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Arbitration of day-ahead real power market clearing under the influence of voltage dependent load models

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ABSTRACT

Social welfare maximization is used as an objective function to clear day-ahead real power electricity markets with elastic loads. The conventional way is to model loads as voltage independent. This paper investigates behaviour of day-ahead market clearing in the presence of voltage dependent load models at different loading conditions. In a multi-objective framework, different objective functions (load served, generation cost, emission and voltage stability enhancement index) are combined with social welfare so as to examine each function's behaviour. However, it is observed and demonstrated that the objective functions are either in accord or discord with social welfare at different loading conditions. Therefore, Pareto fronts are obtained to decide the most optimal functioning condition subject to all operating and technical constraints for the judgement making authority. The differential evolution algorithm is applied for single and multi-objective optimization purposes. The model is implemented on IEEE 30 bus system for testing and verification.

Introduction

Improvements in deregulated electricity market have been the main focus of researchers in recent decade for its smooth operation. In the day-ahead market which is also a financially binding market, all the participants are allowed to bid in the market. From the submitted bids, ISO performs the unit commitment and, accordingly, schedule generators subject to operational and technical constraints. The bids, provided by the participants, hedge the risk involved in the real time price variations.

Day-ahead market clearing mechanism helps the customers to adjust their schedule by postponing the use of heavy duty machines at the time of high prices and, on the contrary, consumptions can be increased at the time of low prices [1]. This concept of load shifting behaviour by submitting the price sensitive bids provided by demand is discussed in [2]. Similarly, price sensitivity based demand response bidding is mentioned in [3] to observe its influence on congestion & marginal price and a Monte-Carlo based algorithm in air conditioning optimization for demand response price sensitivities is proposed in [4]. In [5], the wholesale energy market is modelled for load reduction demand response framework with integrating renewable energy resources for the participants. A day-ahead scheduling model along with hourly demand response is implemented to reduce the operational cost and the ramping cost of the thermal generators by considering it as a penalty in the scheduling problem [6]. A chance-constrained stochastic model for day-ahead market is observed in [7] for economic and reliability criteria with the consideration of outages, renewable energy resources and forecast error of system loads.

The formation of customer function and their bids is a difficult task. In [8], authors have considered constant bids for each demand, i.e. infinite price elasticity of demand, to manage the transmission problem specifically, congestion issue. A discussion on the customer demand–price relationship or customer response that is assumed to be a decreasing function (instead of fixed) as it depends on external factors such as weather, time, and season is presented in [9]. In [10], a discussion on the presence of low demand elasticity on electricity (an undifferentiated good) as customers will not reduce their consumption for fractional benefit in costs is presented. Also, a discussion on benefits of demand participation in electricity market towards system security and reliability is presented in [11]. Moreover, the knowledge of bidding strategically is discussed in [12,13] is itself a another research area. However, bidding strategy is not the main focus of the paper.

Issues and methods for profit maximization for supplier side competition for attaining the equilibrium in electric power auction market with unit commitment is discussed in [14]. In [15], suggestion on considering all offers and bids in order to maximize the day

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ahead benefits subject to security constraints. In [16], bid cost minimization and social welfare maximization is discussed for the pool market with demand elasticity. In [17], a weighted multi-objective optimization algorithm for maximizing social welfare and loads is proposed with voltage stability as prime concern. In [18], the different bids are provided by the consumers on the basis of low and high demand scenario as they are stringent to pay the same price per unit consumption for both the scenarios.

Many optimization techniques are adopted to reach global optimum of the problem. These are, in general, heuristic in nature. These algorithms need to be very fast as well as reliable. In [19,20], a multi-objective optimization problem for different objectives subject to system constraints are explained. However, a preliminary attempt is made by us in [21] for deciding on the optimization tool.

In [19], authors have considered an approach of the problem that is based on the seller and buyer bids. However, it has been observed that there are two ways of looking into the problem (a) loading condition and (b) seller and buyer bids. Moreover, a behavioural change in objectives is observed in the market settlement process at different loading conditions. Further, selection of these objectives is critical and need to address it properly. This paper models social welfare (SW) with generation cost (GC), load served (LS), voltage stability enhancement index (VSEI) and emission.

Before deregulation in power system, minimization of GC was the only objective. However, after deregulation where demands also have role in market settlement along with generators an observation is made to see the shift in the SW pattern with GC. Voltage has always been a concern and, thus, it has been mandated for the generators to provide bids as an ancillary service scheme in the centralized market. Also, various loads depend on voltage variations such as incandescent lamps, fluorescent lamps, and uncontrolled motor loads which are, generally, a major portion of total system demand. In one of studies conducted by BC hydro, it is shown that by decreasing the substation voltage by 1%, the active and reactive demand decrease by 1.5% and 3.4%, respectively [22]. When, many such distribution systems get lumped at EHV bus, equivalent voltage dependent load representation is required. Hence, LS and VSEI are modelled in the market settlement process. Consideration of emission in market clearing is one of the essential part of power market. Various energy exchanges operate on allowance of emission such as European Energy Exchange operates both spot and derivatives in emission allowances for carbon dioxide (CO_2), California electricity market operates on emission permit market of nitrogen oxides (NOX) [23], etc. Moreover, in [23], authors have mentioned that increase in emission permit prices is likely to increase the electricity prices significantly. Therefore, it is necessary to observe emission in market clearing process. Hence, the objectives considered in the paper are of practical importance and need special attention in addressing market related issues.

The report by the World Meteorological Organization (WMO) Global Atmosphere Watch network [24] suggest that reduced CO_2 uptake by plants and soils might add to the worrying increase in atmospheric CO_2 concentrations resulting from fossil fuel burning. Atmospheric CO_2, the most important long-lived greenhouse gas, has reached at new heights, mostly due to increased emissions from fossil fuel burning. Thermal power generation is one of the prime contributors in this increase which emits various other noxious gases such as SOX and NOX. Between 1990 and 2013, greenhouse gases have increased by 34%, according to this report. Due to this, various ISO's have included emission as one of the derivatives in their day-ahead or spot market clearing model such as European energy exchange, California ISO, Midwest ISO [25,26]. Also, the Clean Power Plan (CPP), issued by the Environmental Protection Agency (EPA) on June 2, 2014, proposes to reduce carbon dioxide (CO_2) emissions from the existing fleet of electric generating units by approximately 30% from 2005 levels. This level is reached through proposed specific goals that vary by state. The rule has the potential to change the economics of the power system [23]. Therefore, emission is necessary to be considered as one of the objectives.

In [19], authors has brought out the impact of voltage dependent load models in the context of buyer and seller bids for day ahead real power market clearing (DA-RPMC). The objectives considered to make a judicious decision on power system operation are GC, LS, VSEI and SW. Genetic algorithm (GA) is used for single objective optimization and Multi-objective Strength Pareto Evolutionary Algorithm (SPEA) has been used to solve the DA-RPMC. Initial understanding of our method was adopted from [19]. However, they have not addressed the concerns and behaviour of these objectives at low and high loading conditions. At both the scenarios, observation will change for all the objectives drastically. Moreover, emission is a prime concern after the initiation of various penalizing protocols. Also, chances are very less in attaining an optimal solution from GA and SPEA methods in comparison of more recent techniques available in literature.

Our paper bridges these gaps by considering loading conditions along with buyer and seller bids incorporating voltage dependent loads in the day-ahead real power market clearing model. The main aim of the paper is to demonstrate the fact that under the aegis of multi-objective market clearing scheme, combining different objective functions with social welfare exhibits different nature of market clearing results at different loading conditions. Various observations are made with different objectives such as GC, LS, VSEI, Emission and SW. It has been observed that different objective functions, when combined with social welfare to form multi-objective optimization provide favouring behaviours under one loading condition while conflicting behaviour at the other loading condition. Comparatively latest optimization technique is utilized in taking a judicious decision. Differential evolution (DE) algorithm is used for single objective optimization and crowding distance based non-dominated sorting variant of DE is implemented for multi-objective optimization. The method of DE is applied to real-valued problems over continuous space with much more ease than GA. Especially, in mutation process; GA acts as a local search tool whereas DE acts as a global search tool.

The paper is organized as follows: Section 'Motivation' explains the formulation of DA-RPMC in presence of voltage dependent load models, Section 'DA-RPMC objective functions' indicates the mathematical model of the components which will be adjudged by ISO for optimal scheduling, Section 'Multi-objective optimization' accounts for the use of multi-objective optimization for achieving those objectives. Results are shown in Section 'Results'. A brief discussion is presented in Section 'Discussion' and conclusion is made in Section 'Conclusion'.

Motivation

The system operator dispatches the generators in a way to reduce the total generation cost (GC) taking care of operational and technical constraints at any loading condition of the system. A typical model for an optimal power flow based approach for solving a non-linear constrained optimization problem consists of quadratic objective functions is shown in (1).

$$\text{Min. } GC = \sum_{i=1}^{N^g} C_i(P_i^g) \tag{1}$$

subject to

$$P_i^g - P_i^l = \sum_j (V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i)) \;\; \forall\, i,\; j \in N^b \tag{2}$$