Electric Power Systems Research 147 (2017) 10–21

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Integrated mathematical model for uniform purchase prices on multi-zonal power exchanges

Ádám Sleisz*, Dávid Raisz

Department of Electrical Power Engineering, Budapest University of Technology and Economics, Egry József str. 18., Budapest H-1111, Hungary

ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 9 February 2017
Accepted 12 February 2017

Keywords:
Power exchange
Power generation
Economic modeling
Mathematical programming
Internal Energy Market

ABSTRACT

Electricity market integration is an important aspect of the planned Internal Energy Market in Europe. Day-ahead power exchanges (PXs) are going to be merged into a unified trading platform with a single clearing algorithm. This algorithm – called EUPHEMIA – practically handles an innovative hybrid of currently operating PXs: it includes elements that are new or have never been used together.

As a result, difficulties arise during the mathematical formulation of several components. The officially described calculation of uniform purchase prices for demand bids across different price regions is one of the most complicated issues. It can be straightforwardly implemented only in non-convex mixed integer programs (MIPs) which are extremely hard to solve. This paper presents a new formulation to incorporate these prices into the usual and computationally efficient convex MIP model of European PXs. Benefits and limitations of the proposal are discussed and also demonstrated with numerical tests.

1. Introduction

The worldwide energy sector liberalization process has particular consequences in Europe because it is accompanied by a strong intention of geographic market integration. In order to create the so-called Internal Energy Market, the overall organization and structure of electricity trade have to undergo a comprehensive transformation.

Most important modifications necessarily include the operation of day-ahead power exchanges (PXs) because an ever greater portion of power trade is occurring on these platforms. An ongoing project attempts to merge European PXs into a unified entity with a single clearing algorithm, a task made possible by the recent evolution of advanced market coupling techniques [1]. The aim is to improve the efficiency of the European power system in a way that allows the more economic exploitation of the transmission grid while providing new trading opportunities for actors on a bigger and supposedly more liquid market. Practical experiences in similar but smaller projects usually verify the underlying assumptions [2,3], though the exact results generally depend on certain policy decisions in corresponding market regions [4].

From the algorithmic point of view, fine-tuned versions of existing market coupling methods can be adequate to install large, multi-zonal markets. Nonetheless, constraining effects of the transmission network are not the only challenge that has to be faced during the construction of the common European PX algorithm. Special characteristics of several joining PXs also have to be taken into account because they usually represent crucial technical and economic conditions in the power systems of corresponding geographic regions. Therefore, the officially proposed algorithm – called EUPHEMIA [1] – has to handle an unusually diverse set of order types some of which are essentially new or seemingly incompatible with each other evoking difficulties during the mathematical formulation of the clearing problem.

One of the most complicated issues emerge around the implementation of uniform purchase prices across different price zones (PZs). The idea is that a set of PZs can be declared in which demand bidders pay the same price regardless of possible transmission bottlenecks while suppliers sell energy at the prices of their respective PZs. In the case of network congestions, zonal clearing prices might be different, hence the balance of incomes and expenses must be ensured directly. The idea itself originates from Italy where inland congestions are a relevant factor due to a variety of geographic and economic reasons. The country is divided into six PZs but buyers pay a uniform price, the so-called Prezzo Unico Nazionale (the Italian abbreviation PUN is widely used in Europe) [1,5].

The main problem is that the straightforward calculation of PUNs is not viable in a wider European setting because it introduces continuous non-convexities into the clearing model [6]. With the corresponding equation included, the resulting mathematical

* Corresponding author.
E-mail address: sleisz.adam@vet.bme.hu (Á. Sleisz).

http://dx.doi.org/10.1016/j.epsr.2017.02.011
0378-7796/

program would belong to the category of non-convex mixed integer programs (MIPs) which contains some of the hardest problem classes in the field of optimization [7].

This article attempts to provide a new formulation for PUNs which can be inserted into a convex MIP model widely used in Europe. Compatibility with other components of EUPHEMIA is investigated because the revised clearing problem contains an indirect calculation procedure for PUNs which requires overall knowledge about other order types on the market.

Section 2 describes the most important details about uniform purchase prices in the European setting while the proposed formulation and discussions on compatibility issues are included in Sections 3 and 4, respectively. Demonstrational case studies are presented in Section 5 followed by conclusions in Section 6.

2. Basic concepts about uniform purchase prices

2.1. A new demand order type

The meaningful application of uniform purchase prices is possible only on multi-zonal PXs where network congestions routinely cause zonal market clearing prices (MCPs) to diverge from each other. Under such circumstances, EUPHEMIA is designed to use PUNs to clear a special set of demand orders, the so-called PUN orders [1]. These bids are very similar to ordinary hourly demand step bids; the only difference is that their acceptance depends on PUNs instead of the zonal MCPs ($\forall h \in H, \forall k \in SP_h$ where H is the set of trading hours and SP_h stands for the set of PUN orders for hour h).

$$ACC_k > 0 \rightarrow PUN_h \leq p_k \quad (1)$$

$$ACC_k < 1 \rightarrow PUN_h \geq p_k \quad (2)$$

Individual bid prices and acceptance ratios are denoted by p_k and ACC_k, respectively. The pricing rules (1)–(2) allow three essential scenarios any PUN bid:

- *It is fully accepted* ($ACC_k = 1$): the corresponding PUN must not be larger than the bid price according to (1).
- *It is partially accepted* ($0 < ACC_k < 1$): since the logical conditions of both (1) and (2) are true, the corresponding PUN must be equal to the bid price.
- *It is fully rejected* ($ACC_k = 0$): the corresponding PUN must not be smaller than the bid price according to (2).

Without the inclusion of these rules, other scenarios would be also possible. The acceptance of bids that have to pay too much (so-called out-of-the-money bids) and the rejection of bids that would be capable of paying more (in-the-money bids) would be disadvantageous decisions for the bidders in question and for the whole market as well.

2.2. The calculation of prices

The calculation of hourly *PUN*s in EUPHEMIA is clearly defined. For each time period ($\forall h \in H$), the sum of the accepted PUN order volumes multiplied by the corresponding *PUN* has to be (nearly) equal to the summed value of the accepted PUN orders volumes multiplied by the corresponding *MCP*s.

$$PUN_h \sum_{k \in SP_h} ACC_k q_k = \sum_{k \in SP_h} MCP_{pz(k),h} ACC_k q_k + \Delta_h \quad (3)$$

Bid quantity is signified by q_k; order k is submitted to the PZ denoted by $pz(k)$. The equation practically means that – aside from the presence of Δ_h – the collective expense of PUN orders is the same as the amount of money sellers receive for the allocated energy. The tolerance variable Δ_h is called PUN imbalance. It is firstly introduced in EUPHEMIA [1] for numerical reasons. The PUN imbalance is constrained to be small, between −1 € and 5 €. Considering that q_k is conventionally negative for demand bids [1,8], the asymmetric settings express that consumers are willing to pay a little more in order to have uniform prices.

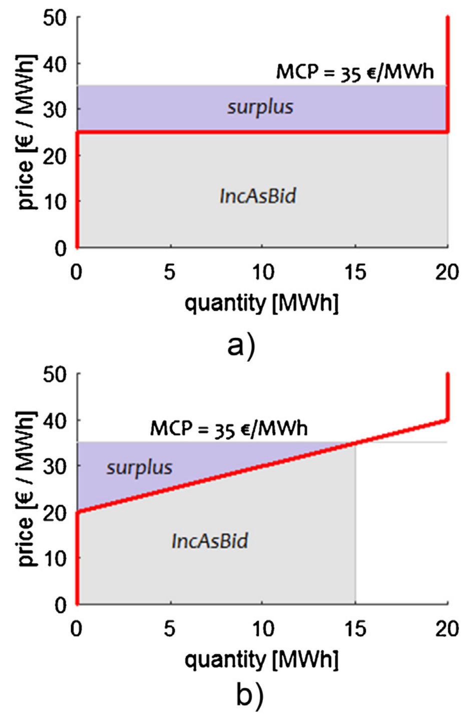

Fig. 1. Illustration of income and surplus for (a) hourly step bids and (b) hourly linear bids on the supply side. The sums of highlighted areas are the actual incomes (*INC*) of corresponding orders.

It has to be noted that the conditions concerning PUN orders (1)–(3) cannot lead to infeasibility because there is always a trivial clearing solution for them: full rejection. In this scenario, (3) is valid regardless of *PUN* values, therefore sufficiently high uniform purchase prices can be chosen deliberately. This option is vaguely reminiscent of the paradox rejection of non-convex bid types e.g. block orders.

There are no algorithmic barriers preventing consumers from defining other types of demand bids such as ordinary hourly bids or blocks. As a matter of fact, even in the original Italian practice, there are buyers who regularly pay *MCP*s for their purchases. However, it is allowed only for traders associated with pump storage facilities [5].

Market regulation of this kind has to play a crucial role in the applications of *PUN*s. If consumers were allowed to choose freely from different order types, they would choose the offers that are expected to entail lower prices. Purchasers in PZs with usually comparably low MCPs (such as the northern regions in the case of Italy) would be motivated to avoid PUN orders because of their generally higher prices. Since this choice would proportionally reduce the weights of these regions in the calculation of PUNs (3), the "unified" purchase price would become only slightly different from the MCPs in most expensive PZs. In other words, the intended concept of PUNs would be barely relevant on the market.

2.3. Appearance in social welfare

Using the described *PUN* definition, the overall balance of expenses and incomes practically remains valid on the market. This fact is critical because the transactions can be simply managed