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A new multi-objective solution approach to solve transmission congestion management problem of energy markets

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HIGHLIGHTS

- A comprehensive congestion management model is presented.
- A new multi-objective solution approach is proposed.
- A novel optimality-based decision maker is suggested.
- The effectiveness of the proposed solution approach is extensively illustrated.

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ABSTRACT

Transmission congestion management plays a key role in deregulated energy markets. To correctly model and solve this problem, power system voltage and transient stability limits should be considered to avoid obtaining a vulnerable power system with low stability margins. Congestion management is modeled as a multi-objective optimization problem in this paper. The proposed scheme includes the cost of congestion management, voltage stability margin and transient stability margin as its multiple competing objectives. Moreover, a new effective Multi-objective Mathematical Programming (MMP) solution approach based on normalized normal constraint (NNC) method is presented to solve the multi-objective optimization problem of the congestion management, which can generate a well-distributed and efficient Pareto frontier. The proposed congestion management model and MMP solution approach are implemented on the New-England's test system and the obtained results are compared with the results of several other congestion management methods. These comparisons verify the superiority of the proposed approach.

1. Introduction

In a competitive energy market, the market participants offer their bids to independent System Operator (ISO). The ISO is responsible for market clearing and providing an acceptable security level for power system [1]. Moreover, ISO is accountable for prediction of load level using a load forecasting procedure [2]. In other side, the generation companies (GENCOs) anticipate their future generation independently to offer to the market [3]. The market participants try to maximize their own profit using efficient bidding strategies [4]. The transition from cost-based pricing to bid-based pricing in a deregulated energy market has been modeled in [5]. The new conditions of open energy markets create a competitive situation where transmission networks are loaded up to their stability margin to gain more economical operating point. Transmission congestion appears in power system when the amount of electric power, which should be transmitted on the network to meet the total demand, surpasses the capacity of the transmission facilities. Congestion management refers to the activities performed to eliminate the congestion in the network. It can also be considered as an organized mechanism used to dispatch, schedule and adjust the generation units and demands in order to handle congestion in the power grid.

Traditional congestion management schemes only consider thermal overloads, while the recent incidents in North America and Europe that caused major blackouts [6] show that security requirements are an important factor that should be considered in the congestion management problem. Congestion management

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is inherently an optimization problem with numerous constraints. Therefore, after mitigating the congestion, some constraints may reach their upper or lower limits. Although the constraints have not been violated, it is likely that the system goes to an unstable condition by even a small disturbance. In other words, the stability margin of the system may be low after relieving congestion and so voltage and transient stability margins should be considered in the congestion management framework in addition to congestion management cost.

A survey of congestion management methods can be found in [7,8]. Additionally, some recent congestion management approaches are briefly reviewed in the following.

A congestion management method based on optimal power flow (OPF) is presented in [9] that relieves congestion using load shedding and generation rescheduling. In [10], the authors employ the concept of transmission congestion penalty factor to control power flows in transmission lines for congestion management. A combination of demand response and flexible alternating current transmission system (FACTS) devices for congestion management is presented in [11]. In [12], a congestion alleviation method ensuring voltage stability, using loadability limits in pool electricity markets, is proposed. In [13], modal analysis and modal participation factors are used for saving voltage stability within a congestion management framework. The research work of [14] introduces a new measure for transient stability margin (TSM) and incorporates it into a congestion management framework to mitigate congestion while enhancing the transient stability of the power system. Particle swarm optimization (PSO) has been used in [15] to determine the minimum-cost generation-redispatch strategy for congestion management. In [16], a congestion alleviation method considering dynamic voltage stability boundary of power system is proposed. A two-stage strategy based on modified Benders decomposition approach is presented in [17] to solve the congestion management problem in a hybrid power market. In [18], a congestion management approach considering congestion management cost and power system emission is proposed, which is based on stochastic augmented ε-constraint method. In [19], a probabilistic strategy incorporating demand response in distribution energy market is proposed. Their method allows cost saving for the end-user consumer and also mitigates the network's congestion. In [20], a mixed integer linear programming scheme is developed to coordinate applications of distributed energy storage systems, which maximizes their net profit and supports distribution's network congestion management. In [21], a hybrid approach using bacterial foraging algorithm and Nelder–Mead method is proposed to solve TCSC (Thyristor-Controlled Series Compensator) placement problem of congestion management. A congestion management strategy based on rescheduling of hydro and thermal units in a hybrid electricity market is presented and formulated as mixed integer nonlinear programming problem in [22]. The objective function of their model solely minimizes the congestion management cost considering units' up and down generation bids. In [23], a multi-objective group search optimizer with adaptive covariance and Lévy flights, considering economic and reliability objectives, is proposed to optimize the power dispatch in a large-scale integrated energy system. However, the methods reviewed above either do not consider voltage and transient stabilities or only model one of them.

To remedy this problem, some congestion management frameworks based on multi-objective models have recently been presented including both voltage and transient stability margins in addition to congestion management cost to enhance power system security. In [24], a multi-objective congestion management framework based on ε-constraint approach is presented for this purpose. An improved version of [24], called modified augmented ε-constraint method, is proposed in [25], to enhance the quality of solutions of the multi-objective problem by generating efficient Pareto frontier. In line with [24,25], this paper proposes a multi-objective congestion management model incorporating transient and voltage stability margins in addition to congestion management cost as the objective functions. Additionally, AC power flow, system security and prevailing generator limits are considered as the constraints of this model.

The new contributions of this paper can be summarized as follows:

(1) An important contribution of this paper with respect to the previous research works in the area, such as [24,25], is presenting a new multi-objective mathematical programming approach, based on normalized normal constraint (NNC) method, for solving multi-objective congestion management problem. Even distribution of Pareto points on the Pareto surface and systematic approach for reducing the feasible objective space are among the important advantages of the proposed NNC-based multi-objective optimization approach.
(2) A novel optimality-based decision maker is proposed to efficiently select the most preferred solution for the MMP problem within the Pareto optimal set. This decision maker considers both optimality degree and importance of different objectives.

To the best of the authors' knowledge, the above contributions are specific to this paper and have not been presented in the previous research works in the area.

The remaining parts of the paper are organized as follows. In Section 2, the multi-objective congestion management model including the objective functions and constraints is presented. The proposed NNC-based MMP solution approach and optimality-based decision maker are introduced in Section 3. Numerical results obtained from the proposed solution approach for the multi-objective congestion management problem are presented in Section 4 and compared with the results obtained from several other MMP solution methods. Section 5 concludes the paper.

2. Formulation of the multi-objective congestion management problem

The objective functions of the multi-objective congestion management model are as follows:

Congestion management cost (f_1):

$$f_1 = \sum_{j \in SG} \left(B_{Gj}^{up} \cdot \Delta P_{Gj}^{up} + B_{Gj}^{down} \cdot \Delta P_{Gj}^{down} \right) + \sum_{k \in SD} \left(B_{Dk}^{up} \cdot \Delta P_{Dk}^{up} + B_{Dk}^{down} \cdot \Delta P_{Dk}^{down} \right) + \sum_{k \in SD} \left(\mathrm{VOLL}_{Dk} \cdot \Delta P_{Dk}^{I} \right) \quad (1)$$

where B_{Gj}^{up} and B_{Gj}^{down} are bid prices of jth generator to change its output power; ΔP_{Gj}^{up} and ΔP_{Gj}^{down} are up and down generation shifts of unit j, respectively, which are determined by the congestion management method. Similarly, $B_{Dk}^{up}, B_{Dk}^{down}, \Delta P_{Dk}^{up}$ and ΔP_{Dk}^{down} are analogous parameters of demand side bidding. Also, ΔP_{Dk}^{I} and VOLL_{Dk} are the amount of involuntary load shedding and value of lost load (VOLL), respectively [25]. In (1), *SG* and *SD* indicate set of participating generators and demands in the congestion management, respectively. From (1), it is seen that the congestion management cost f_1 includes three parts in which the first two parts are the payments of the ISO to GENCOs and demands respectively, for changing their powers as their offered bids. The third part represents the payment of ISO for involuntary load shedding employed in severe