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Designing time-of-use program based on stochastic security constrained unit commitment considering reliability index

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ABSTRACT

Recently in electricity markets, a massive focus has been made on setting up opportunities for participating demand side. Such opportunities, also known as demand response (DR) options, are triggered by either a grid reliability problem or high electricity prices. Two important challenges that market operators are facing are appropriate designing and reasonable pricing of DR options.

In this paper, time-of-use program (TOU) as a prevalent time-varying program is modeled linearly based on own and cross elasticity definition. In order to decide on TOU rates, a stochastic model is proposed in which the optimum TOU rates are determined based on grid reliability index set by the operator. Expected Load Not Supplied (ELNS) is used to evaluate reliability of the power system in each hour. The proposed stochastic model is formulated as a two-stage stochastic mixed-integer linear programming (SMILP) problem and solved using CPLEX solver. The validity of the method is tested over the IEEE 24-bus test system. In this regard, the impact of the proposed pricing method on system load profile; operational costs and required capacity of up- and down-spinning reserve as well as improvement of load factor is demonstrated. Also the sensitivity of the results to elasticity coefficients is investigated.

1. Introduction

By increase of demand in a power system which does not have enough transmission capacity to handle such increase, demand response (DR) has been introduced as a main resource. There are different DR options that have been categorized into time-based and incentive-based programs, which are offered to customers to reduce their consumption or shift it to other periods. Time-of-use (TOU) program, critical peak pricing (CPP), and real-time pricing (RTP) are the three well-known time-based programs. Also, there are different types of incentive-based programs in the forms of long-term to short-term and even real-time offered programs, each of which has its own goal. Recently a massive focus in various countries has been made on fostering DR options [1–5]. Creating a proper design structure for DR options is a main issue involved with the pricing process. This could lead to achieving certain economic and technical benefits. Security improvement of power system is one of the important technical benefits. DR has also some advantages such as diminishing operation cost, increasing financial profit, shifting and reducing peak loads and limiting participants to exercise market power [6–8].

TOU programs are the most prevalent demand response options which are referred to as time-based programs. Most customers are exposed to some form of TOU rates, if only with rates that vary by six-month seasons. Other forms of TOU rates involve two or more daily periods that include peak and off-peak time periods with a higher rate during peak time periods.

The literature of research has been reviewed in the following and afterward the research problem has been introduced.

2. Literature review

In [9–14], linear models of DR have been developed, in which it is assumed that demand is changing linearly in respect to the elasticity. Leading research about modeling of DR considering linear demand function has been presented and studied in [13,14].

In several power markets, the ISO plans the day-ahead schedule using security constrained unit commitment (SCUC) program [15]. There are different solutions to SCUC problem. In [16] SCUC is decomposed into a master problem and two sub-problems where the Benders decomposition approach is utilized to find the solution. In the first sub-problem, network violations are minimized and the second sub-problem minimizes the expected unserved energy. Stochastic programming is considered as an approach to

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incorporate uncertainties into problem formulation which is introduced in [17]. This approach has been used widely in formulations of the power market problems. Bouffard et al and Saric et al have incorporated contingencies into market clearing problem by use of stochastic programming [18,19]. In [20] a stochastic model has been presented for energy and reserve pricing that has been extended in [21]. Shahidehpour et al presented a stochastic model for long-term SCUC, involving generator and line outages as well as load forecasting errors [22]. In [23], an expansion stochastic approach for determining required optimal reliability level in a composite power system has been proposed and solved based on linear programming and Benders' decomposition algorithm. A short-term stochastic SCUC model has been formulated in [24]. Different indices have been introduced to evaluate security of power systems. In 2004 Bouffard and Galiana proposed expected load not supplied (ELNS) index in order to measure system security in deregulated power systems [25].

3. Research problem

In this paper, we propose a short-term stochastic SCUC model for determining TOU rates based on desired maximum ELNS value. In proposed model, TOU rates are determined in each load bus depending on desired maximum hourly ELNS value. Also, hourly power generated by generating units and deployed up- and down-spinning reserve for each scenario are determined. In this regard, uncertainties and TOU model are incorporated into SCUC problem by employing two-stage stochastic mixed-integer linear program (SMILP) model. The 1st stage contains conventional SCUC combined with TOU model in steady state condition while in the 2nd stage the system security is checked for each scenario. The N-1 criterion is used to choose scenarios which consist of outage of a generating unit or a transmission line. The proposed method is formulated by GAMS programming language and solved using CPLEX as a powerful solver of mixed integer linear program (MILP). It should be mentioned that although the problem formulation is a "two stages" problem, it is solved in one step.

The remaining parts of the paper are organized as following: Modeling responsive load based on the concept of price elasticity of demand is introduced in Section 2. The proposed short-term stochastic SCUC formulation for pricing TOU with desired ELNS is introduced in Section 3. In Section 4, the proposed method is tested over the IEEE 24-bus test system where different cases are studied. Also the sensitivity of the results to elasticity coefficients is investigated. Finally, the paper is concluded in Section 5.

4. Linear demand response model

The elasticity of demand is obtained by relative slope of demand curve [13]:

$$e = \frac{\Delta d/d^0}{\Delta \rho/\rho^0} \tag{1}$$

where Δd and $\Delta \rho$ are changes in demand and price, respectively, d^0 and ρ^0 are initial demand and price, respectively.

The load of power system varies within different time periods. Price change in one time period affects load change in other time periods. Hence, cross-time elasticity is determined by use of cross-time coefficients. The own elasticity coefficient e_{tt}, with negative value, represents elasticity for load change at time period t caused by price change in the same time period and the cross-elasticity coefficient $e_{tt'}$, with positive value, represents elasticity for load change at time period t caused by price change at time period t' which are formulated by following equations:

$$e_{tt} = \frac{\Delta d_t/d_t^0}{\Delta \rho_t/\rho_t^0} \tag{2}$$

$$e_{tt'} = \frac{\Delta d_t/d_t^0}{\Delta \rho_{t'}/\rho_{t'}^0} \tag{3}$$

where Δd_t and $\Delta \rho_t$ represent demand and price changes at time period t, respectively, d_t^0 and ρ_t^0 are the initial values of demand and price at time period t, respectively, and also, $\rho_{t'}^o$ and $\Delta \rho_{t'}$ are the initial value of price and its change at time period t', respectively.

By considering time varying load, the elasticity coefficients can be arranged in an NT by NT matrix E.

$$E = \begin{bmatrix} e_{1,1} & \cdots & e_{1,NT} \\ \vdots & \ddots & \vdots \\ e_{NT,1} & \cdots & e_{NT,NT} \end{bmatrix} \tag{4}$$

With linearity assumption, matrix equations of demand response model for NT time periods are as follows:

$$\begin{bmatrix} \Delta d_1/d_1^0 \\ \vdots \\ \Delta d_{NT}/d_{NT}^0 \end{bmatrix} = E \times \begin{bmatrix} \Delta \rho_1/\rho_1^0 \\ \vdots \\ \Delta \rho_{NT}/\rho_{NT}^0 \end{bmatrix} \tag{5}$$

5. Proposed two-stage stochastic formulation

Generally, in stochastic programming (SP) model, probability of each scenario which is usually random outages of generating units and transmission lines is incorporated with problem formulation [17]. In two-stage SP model, decisions are made in two stages that the 1st stage decisions must be taken before the scenarios are revealed and the 2nd stage decisions are taken after the scenarios have been utilized. In this paper we are using two-stage stochastic mixed-integer linear program in which the linear functions of variables are used as objective function and constraints.

In proposed model, objective function consists of the base case cost including 1st stage variables as well as the expected recourse function including 2nd stage variables [26]. The recourse function demonstrates the value of scenario occurrence cost.

The base case cost is the total cost of energy generated by units and expected recourse function is the expected cost of deployed spinning reserve and load shedding. Hence, considering generator cost function as piece-wise linear, objective function is formulated as follows:

$$\begin{aligned} \sum_{t=1}^{NT} \Bigg\{ & \sum_{i=1}^{NG} \left(SUC_{it} + MPC_i \cdot u_{it} + \sum_{m=1}^{NL} \pi_{it}^m \cdot \sigma_{it}^m \right) \\ & + \sum_{s=1}^{NS} Pr_s \left(\sum_{i=1}^{NG} \left(SR_{it,s}^{up} \cdot q_{it}^{up} + SR_{it,s}^{down} \cdot q_{it}^{down} \right) \right. \\ & \left. + \sum_{b=1}^{NB} VOLL_{bt} \cdot LS_{bt,s} \right) \Bigg\} \end{aligned} \tag{6}$$

where NT is the number of scheduling hours, NG is the number of generating units, NL is the number of blocks of the piecewise linearization of the cost function, NS is the number of scenarios, NB is the number of buses, SUC_{it} is the startup cost of unit i at time t, MPC_i is the minimum production cost of unit i, u_{it} is the commitment state of unit i at time t, π_{it}^m is the slope of segment m of the piecewise linear cost function of unit i at time t, σ_{it}^m is the real power generation of unit i in segment m at time t, Pr_s is the probability of scenario s, $SR_{it,s}^{up}$ and $SR_{it,s}^{down}$ are the deployed up- and down-spinning reserve of unit i at time t in scenario s, respectively,