment cost
K	expected income in a period
K(0)	initial investment
m	segment index for linearized fuel cost and total incentive curve
$MD(\cdot)$	minimum down time
$MU(\cdot)$	minimum up time
N_t	scheduling time horizon
N_i	number of units
NSF_i	number of segments for the piecewise linearized fuel cost curve
NSI_i	number of segments for the piece-wise linearized total incentive curve
$P(\cdot)$	power generation output
$\underline{P}(\cdot)$, $\overline{P}(\cdot)$	minimum and maximum generation capacity of a unit
$p_m(\cdot)$	generation of mth segment in linearized fuel cost curve
$P(\Delta D(t))$	total incentive to customers in a period
$SU(\cdot)$	start up cost
$SD(\cdot)$	shutdown cost
t	time index
$TC(\cdot)$	number of continuous hours while a unit is decommitted
$u(\cdot)$	On/Off status of a unit status
$v_m(\cdot)$	award of mth segment in linearized total incentive curve
$X(.)^{on}$	duration of continuous on status of a unit at a time
$X(.)^{off}$	duration of continuous off status of a unit at a time
$\gamma(\cdot)$	start-up indicator
$z(\cdot)$	shutdown indicator
$\delta(\cdot)$	efficiency-price cross elasticity of demand
$\gamma(.)$	elasticity of demand with respect to energy efficiency investment
$\rho(\cdot)$	final price of electricity
$\rho_0(\cdot)$	initial price of electricity
$\Gamma^s(\cdot)$	demand ratio parameter of an hour
λ	penetration rate of EEPs
η	penetration rate of DR
ε	discount rate

been handled in [14] under the smart grid environment. The security-constrained unit commitment with consideration of DR programs as virtual power plants, is presented in [15]. The comprehensive energy dispatch including electricity, heating, cooling which connects the DR end user is provided in the wholesale market [16]. Multi-objective optimization with prevailing constraints and utility trade-off based on the model of a large-scale MG with flexible loads is suggested in [17] whereas DR's implementation reduces 17.5% of peak demand as well as declining 8.8% of financial burden.

Although the individual utilization of the DR programs as well as EEPs is efficient; however, the implementation of EEPs in presence of DR takes valuable advantages for the power system. In [18], requirement tools for combined usage of EEPs and DR have been scrutinized. In [19], EEPs and DR are considered for the optimal generation mix problem. In [20], DR and EEPs are considered in the forward capacity market. It should be mentioned that system operator has been incurred a considerable expenditures in EEPs. Therefore, coordination of the energy efficiency and the demand response programs is a fundamental requirement which can have significant effects on power systems scheduling and, is contemplated as an essential issue due to following reasons [1]:

- Energy efficiency affects how much load shift is available from a customer.
- Selected energy efficiency measures affect how much money the customer and utility have available to spend on demand response and, vice versa.
- Loads to be provided by operator to consumers after investments in energy efficiency and determination of incentives offered to consumers.

However, multifarious concerns and conflictions about simultaneous performance of energy efficiency and demand response programs will arise in order to have a suitable economic analysis as follows:

- The consumers, who participate in the demand response programs, are not interested in cooperation in the energy efficiency programs due to economic reasons. In the other words, the incentive in DRPs which is paid to consumers is proportional to the peak load of the system while energy efficiency programs decline the peak load of the system and as results reducing the incentives.
- The customers' revenue in DRPs is an uncertain probabilistic parameter; however, incentive in energy efficiency programs is more certain.

Therefore, it can be concluded that coordination of DR programs and EEPs can be considered as an attractive issue in power system studies. However, this issue has not been addressed in previous researches. In this paper, a novel combined demand model associated with EEPs and DR based upon the price elasticity of demand and the energy efficiency elasticity is provided. The nominated model is implemented to a Two-Stage Structure to Coordinate the EEPs and DR programs, namely $\mathrm{TSSC}_{\mathrm{DR}}^{\mathrm{EEP}}$. The presented model includes different economic targets over a midterm and short term horizon time to determine the level of energy efficiency invested by the government as well as participation level of customers in DR programs, respectively.

The rest of the paper is organized as follows. Section 2 provides a background of DSM including energy efficiency and demand response. The hierarchy of $\mathrm{TSSC}_{\mathrm{DR}}^{\mathrm{EEP}}$ incorporating DR as well as EEPs from system operator perspective is presented in Section 3. The suggested load model and the proposed formulation of $\mathrm{TSSC}_{\mathrm{DR}}^{\mathrm{EEP}}$ are also elaborated in Section 3. Section 4 conducts the numerical studies on IEEE 10-unit test system and, finally the concluding remarks are explained in Section 5.

2. Demand side management (DSM)

The concept of demand side management was proposed for the first time in 1970 [21]. The scope of DSM has been expanded to include purposes such as system expenditures reduction as well as power system's loading, reliability and stability improvement [22,23]. In fact,