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Nonlinear demand response programs for residential customers with nonlinear behavioral models

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ABSTRACT

To mitigate environmental issues of the thermal power plants, their greenhouse gas emissions are factored into the unit commitment (UC) problem. Moreover, demand side management as an effective strategy can relieve the energy security and environmental issues. Thus, the residential customers as one of the major groups of the customers, should be incorporated in the UC and generation scheduling problems. In this study, implementation of demand response (DR) programs in the UC problem are modeled. Herein, the implemented DR programs are entitled nonlinear DR (NDR) programs because nonlinear behavioral models for the residential customers are considered. In addition, the value of cost correlated with the implementation of the NDR programs in the UC problem (UC-NDR) are modeled. It is demonstrated that cooperation of the residential customers in the UC-NDR problem can be beneficial in decreasing cost and greenhouse gas emissions of the thermal power plants. In addition, it is concluded that comprehensive studies are needed to realistically model the residential customers behavior, since the different behavioral models result in different solutions and outcomes for the UC-NDR problem.

1. Introduction

A major part of the environmental concerns is caused by burning fossil fuel in the thermal power plants and emitting several contaminants into the atmosphere [1]. Fig. 1 illustrates the rised greenhouse gas emissions from a thermal power plant in Gelsenkirchen, Germany [2]. A new regulation has been adopted by the Clean Air Act Amendment to force the utilities to modify their design or operational strategies for reducing pollution and atmospheric emissions of their thermal power plants [3]. Thus, the fuel consumption and greenhouse gas emissions level of the thermal power plants must be simultaneously taken into consideration in the unit commitment (UC) problem. The problem of UC involves finding the least-cost dispatch of available generation resources (e.g., thermal power plants) to meet the electrical load. In fact, converting the greenhouse gas emissions of the each thermal power plant into the greenhouse gas emissions cost function and merging it into the UC problem is able to mitigate the environmental issues of the thermal power plants [4].

Demand side management (DSM) is considered as the first precedence in all the energy policy decisions due to its benefits from economic and environmental viewpoints [5,6]. DSM provides short-term responses to electricity market conditions to reduce overall costs of energy supply, increase reserve margin, and mitigate price volatility [5]. Also, it achieves environmental goals by deferring commitment of polluted units leading to increased energy efficiency and reduced greenhouse gas emissions [5].

Several studies have investigated the implementation potential of demand response (DR) programs [7–9]. The U.S. federal energy regulatory commission estimates that the contribution from the existing customers in the U.S. is around 41,000 MW equal to 5.8% of the 2008 summer peak demand [7]. A study presented in Ref. [8] shows that incentive-based programs (IBPs) are responsible for 93% of peak load reduction in the U.S. The studies presented in Refs. [9–13], have investigated the effects of DR programs on the residential customers demand.

Nowadays, considering presence of residential customers in the generation scheduling and UC problems is mandatory due to active participation of residential customers in the power market and DR programs. Some papers have investigated DR programs in the UC and generation scheduling problems [14–20]. In Ref. [14], the authors have determined value of demand to be shifted from peak period to other periods by direct load control for congestion management and increasing utilization of wind power. The authors in Ref. [15], have implemented DR program in the UC problem to increase the amount of wind power that can be economically injected to the system. In this paper, the responsive customers are

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Nomenclature

A. Indices and sets

$\phi \in S_\phi$	Residential customers' class
$\delta \in S_\delta$	DR program
$g \in S_g$	Generation unit
$t \in S_t$	Hour
$\xi \in S_\xi$	Responsive customer behavioral model

B. System parameters and variables

$C^{\delta}_{\phi,\xi}(.)$	DR program implementation cost for residential customers in class ϕ with behavioral model ξ
$C^{\delta}_{Tot}(.)$	DR program implementation cost for all classes of residential customers
$C^{F}_{g}(.)$	Fuel cost of unit g
$C^{E}_{g}(.)$	Greenhouse gas emissions cost of unit g
c^{STU}_{g}	Start-up cost of unit g
c^{SHD}_{g}	Shut down cost of unit g
$D^{0}_{\phi,\xi}(.)$	Initial demand of residential customers in class with behavioral model ξ
$D^{\delta}_{\phi,\xi}(.)$	Demand of residential customers in class ϕ with behavioral model ξ after implementation of NDR program
$E_{\phi}(.,.)$	Price elasticity of demand of residential customers
$I^{EDRP}(.)$	Value of incentive in EDRP
MDT_g, MUT_g	Minimum down time and minimum up time of unit g, respectively
$OFFT_g$, ONT_g	Number of hours that unit g has been kept "off" and "on", respectively
$P_g(.)$	Generation of unit g
P^{min}_{g}, P^{max}_{g}	Minimum and maximum generation of unit g
RDR_g, RUR_g	Ramp down rate and ramp up rate of unit g, respectively
SR	Spinning reserve amount
x^{EDRP}	Incentive as variable of EDRP
x^{TOU}	Price regulator as variable of TOU
$y^{CS}_{g}(.)$	Binary variable as commitment status of unit g
$y^{\delta}(.)$	Binary variable as indicator for implementation of NDR program
$\pi^{0}(.)$	Initial price of electricity
$\pi^{TOU}(.)$	Price of electricity after implementation of TOU program
$\alpha^{F}_{1,g}$, $\alpha^{F}_{2,g}$, $\alpha^{F}_{3,g}$	Fuel cost coefficients of unit g
$\alpha^{E}_{1,g}$, $\alpha^{E}_{2,g}$, $\alpha^{E}_{3,g}$	Greenhouse gas emissions level coefficients of unit g
β^{E}	Greenhouse gas emissions cost factor

C. SA algorithm parameters and variables

N^{SA}	Number of generating new state at every temperature
p_k	Adaptive probability for acceptance of new solution at stage k
r_k	Random number in range of [0,1) at stage k
y^{SA}_{k}	Binary variable as indicator for acceptance of new solution at stage k
μ	Coefficient for gradually decreasing temperature of molten metal
ε_k	Internal energy of molten metal at stage k
θ_0	Initial temperature of molten metal
θ_k	Temperature of molten metal at stage k

Fig. 1. The rised greenhouse gas emissions from a thermal power plant in Gelsenkirchen, Germany [2].

linked to the hourly market prices and their loads are curtailed or shifted to other hours.

However, in the above mentioned studies, the behavior of responsive customers with respect to the different strategies of DR program designer have not been modeled in the problem. In Refs. [16–18], a model for cooperation of risk-cost based UC with customers, considering linear model for the responsive customers behavior, has been presented. In Ref. [19], nonlinear models of responsive customers behavior and nolinear DR (NDR) programs have been investigated in some real power markets. However, the NDR programs have not been implemented in the UC problem (UC-NDR). In addition, the implementation cost of the NDR program have not been modeled.

In this study, NDR programs are investigated in the UC-NDR problem considering different nonlinear behavioral models for the responsive customers behavior and greenhouse gas emissions of the thermal power. Herein, nonlinear emergency demand response program (EDRP) as the voluntary IBP and nonlinear time of use (TOU) program as the voluntary time-based rate (TBR) program are applied in the UC problem to form the UC-NEDRP and UC-NTOU problems, respectively. In EDRP, the responsive customer receives incentive because of demand reduction at peak period [20–22]. Also, in TOU program, value of the price of electricity are different at different periods of the day [20–22]. In other words, the electricity price at valley, off-peak, and peak periods are low, moderate, and high, respectively. The voluntary DR programs have the advantage of neither requiring a bidirectional communication interface, nor knowledge of residential customers' information. The recent studies indicate a reluctance among participants of mandatory DR programs due to the inconvenience caused by interruption of power [20]. Herein, the aim of the UC-NDR problem is to design the optimal scheme for the implementation of the NDR program to minimize the total cost of the problem that includes cost of power generation, cost of greenhouse gas emissions, and cost of NDR program implementation. Moreover, the explicit NDR program implementation cost modelings considering nonlinear behavior of the responsive customers behavior are presented in this study.

The rest of the paper is outlined as follows. In Section 2, the UC-NDR formulation is presented and described. The NDR models are presented in Section 3. In Section 4, an optimization method for solving the UC-NDR problem is presented. Numerical studies and sensitivity analyses carried out are explained in Section 5. Finally, the conclusion is given in Section 6.