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Congestion management using demand response and FACTS devices

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ABSTRACT

An approach is proposed for transmission lines congestion management in a restructured market environment using a combination of demand response (DR) and flexible alternating current transmission system (FACTS) devices. To achieve this aim, a two-step market clearing procedure is formulated. In the first step, generation companies bid to the market for maximizing their profit, and the ISO clears the market based on social welfare maximization. Network constraints including those related to congestion management are represented in the second step of the market-clearing procedure. The paper develops, using mixed integer optimization technique, a re-dispatch formulation for the second step in which demand responses and FACTS device controllers are optimally coordinated with conventional generators.

1. Introduction

1.1. Motivation and technique

Restructuring in electric power industry has led to intensive usage of transmission grids. In a competitive market environment, transmission companies usually maximize the utilization of transmission systems as construction of new transmission lines is not as straightforward as in centrally planned systems. Thus, in high demand periods, the system operates near its transmission capacity limit with security margin being reduced [1]. Existence of network constraints dictates the finite amount of power that can be transferred between two points on the electric grid. In practice, it may not always be possible to deliver all bilateral and multilateral contracts in full and to supply the entire market demand due to violation of operating constraints such as voltage and line power flow limits. The presence of such network or transmission limitation is referred to as congestion. Congestion or overload in one or more transmission lines may occur due to the lack of coordination between generation and transmission companies or as a result of contingencies [2]. Congestion may be relieved, in many cases by cost-free means such as network reconfiguration, operation of transformer taps and operation of flexible alternating current transmission system (FACTS) devices [3–8]. In other case, however, it may not be possible to remove or relieve congestion by cost-free means, and some non-cost-free control methods, such as re-dispatch of generation and curtailment of loads, are required [9–11]. Since there is a wide range of events which can lead to transmission system congestion, a key function in system operation is to manage and respond to operating conditions in which system voltages and/or power flow limits are violated [2]. A congestion management method proposed in this paper is based on a combination of FACTS devices and demand response programs. In the present paper, Demand response is modeled considering incentives and penalty factors. The incentive and penalty factors would lead to more control on responsive demand contributions rather than just relying on changing the electricity price in the market and its effects on response rate of elastic loads. The penalty factor can also improve the response rate of responsive demands and also enhance the reliability level of these resources by decreasing the rate of response failure. In addition, deploying demand response resources at appropriate locations would allow generation to operate at a lower cost as the congestion is reduced and also transmission network investment can be postponed while maintaining the existing level of security [12–14]. In fact, the responsive demand improves the operation of electricity market and also would make electricity market more efficient and more competitive [12].

1.2. Literature review and contribution

In general, three main forms of congestion management exist in competitive electricity markets [2]. The first is based on centralized optimization with some form of optimal power flow program or depends on specific control measures operated by the independent system operator (ISO). The second is based on tariff and use of price signals derived from the market to release congestion by generator re-scheduling. Lastly, the third form seeks to mitigate congestion

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Nomenclature

$P_{gi}^{\max}$	maximum power output of generator i
$P_{gi}^{\min}$	minimum power output of generator i
$P_{reDi_{\min}}^{down}$	minimum load reduction by responsive demand i
$P_{reDi_{\max}}^{down}$	maximum load reduction by responsive demand i
$C_i(P_{gi})$	generation cost function
$X_{\text{TCSC}}^{\min}$	minimum reactance limit of TCSC
$X_{\text{TCSC}}^{\max}$	maximum reactance limit of TCSC
$B_{\text{SVC}}^{\min}$	minimum susceptance limit of SVC
$B_{\text{SVC}}^{\max}$	maximum susceptance limit of SVC
$E(i)$	elasticity of the demand
$\rho(i)$	electricity price
$L_0(i)$	customer demand before demand response program
$L(i)$	customer demand after demand response program
P_{Dik}	power block k that demand i is willing to buy at price λ_{Dik} up to a maximum of $P_{Dik}^{\max}$
P_{fd}	non-dispachable load.
λ_{Dik}	price offered by demand i to buy power block k
r_{Di}^{down}	price offered by demand response i to decrease its demand
ΔP_{reDi}^{down}	decrement in the schedule of demand response i
N_D	number of demands
N_{Di}	number of blocks requested by demand i
N_G	number of generators
N_{reD}	number of demand responses

by allowing or disallowing bilateral transmission agreements between a producer and a consumer [1,2].

FACTS devices are considered to be one technology that can benefit transmission systems in many ways including congestion management and enhancing the loadability of the transmission lines [6]. FACTS devices and their associated benefits for efficient operation of electricity markets have been widely addressed in the literature [2–4,6,7,15].

The effectiveness of FACTS devices in congestion management depends importantly on their locations. The issue of FACTS devices placement has been extensively investigated and reported in literature [3,6,7,15].

Additionally, a significant volume of technical literature focuses on demand response [16–20] and the associated benefits for electricity network which include the improvement in the operation of renewable generation [21], providing ancillary services for the market [22,23], enabling infrastructure for utilizing large amount of renewable resources [24], network reliability enhancement [25], improving the loadability of the transmission lines and congestion management in electricity networks [9].

The role of demand elasticity in congestion management in a competitive electricity market is investigated in [10], where elasticity of demand at different prices is known. The load at each bus ceases to be a fixed quantity and becomes a decision variable in the ISO's optimization problem. In this way, the ISO has additional degrees of freedom in determining the necessary actions for congestion management. An optimal power flow based framework is proposed in [26] to determine the optimal incentive rates in an interruptible tariff mechanism. It is shown that interruptible tariffs are able to aid system operation during peak load periods by increasing the reliability margin, improving voltage profile and relieving network congestion. An integrated technical market based framework for congestion management, that uses interruptible load services as a tool for the ISO to provide transmission congestion relief is investigated in [9], where interruptible load service procurement by the ISO is explored. Additionally, the technical literature includes a significant number of references dealing with demand response modeling and its effects on improving the market operation. The impact of incentive-based demand response (DR) programs on capacity markets is investigated in [27]. The response of a nonlinear mathematical model is analyzed in [28] for the calculation of optimal prices for electricity assuming typical customers under different scenarios using five different mathematical functions. The electricity cost saving potential of real time pricing (RTP) through demand management is presented in [29].

The main contribution of this paper is to develop a formulation for coordinating both FACTS device controllers and demand responses through constrained optimization to achieve congestion management at a minimum cost. In addition, the incentive and penalty terms are added to the existing mathematical model of demand response to enable the ISO through the aggregator to have two factors to control the capacity of responsive demands, and also increase the number of demand response participants at specific load buses which are important for the security of the system.

1.3. Paper organization

The rest of this paper is organized as follows. The demand response formulation is presented in Section 2. The proposed method including the problem formulation is described in Section 3. Results from a case study are provided and discussed in Section 4 and some relevant conclusions are given in Section 5.

2. Demand response bidding formulation

2.1. Demand response allocation

For successful implementation of demand response programs, a set of candidate load buses should be selected, based on their influences on network response. In this regard, loads with high impact on transmission system element loadings are chosen. To achieve this goal, generation shift factor (GSF) is used [30]. In addition, this index could be either positive or negative, and for effective demand response implementation, those buses with negative indices are selected from a ranking process where higher priority is given to index with greater magnitude. However, this selection criterion is subject to the availability of the responses from the demand side at the identified locations. The load model developed in the following section will be used to quantify the expected demand response at load buses.

2.2. Economic model of elastic demand

2.2.1. Outline

This section derives an elastic demand model based on incentive and penalty together with the customer benefit function for the purpose of estimating the demand response capacity. This provides an economic basis on which the demand response aggregator at each location as identified in Section 2.1 formulates the bidding curve to be submitted to the market operator. The load change at