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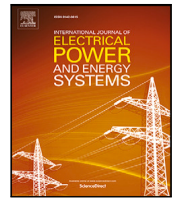
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A bidding mechanism for maintenance of generation units considering inter-ISO power exchange

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ABSTRACT

To ensure the reliability of power systems, the independent system operator (ISO) manages the planning process of the maintenance of generation units for generation companies (GENCOs). This paper focuses on a widely studied two-layer long-term predictive maintenance decision making framework in a deregulated environment. In the first layer the ISO-wide maintenance schedule is optimized for the GENCOs, targeting minimal total maintenance cost and degradation statuses. In the second layer, a bidding mechanism is designed for GENCOs who are not satisfied with the time slots scheduled by the first layer, so that they can bid for their preferred time slots. A novel bidding mechanism for the host ISO (i.e., the ISO that manages the maintenance planning process) is proposed, called interchangeable bidding mechanism for maintenance (IBMM). In this mechanism, the GENCOs of the host ISO can use their bid price to purchase the supportive energy from the GENCOs of the neighbor ISOs. Furthermore, they also can pay a penalty fee for reducing the amount of energy transmitted from the host ISO to the neighbor ISO with respect to what has been stipulated in the long-term inter-ISO power exchange contract. IBMM provides more opportunities for GENCOs of the host ISO to obtain their preferred maintenance time slots. Additionally, the power system reliability can be ensured. IBMM is formulated as a mixed-integer non-linear bidding programming problem. Then, the bidding programming problem is recast into a mixed-integer second-order cone programming (MISOCP) problem that can be solved using Gurobi. In the case study, the IEEE 118-bus network is studied to illustrate the performance of the proposed bidding strategy.

1. Introduction

To ensure the reliability of a power system, keeping generation units in a good condition is one of the responsibilities of an independent system operator (ISO) [1–3]. In addition, the reserved energy should be above a certain level when some of the generation units are undergoing maintenance, so that the risks of large-scale load loss caused by a reserved energy shortage can be avoided. Thus, the maintenance schedules are required to be properly planned [4–7]. The ISO manages the planning process of the maintenance considering the costs of maintenance actions for the generation units and the power system reliability. Maintenance scheduling is usually performed in a multi-time-scale manner and can consequently be categorized into long-term scheduling [8–11], mid-term scheduling [12,13], and short-term scheduling [14,15]. The current paper focuses on the design of a long-term maintenance scheduling framework.

Long-term maintenance of generation units (MGU) coordination frameworks that consider both the total benefits of the entire power

system and the benefits of individual generation units are widely considered in the literature [16–21]. For instance, a maintenance decision making model for generation companies (GENCOs) in an oligopolistic electricity market environment is proposed in [16]. The maintenance plans developed by GENCOs are reviewed and have to be approved by the ISO. In [19], a coordinating framework is introduced based on incentives/disincentives to balance the profits of producers and the reliability of the power system. In [20], the maintenance plan of generation units is scheduled considering N-1 examination for transmission lines random failures. Then, the maintenance budget and power system reliability are balanced. In [21], random failures on transmission lines are considered in the maintenance scheduling of generation units. The uncertainty of the line failure is modeled via scenarios, and these scenarios are obtained randomly according to arbitrary failure rate functions. In [8], a risk-based model is proposed to schedule the preventive maintenance of generators by considering the stochastic wind energy. The model includes the risk of load loss and the desired

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Nomenclature	
Acronyms	
<i>GENCO</i>	Generation company
<i>IBMM</i>	Interchangeable bidding mechanism for maintenance
<i>ISO</i>	Independent system operator
<i>MISOC</i>	Mixed-integer second-order cone programming
<i>MGU</i>	Maintenance of generation units
<i>NBMM</i>	Non-interchangeable bidding mechanism for maintenance
Sets and Indices	
i	Maintenance action index
k	Time slot index
m	Neighbor ISO index
n	GENCO index in neighbor ISOs
$\mathcal{I}$	Set of maintenance actions in the bidding process
$\mathcal{K}$	Set of time slots in the bidding process
$\mathcal{M}$	Set of neighbor ISOs that join the bidding process
$\mathcal{N}_m$	Set of GENCOs that intend to sell their supportive energy in neighbor ISO m
$\mathcal{K}_m^{\text{in}}$	Set of time slots when the power flow in the contract of inter-ISO power exchange goes from the host ISO to neighbor ISO m
$\mathcal{K}_m^{\text{out}}$	Set of time slots when the power flow in the contract of inter-ISO power exchange goes from neighbor ISO m to the host ISO
Parameters	
$C_{\text{Tr}}(m)$	Energy passing-by fee for one unit of transmitted energy from neighbor ISO m to the host ISO
$C_{\text{pen}}(m, k)$	Penalty for reducing one unit of energy transmitted to neighbor ISO m in time slot k with respect to what has been stipulated in the inter-ISO power exchange contract
$G_{\text{g}}^{\text{bid}}(i, k)$	Bid price of maintenance action i in time slot k
$G_{\text{neigh}}^{\text{bid}}(m, n, k)$	Bid price of GENCO n of neighbor ISO m in time slot k
$P_{\text{G},i}$	Capacity of generation unit i
$P_{\text{Tr}}(m, k)$	Transmission power in the power exchange contract on the tie line between the host ISO and neighbor ISO m in time slot k
R_m	Resistance on the tie line between the host ISO and ISO m
U_m	Terminal voltage at the host ISO side terminal of the tie line between the host ISO and ISO m
$q_{\text{G}}^{\text{max}}(m, n, k)$	Maximum supportive energy of GENCO n of neighbor ISO m in time slot k
$q_{\text{H}}^{\text{max}}(k)$	Maximum available reserved energy of the host ISO in time slot k

level of risk. In [22], a multi-objective maintenance scheduling strategy for generation units in deregulated power systems is proposed. The objectives of GENCOs and the ISO are both considered in the strategy.

$q_{\text{N}}^{\text{max}}(m, k)$	Maximum reserved energy for neighbor ISO m in time slot k
$q_{\text{Tr}}^{\text{max}}(m, k)$	Maximum energy that neighbor ISO m can transmit in time slot k
ϵ	A very small positive value
M	A very large positive value
τ_i	Duration of maintenance action i
Variables	
$p^{\text{re}}(m, i, k)$	Reduced transmitted energy from the host ISO to neighbor ISO m with respect to what has been stipulated in the inter-ISO power exchange contract for performing maintenance action i in time slot k
$q(m, n, i, k)$	Amount of energy purchased from GENCO n of the neighbor ISO m in time slot k for performing maintenance action i
$q_{\text{H}}(i, k)$	Amount of reserved energy of the host ISO that maintenance action i occupies in time slot k
$q_{\text{loss}}(m, n, i, k)$	Additional energy that GENCO n of neighbor ISO m needs to generate to compensate the energy losses when transmitting supportive energy to the host ISO for performing maintenance action i in time slot k
$q_{\text{loss}}^{\text{total}}(m, k)$	Total additional energy to be generated for compensating the energy losses when transmitting supportive energy from neighbor ISO m to the host ISO in time slot k
$q_{\text{loss}}^{\text{ref}, \text{out}}(m, k)$	Additional energy generated by the GENCOs of ISO m in time slot k for Case 1 (see Section 2.2 for details).
$q_{\text{loss}}^{\text{ref}, \text{in}}(m, k)$	Additional energy generated by the GENCOs of ISO m in time slot k for Case 3 (see Section 2.2 for details).
$Q(m, n, i, k)$	Auxiliary variable.
$\delta_{m,k}$	Case indicator. Equals 1 if Case 2 occurs (see Section 2 for details). Equals 0 if Case 3 occurs (see Section 2.2 for details).
$\Delta(i, k)$	Equals 1 if the maintenance action i is performed in time slot k , and 0 otherwise.

Just as in the above literature, this paper also focuses on designing a coordination framework to obtain a balanced trade-off between the overall power system benefit and the benefits of individual generation units.

In practice, some power systems operate in a deregulated environment, while others do not. In the case of the traditional regulated environment, the scheduling of the maintenance actions is managed by the power system operator. Then, the power producers are forced to perform maintenance actions according to the schedule defined by the operators [18]. In a deregulated environment, the GENCOs and the ISO are different entities. The role of the GENCOs is to supply energy to the power system with a major focus on obtaining profits. An important role of the ISO is to guarantee the reliability of the power system, considering the profits of the GENCOs. So, when the ISO manages the MGU processes, GENCOs schedule their maintenance actions by maximizing their profits and submitting them to the ISO. The ISO may reject some of the submitted schedules from the GENCOs to guarantee the reliability of the power system. Afterward, the GENCOs of the rejected schedules should reschedule their maintenance actions and then

resubmit them. This process is iteratively implemented between the ISO and GENCOs until the reliability of the power system is guaranteed and the maintenance actions submitted by the GENCOs are all scheduled (if the reserve energy is sufficient) [17]. Other coordination strategies for deregulated environments have also been studied in the literature. For example, in [18], a competitive bidding mechanism after maintenance planning is proposed. The goal is to balance the benefits of the GENCOs by considering the system reliability and the health condition of the generating units. In [17], a framework is proposed in which first the ISO maximizes the reliability index of the whole power system by using a reliability-centered maintenance strategy. Then, GENCOs can bid for their preferred maintenance slots under the constraint of a given power system reliability index. Afterward, the ISO determines the bidding results.

This paper considers coordinating the power system reliability and the profits of GENCOs via a bidding mechanism as proposed in [17]. The mechanism is implemented after an initial maintenance schedule is proposed. This initial schedule is usually based on global optimization of the ISO-wide profits of all the GENCOs. This solution (which may also be called a one-shot solution) might conflict with the individual profit of some GENCOs. Thus, the bidding mechanism allows GENCOs to have a platform where they can chase their profit. From the various strategies in the literature, this paper selects the bidding mechanism because it will obtain maintenance schedules within less iterations and it is more straightforward. In this strategy, the ISO firstly determines the ISO-wide optimal MGU schedule. Then if the GENCOs are not satisfied with their scheduled time slots, they can join in the bidding process to change their time slots. The ISO determines the bidding result by maximizing the net benefit of the bids. Then the net benefit received by the host ISO (a non-profitable organization) is used to improve the power system operation and power quality. Thus, the net benefit received from the bidding process is also the social welfare. However, in [17], it is mentioned that, if after the bidding process the reliability goal of the power system cannot be reached, the ISO should seek other means, such as utilizing inter-regional power exchange, to ensure the reliability of the power system.

This paper argues that it may be beneficial to include the inter-ISO power exchange in the bidding process for coordination directly, rather than after the bidding process. Thus, a novel bidding mechanism is proposed where the host ISO (the ISO who manages the planning process of MGU for its GENCOs is called the *host ISO* in this paper) can start the bidding processes for MGU with the participation of the GENCOs of the host ISO and the GENCOs of the neighbor ISOs. The GENCOs of the host ISO can use their bid prices to buy supportive energy from the GENCOs of the neighbor ISOs of the host ISO, or to a pay penalty fee for reduction of the transmitted power from the host ISO to the neighbor ISO with respect to what has been stipulated in the inter-ISO power exchange contract. Then, the reserved energy level of the host ISO can be sustained when the generation units of the GENCOs that bid for their preferred time slots are undergoing maintenance. Moreover, buying supportive energy, reducing the transmitted power, or both buying supportive energy and reducing the transmitted power are influenced by to the direction and amount of the power flow on the tie line between the host ISO and its neighbor ISO. The direction and amount of this power flow can be contracted via the long-term inter-ISO power exchange transactions [23]. The host ISO determines the maintenance plans via bidding, by considering the reserved energy level of itself and of its neighbor ISOs, the tie line limitations (congestion), energy loss allocation during transmission, and so on. It should be mentioned that the neighbor ISOs cannot sell energy because they are non-profitable organizations [19], but they should monitor their own operation conditions, e.g., reserved energy levels, in the bidding process. The neighbor ISOs should prevent their GENCOs to over-support energy to the host ISO and as this could result in lack of reserved energy (i.e., a high marginal price) in the grids of the neighbor ISOs.

This proposed interchangeable bidding mechanism for maintenance (IBMM) has two distinguished advantages compared with bidding mechanisms that do not consider the direct participation of the GENCOs of the neighbor ISOs in the bidding process, namely helping the GENCOs to obtain their preferred time slots, and ensuring the reliability of the power system. Later on in this paper, these two advantages will be analyzed based on simulation results.

It will also be discussed how to organize the bidding processes for the situation in which there are multiple ISOs in a large grid. In particular, three organization schemes for starting the bidding processes will be discussed and analyzed: centralized bidding, priority bidding, and impromptu bidding.

The contributions of the current paper are:

- (1) A novel interchangeable bidding mechanism is proposed for helping the GENCOs to obtain their preferred time slots while also ensuring the reliability of the power system.
- (2) In our proposed bidding mechanism, GENCOs of the host ISO can change their scheduled maintenance slots to their preferred ones by buying supportive energy from the GENCOs of the neighbor ISOs, reducing the transmitted energy to the neighbor ISOs, or both.
- (3) Three possible organization schemes for starting the bidding processes in a large power grid associated with multiple ISOs are discussed.

The outline of this paper is as follows. Section 2 introduces three ways the GENCOs can use to ensure the reserved energy level of the host ISO, when they intend to change their scheduled maintenance time slots. In Section 3, the proposed bidding mechanism, the formulated bidding programming problem, and the details of recasting will be introduced. In Section 4, a case is studied and the performance of the proposed bidding mechanism is analyzed via comparison. Discussions of three bidding organization schemes for large grids, implementation of the proposed bidding strategy, and a larger scheduling period of maintenance are provided in Section 5. Finally, Section 6 concludes the paper.

2. Preliminaries

2.1. Illustration of the working principles via an example

To ensure fairness in a market environment, the GENCOs that are not satisfied with the first-stage MGU scheduling results will be given the opportunity to bid for their preferred time slots for maintenance of their generation units. However, when these GENCOs change the maintenance time slots for their generation units, the reserved energy may fall below the safety level, and consequently the power system of the host ISO may face a reliability problem. Thus, this paper proposes to consider three possible cases for the GENCOs of the host ISO for obtaining inter-ISO energy. As shown in Fig. 1, a simple illustrative example is given below for an intuitive understanding of the reliability problem caused by changing the maintenance time slots and the three cases for obtaining the inter-ISO energy.

In the example of Fig. 1, the host ISO manages the PJM 5-bus network [24,25]. Generation units G1, G3, and G4 are satisfied with the first-stage MGU scheduling results, while generation unit G2 is not. The maintenance action of G2 takes one maintenance time slot, and G2 intends to change its scheduled maintenance slot to time slot k_{G2} . Furthermore, there are three neighbor ISOs of the host ISO. In time slot k_{G2} , the power flows are from neighbor ISO 1 to the host ISO, and from the host ISO to neighbor ISOs 2 and 3 in the long-term inter-ISO power exchange contract.

In time slot k_{G2} , there is 80 MW of reserved energy in the PJM 5-bus network. Thus, if G2 intends to perform its maintenance action in time slot k_{G2} , there will be an energy gap of $200 - 80 = 120$ MW between the

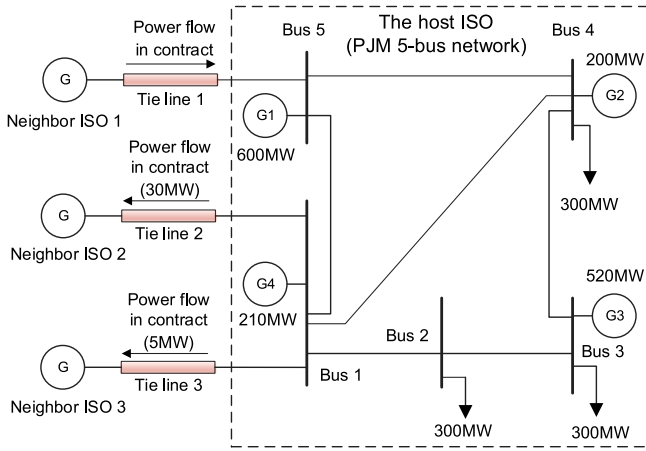


Fig. 1. The power network topology of the example.

generated energy and the demand. The gap cannot be filled if the inter-ISO power exchange is not considered. Then, if the non-interchangeable bidding mechanism for maintenance (NBMM) is adopted, G2 cannot change its maintenance slot to k_{G2} . Using IBMM, the energy gap may be filled via the following three measures with the inter-ISO power exchange.

First, neighbor ISO 1 can provide 80 MW supportive energy to the host ISO. Second, the power flow from the host ISO to neighbor ISO 2 can be reduced by 20 MW. Third, the power flow from the host ISO to neighbor ISO 3 can be reduced to 0 MW, and then the power flow turns inversely, and neighbor ISO 3 can provide 15 MW supportive energy to the host ISO. In this way, the 120 MW energy gap in time slot k_{G2} can be filled.

These three measures imply that G2 can change its maintenance time slot to k_{G2} via purchasing supportive energy from neighbor ISOs 1 and 3, and via paying the penalty fees for reducing the transmitted energy to neighbor ISOs 2 and 3. Additionally to the requirements of energy, G2 must consider its budget for changing its maintenance time slot and will aim to change it at the lowest costs. Thus, this paper proposes a bidding mechanism, i.e., IBMM, that can help G2 purchase the cheapest supportive energy from the neighbor ISOs and pay the least penalty fees for reducing the transmitted energy.

2.2. Cases for obtaining inter-ISO energy

In the example in Section 2.1, the three measures can be generalized as three cases. These three cases are defined based on the long-term inter-ISO power exchange contract regarding the exchange of power between ISOs. In the long-term power exchange contract, the host ISO may transmit energy to support some of the neighbor ISOs and be supported by other neighbor ISOs.

Case 1 is with respect to the neighbor ISOs that transmit the energy to the host ISO in the long-term power exchange contract. In Case 1, the GENCOs of the host ISO can use their bid price to purchase the supportive energy generated by the GENCOs of these neighbor ISOs.

Case 2 is with respect to the neighbor ISOs that receive the energy from the host ISO in the long-term power exchange contract. In Case 2, the host ISO can reduce the power transmitted to the neighbor ISOs w.r.t. the long-term inter-ISO power exchange contract, and use the bid prices of the GENCOs of the host ISO to pay the penalty fee for reducing the transmitted power.

Finally, Case 3 is also with respect to the neighbor ISOs that receive the energy from the host ISO in the long-term power exchange contract. In Case 3, the host ISO reduces the power transmitted to the neighbor ISOs to zero but still it is not enough to fill the shortage of reserved energy; so then the GENCOs of the host ISO need to purchase the

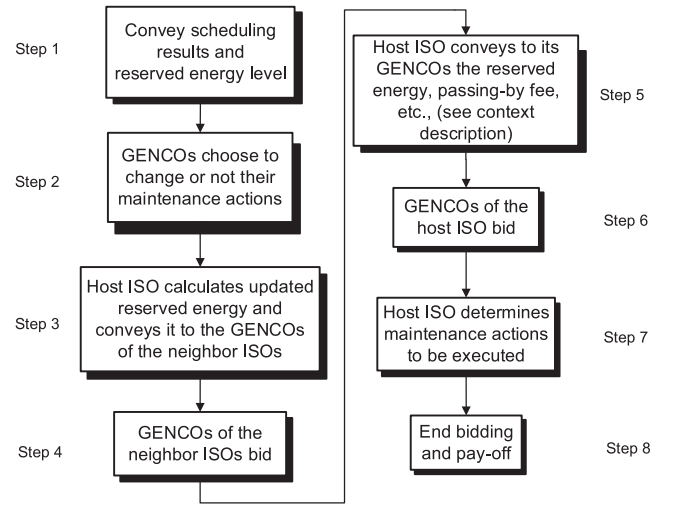


Fig. 2. Flowchart for the bidding process.

supportive energy from the GENCOs of the neighbor ISOs. Thus, the bid price of the GENCOs of the host ISO should be used to pay the penalty fee, and also to buy the supportive energy from the GENCOs of the neighbor ISOs.

In Cases 1 and 3, if the supportive energy is so expensive that the GENCOs in the host ISO cannot afford it, the GENCOs in the host ISO cannot change their time slots via purchasing supportive energy to fill the energy gap when they are under maintenance. Furthermore, in Cases 2 and 3, if the inter-ISO power exchange is not allowed for some neighbor ISOs, the penalty fee can be set to a very large value. Moreover, the amount of purchased supportive energy should be constrained by the capacity of the tie lines to avoid congestion. The cases will then be mathematically modeled in the bidding problem in Section 3.2. Note that, since the paper focuses on the transmission layer, the distribution layer is not considered in the proposed bidding mechanism.

3. Bidding mechanism for the host ISO

In this section, how the proposed IBMM is implemented for the host ISO is firstly introduced. Then the bidding programming problem is formulated. Afterward, the formulated problem is recast into a mixed-integer second-order cone programming (MISOCP) problem.

3.1. IBMM bidding mechanism

When the host ISO decides to start a bidding process, it gathers the GENCOs who are not satisfied with the scheduling results, and the GENCOs who intend to sell energy in the neighbor ISOs to participate in the bidding process. A flowchart of the proposed bidding process is shown in Fig. 2. The process consists of the following steps:

- (1) After obtaining the ISO-wide optimal scheduling results, the host ISO conveys the first-stage scheduling results and the amount of reserved energy at each time slot to its GENCOs.
- (2) GENCOs of the *host ISO* choose to fix their scheduled time slots by not participating in the bidding process or to change their scheduled time slots by participating in the bidding process. If there are no GENCOs that intend to participate, the bidding process ends.
- (3) The host ISO calculates the reserved energy by taking the time slots fixed by the GENCOs in Step (2) into account. For example, if in time slot 1, the total generation capacity of the generation units is 1 MW, while the maintenance actions of the generation

units with a total generation capacity of 0.4 MW are fixed by the GENCOs, then the reserved energy in time slot 1 is 0.6 MW. Then the ISO updates the reserved energy and the updated reserved energy is conveyed to the GENCOs of the neighbor ISOs.

- (4) The GENCOs of the neighbor ISOs submit the price and amount of the energy they can deliver for each time slot.
- (5) Then the host ISO conveys the reserved energy level, passing-by fee for inter-ISO power transmission, the maximum amount and penalty fee for reducing transmitted energy on the tie line, and the amounts of available supportive energies from the GENCOs of the neighbor ISOs with their prices to the GENCOs of the host ISO.
- (6) The GENCOs of the host ISO will bid according to the cost to purchase supportive energy, the penalty fee to reduce transmitted energy, the benefits they can obtain by changing the maintenance schedule, among other factors. To obtain the bid price for the GENCOs of the host ISO, a method such as the multi-objective programming approach of [22] can be used. This paper assumes that the bid prices have been determined. The total bid price for a maintenance action that occupies multiple time slots is the sum of the prices of these time slots.
- (7) The host ISO decides which maintenance actions should be performed by maximizing the total social welfare. The corresponding optimization problem will be explained in Section 3.2.
- (8) End the bidding process and pay-off.

3.2. Decision making model for the host ISO

In Step (7) of the bidding process, the host ISO will determine which maintenance actions should be performed. The objective of the bidding process is to maximize the total social welfare. The social welfare obtained from the bidding process can be calculated as:

$$B = \max_{\Delta, \delta, q, q_{\text{loss}}, q_H, p^{\text{re}}} \sum_{i \in I} \sum_{k \in \mathcal{K}} \Delta(i, k) \left(G_{\text{g}}^{\text{bid}}(i, k) - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} (q(m, n, i, k) + q_{\text{loss}}(m, n, i, k)) \cdot G_{\text{neigh}}^{\text{bid}}(m, n, k) - \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} (q(m, n, i, k) + q_{\text{loss}}(m, n, i, k)) \cdot C_{\text{Tr}}(m) - \sum_{m \in \mathcal{M}} p^{\text{re}}(m, i, k) \cdot C_{\text{pen}}(m, k) \right) \quad (1)$$

In (1), the first term involves the bid prices of the GENCOs; the second term involves the price for the GENCOs to purchase supportive energy from the neighbor ISOs; the third term corresponds to the price for paying the passing-by fees on the tie lines; and the fourth term is the penalty fee for reducing the energy transmitted from the host ISO to the neighbor ISOs. Then, the total additional energy $q_{\text{loss}}^{\text{total}}(m, k)$ that should be generated by the GENCOs of neighbor ISO m in time slot k is formulated as:

$$\begin{aligned} q_{\text{loss}}^{\text{total}}(m, k) &= q_{\text{loss}}^{\text{ref, out}}(m, k) \text{ if } k \in \mathcal{K}_m^{\text{out}}, \\ q_{\text{loss}}^{\text{total}}(m, k) &= 0 \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 1, \\ q_{\text{loss}}^{\text{total}}(m, k) &= q_{\text{loss}}^{\text{ref, in}}(m, k) \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 0, \end{aligned} \quad (2)$$

where $q_{\text{loss}}^{\text{ref, out}}(m, k) = \left(\left(P_{\text{Tr}}(m, k) + \sum_{i \in I} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \right)^2 - P_{\text{Tr}}^2(m, k) \right) R_m / U_m^2$

and $q_{\text{loss}}^{\text{ref, in}}(m, k) = \left(\sum_{i \in I} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \right)^2 \cdot R_m / U_m^2$,

$\forall m \in \mathcal{M}, \forall k \in \mathcal{K}$

where $\delta(m, k)$ is the case indicator, i.e. $\delta(m, k) = 1$ represents that the reduced transmission power from the host ISO to ISO m on the tie line at time slot k is smaller than the transmission power in the inter-ISO

power exchange contract, while otherwise $\delta(m, k) = 0$; $P_{\text{Tr}}(m, k)$ is the transmission power on the tie line between the host ISO and ISO m in time slot k that has been stipulated in the inter-ISO long-term energy transactions contract. As mentioned in Section 2, three cases are included in (2). Case 1 corresponds to purchasing supportive energy, Case 2 corresponds to reduce the transmitted power, and Case 3 corresponds to do both. In Case 2 in (2), by reducing the transmitted energy from the host ISO to the neighbor ISO, the energy loss is reduced. Then, the GENCOs of the neighbor ISO do not need to generate additional energy to compensate the additional energy loss, so $q_{\text{loss}}^{\text{total}}(m, k) = 0$.

Then, after adopting the loss allocation method as proposed in [26], $q_{\text{loss}}(m, n, i, k)$ can be obtained by:

$$q_{\text{loss}}(m, n, i, k) = q_{\text{loss}}^{\text{total}}(m, k) \cdot \frac{q(m, n, i, k)}{\sum_{i \in I} \sum_{n \in \mathcal{N}_m} q(m, n, i, k)} \quad (3)$$

$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}_m, \forall i \in I, \forall k \in \mathcal{K}$

The reduced energy for each case can be described as:

$$\sum_{i \in I} p^{\text{re}}(m, i, k) = 0, \text{ if } k \in \mathcal{K}_m^{\text{out}} \quad (4a)$$

$$\sum_{i \in I} p^{\text{re}}(m, i, k) < |P_{\text{Tr}}(m, k)|, \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 1 \quad (4b)$$

$$\sum_{i \in I} p^{\text{re}}(m, i, k) = |P_{\text{Tr}}(m, k)|, \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 0 \quad (4c)$$

The purchased supportive energy for each case can be described as:

$$q(m, n, i, k) \geq 0, \text{ if } k \in \mathcal{K}_m^{\text{out}} \quad (5a)$$

$$q(m, n, i, k) = 0, \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 1 \quad (5b)$$

$$q(m, n, i, k) \geq 0, \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 0 \quad (5c)$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}_m, i \in I$$

The amount of energy obtained from the reserved energy cannot be negative values:

$$q_H(i, k) \geq 0, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}_m, \forall i \in I, \forall k \in \mathcal{K} \quad (6)$$

The constraints for balancing the amounts of energy that include the energy iteration between the host and neighbor ISOs are:

$$\begin{aligned} \Delta(i, k) P_{G, i} &= q_H(i, k) + \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) + \sum_{m \in \mathcal{M}} p^{\text{re}}(m, i, k), \forall i \in I, \forall k \in \mathcal{K} \end{aligned} \quad (7)$$

Constraint (7) ensures that, when $\Delta(i, k) = 0$, $q_H(i, k)$, $q(m, n, i, k)$ and $p^{\text{re}}(m, i, k)$ are all zero (no reserved energy occupied, no supportive energy purchased, and no reduced transmitted power). The bid maintenance actions can only be performed once:

$$\sum_{k \in \mathcal{K}} \Delta(i, k) = 0 \text{ or } \sum_{k \in \mathcal{K}} \Delta(i, k) = \tau_i, \forall i \in I \quad (8)$$

The constraints to consecutively perform maintenance actions are:

$$\sum_{k \in \mathcal{K}} |\Delta(i, k) - \Delta(i, k-1)| \leq 2, \forall i \in I \quad (9)$$

where $\Delta(i, 0) = 0, i \in I$. The reserved energy obtained from the host ISO by generation units cannot exceed the maximum reserved energy $q_H^{\text{max}}(k)$ at each time slot k , while the available energy (constrained by the transmission line capacity limitation) obtained by the generation units from neighbor ISO m cannot exceed the available energy $q_{\text{Tr}}^{\text{max}}(m, k)$ that neighbor ISO m can deliver at each time slot k :

$$\begin{aligned} \sum_{i \in I} q_H(i, k) &\leq q_H^{\text{max}}(k), \\ \sum_{n \in \mathcal{N}_m} \sum_{i \in I} (q(m, n, i, k) + q_{\text{loss}}(m, n, i, k)) &\leq q_{\text{Tr}}^{\text{max}}(m, k), \end{aligned} \quad (10)$$

$\forall i \in I, \forall m \in \mathcal{M}, \forall n \in \mathcal{N}_m, \forall k \in \mathcal{K}$

Furthermore, the neighbor ISOs can restrain the bidding behavior of their GENCOs considering the reserved energy levels of neighbor ISOs:

$$\sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} (q(m, n, i, k) + q_{\text{loss}}(m, n, i, k)) \leq q_N^{\text{max}}(m, k), \quad (11)$$

$$\forall m \in \mathcal{M}, \forall k \in \mathcal{K}$$

The supportive energy $q_G^{\text{max}}(m, n, k)$ of GENCO n of ISO m in time slot k should be limited by the maximum supportive energy bid:

$$\sum_{i \in \mathcal{I}} q(m, n, i, k) + q_{\text{loss}}(m, n, i, k) \leq q_G^{\text{max}}(m, n, k), \quad (12)$$

$$\forall m \in \mathcal{M}, n \in \mathcal{N}_m, k \in \mathcal{K}$$

The bidding programming problem (1)–(12) is a mixed-integer non-linear programming problem.

3.3. Recasting the nonlinear programming problem

Since constraints (2)–(4), (8), and (9) are in mixed-integer non-linear constraints, the problem (1)–(12) is difficult to solve. Therefore, this subsection introduces a method to recast the constraints (2)–(4), (8), and (9) into tractable mixed-integer linear or mixed-integer second-order cone forms. First, regarding (2) and (3), we substitute (2) into (3), such that:

$$q_{\text{loss}}(m, n, i, k) = \left(\sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) + 2P_{\text{Tr}}(m, k) \right) \cdot R_m / U_m^2, \quad (13)$$

$$q(m, n, i, k), \text{ if } k \in \mathcal{K}_m^{\text{out}},$$

$$q_{\text{loss}}(m, n, i, k) = 0 \text{ if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 1,$$

$$q_{\text{loss}}(m, n, i, k) = \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \cdot R_m / U_m^2 \cdot q(m, n, i, k),$$

$$\text{if } k \in \mathcal{K}_m^{\text{in}} \text{ and } \delta(m, k) = 0$$

Then (13) can be refined into:

$$q_{\text{loss}}(m, n, i, k) = \left(\sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) + 2P_{\text{Tr}}(m, k) \right) \cdot R_m / U_m^2, \quad (14)$$

$$q(m, n, i, k), \text{ if } k \in \mathcal{K}_m^{\text{out}},$$

$$q_{\text{loss}}(m, n, i, k) = (1 - \delta(m, k)) \cdot \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \cdot R_m / U_m^2 \cdot q(m, n, i, k),$$

$$q(m, n, i, k), \text{ if } k \in \mathcal{K}_m^{\text{in}}$$

By using the method in [27], (14) can be recast into a mixed-integer second-order cone constraint, such that:

$$q_{\text{loss}}(m, n, i, k) = \left(\sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) + 2P_{\text{Tr}}(m, k) \right) \cdot R_m / U_m^2, \quad (15)$$

$$q(m, n, i, k), \text{ if } k \in \mathcal{K}_m^{\text{out}},$$

$$q_{\text{loss}}(m, n, i, k) = \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \cdot R_m / U_m^2 \cdot q(m, n, i, k) -$$

$$Q(m, n, i, k), \text{ if } k \in \mathcal{K}_m^{\text{in}},$$

$$Q(m, n, i, k) \leq M \cdot \delta(m, k),$$

$$Q(m, n, i, k) \geq -M \cdot \delta(m, k),$$

$$Q(m, n, i, k) \leq \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \cdot R_m / U_m^2 \cdot q(m, n, i, k) + M \cdot$$

$$(1 - \delta(m, k)),$$

$$Q(m, n, i, k) \geq \sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}_m} q(m, n, i, k) \cdot R_m / U_m^2 \cdot q(m, n, i, k) - M \cdot$$

$$(1 - \delta(m, k))$$

Second, (4) can be refined into:

$$\sum_{i \in \mathcal{I}} p^{\text{re}}(m, i, k) = 0, \text{ if } k \in \mathcal{K}_m^{\text{out}} \quad (16a)$$

$$(1 - \delta(m, k)) \cdot |P_{\text{Tr}}(m, k)| \leq \sum_{i \in \mathcal{I}} p^{\text{re}}(m, i, k) \leq |P_{\text{Tr}}(m, k)| - \delta(m, k) \cdot \epsilon, \text{ if } k \in \mathcal{K}_m^{\text{in}} \quad (16b)$$

where ϵ is a very small positive value. Then (16a) is a linear constraint and (16b) is a mixed-integer linear constraint.

Third, (5) can be refined into:

$$q(m, n, i, k) \geq 0, \text{ if } k \in \mathcal{K}_m^{\text{out}} \quad (17a)$$

$$0 \leq q(m, n, i, k) \leq (1 - \delta(m, k)) \cdot M, \text{ if } k \in \mathcal{K}_m^{\text{in}} \quad (17b)$$

where M is a very large positive value. Then (17b) is a mixed-integer linear constraint.

The absolute value and “or” logic in constraints (8) and (9), respectively, can be recast into mixed-integer linear constraints by using the method in [27]. Consequently, the bidding programming problem (1)–(12) can be recast into an MISOCP problem that can be solved by the branch-and-bound algorithm in commercial software, e.g., Gurobi.

4. Case study

To illustrate the performance of the proposed bidding strategies, in this case, the IEEE 118-bus network that is an approximation of the American Electric Power system in the U.S. Midwest is considered. The IBMM will be simulated with a scheduling period of 13 weeks (time slots) for the host ISO. The simulation results will be compared with those of NBMM, where NBMM does not consider the supportive energy from the neighbor ISOs nor the reduction of transmitted energy. In detail, NBMM is the programming problem by fixing $q(m, n, i, k)$ and $p^{\text{re}}(m, i, k)$ to zero in the IBMM problem.

4.1. Parameters and settings

In this simulation test, the host ISO and two neighbor ISOs manage three connected IEEE 118-bus networks, respectively. The data of IEEE 118-bus system are given in [28]. In the IEEE 118-bus network of the host ISO, five generation units intend to bid for changing their scheduled maintenance actions, whose parameters are shown in Table 1. Furthermore, there are two neighbor ISOs of the host ISO, and in each neighbor ISO, three generation units of three GENCOs intend to provide the supportive energy, as shown in Fig. 3. Table 2 indicates the capacity for supportive energy of the GENCOs of the neighbor ISOs and Fig. 3 shows the locations of these neighbor ISOs.

Furthermore, this simulation test considers Cases A to D with different values of parameters $G_g^{\text{bid}}(i, k)$ and $G_{\text{neigh}}^{\text{bid}}(m, i, k)$. The $G_g^{\text{bid}}(i, k)$ and $G_{\text{neigh}}^{\text{bid}}(m, i, k)$ values of Cases A and B are shown in Fig. 4. In Case C, the bid prices of the GENCOs of the host ISO $G_g^{\text{bid}}(i, k)$ are twice those of Case A, while the other parameters are the same. In Case D, the bid prices for supportive energy $G_{\text{neigh}}^{\text{bid}}(m, i, k)$ are twice those of Case B, while the other parameters are the same. Cases A to D are considered to highlight two aspects. First, Cases A and C are designed to analyze the influences of bid prices of the GENCOs of the host ISO on the bidding results. Second, Cases B and D are designed to analyze the influences of bid prices of supportive energy. The maximum available reserved energies $q_H^{\text{amx}}(k)$ of the host ISO for Cases A to D are the same, see Fig. 5.

This paper uses Gurobi to solve the MISOCP bidding optimization problems. For the given case study, the globally optimal solutions of the bidding optimization problems can be obtained within 10 min.

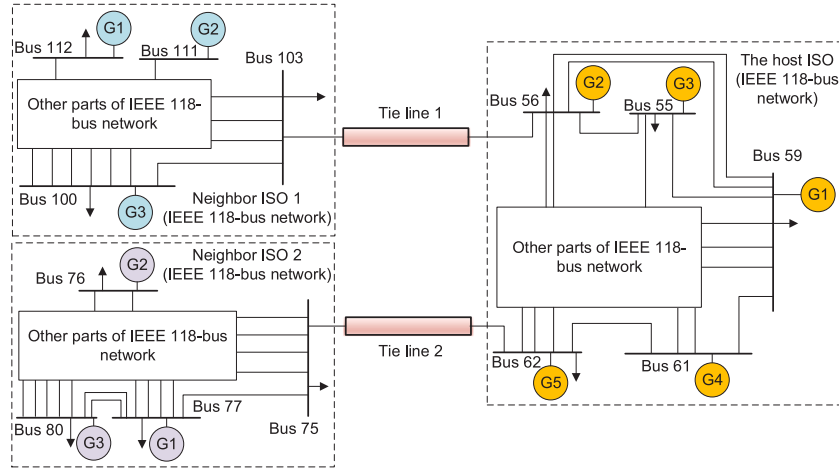


Fig. 3. The power network topology of the case study based on IEEE 118-bus networks.

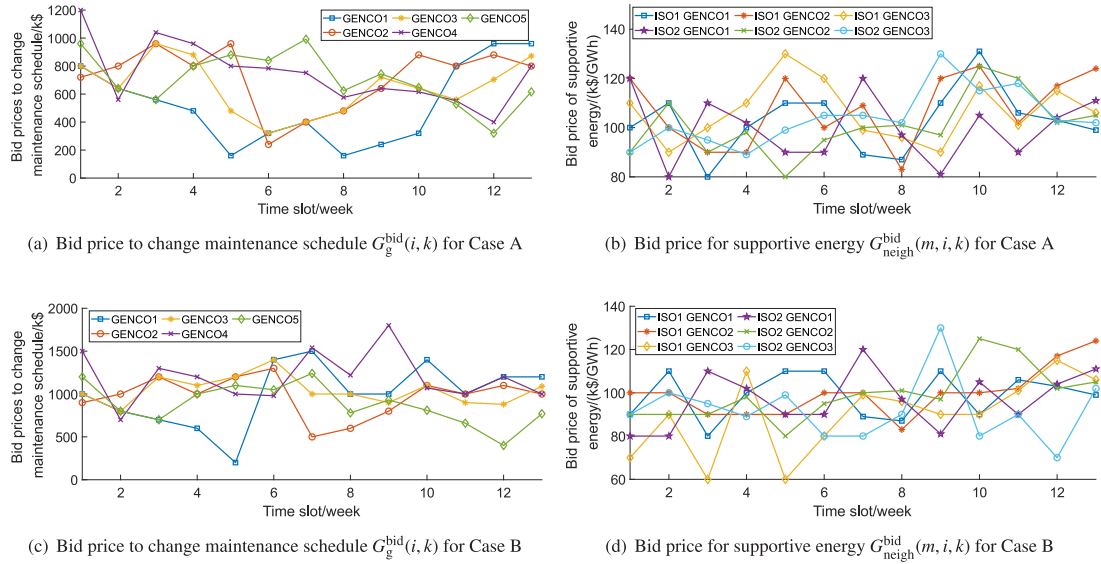


Fig. 4. The parameters of $G_g^{bid}(i, k)$ and $G_{neigh}^{bid}(m, i, k)$ for Cases A and B.

Table 1
Generation unit parameters.

Maintenance action	Maintenance duration (week)	Generation unit capacity (GW h/week)
1	3	20.4
2	2	16.8
3	2	16.8
4	2	20.4
5	1	16.8

Table 2
GENCOs in neighbor ISOs.

	GENCO1 (GW h/week)	GENCO2 (GW h/week)	GENCO3 (GW h/week)
Neighbor ISO 1	10.8	8.8	10.4
Neighbor ISO 2	12.8	9.8	16.8

4.2. Comparison between IBMM and NBMM

Comparative results between IBMM and NBMM for Cases A to D are shown in Fig. 6. For Cases A to D with NBMM, the bidding results are the same and shown in Fig. 6a. Table 3 lists the amount of supportive

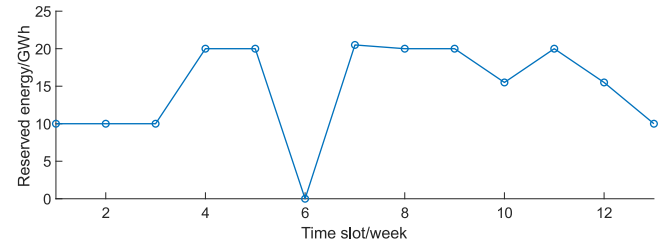


Fig. 5. The same values of $q_H^{ans}(k)$ for Cases A to D.

energy purchased by the GENCOs in the host ISO and the prices for trade-off the supportive energy. In Table 3, “G x of ISO y” represents the GENCO x of ISO y, and “G z” represents GENCO z of the host ISO. For Case D, as shown in Table 3, no supportive energy is purchased. Table 4 lists the amount of reduced energy transmitted from the host ISO to the neighbor ISO for Cases A to D.

Table 3 also reveals the winners/losers of the bidding. For example, the data in the first row of Table 3 represent that, in time slot 4 of Case A, the winner that can sell its supportive energy to GENCO 4 is the GENCO 2 of neighbor ISO 1. From the bidding prices of Case

	1	2	3	4	5	6	7	8	9	10	11	12	13
GENCO1													
GENCO2													
GENCO3													
GENCO4													
GENCO5													

(a) Bidding result with NBMM for Cases A to D

	1	2	3	4	5	6	7	8	9	10	11	12	13
GENCO1													
GENCO2													
GENCO3													
GENCO4													
GENCO5													

(b) Bidding result with IBMM for Case A

	1	2	3	4	5	6	7	8	9	10	11	12	13
GENCO1													
GENCO2													
GENCO3													
GENCO4													
GENCO5													

(c) Bidding result with IBMM for Case B

	1	2	3	4	5	6	7	8	9	10	11	12	13
GENCO1													
GENCO2													
GENCO3													
GENCO4													
GENCO5													

(d) Bidding result with IBMM for Case C

	1	2	3	4	5	6	7	8	9	10	11	12	13
GENCO1													
GENCO2													
GENCO3													
GENCO4													
GENCO5													

(e) Bidding result with IBMM for Case D

Fig. 6. The comparison between IBMM and NBMM.

Table 3

Amount of purchased energy for Cases A to D.

Case	From	To	Time slot	Purchased energy (GW h)	Paid price (k\$)
A	G 2 of ISO 1	G 4	4	0.4	36
	G 2 of ISO 2	G 4	5	0.4	32
	G 1 of ISO 1	G 2	12	1.3	133.9
B	G 1 of ISO 2	G 2	2	6.8	544
	G 3 of ISO 1	G 2	3	3.8	380
	G 3 of ISO 1	G 4	9	0.4	36
	G 3 of ISO 2	G 1	10	4.9	563.5
	G 3 of ISO 1	G 1	11	0.4	40.4
	G 3 of ISO 2	G 1	12	2.9	298.7
C	G 2 of ISO 2	G 3	3	6.8	612
	G 1 of ISO 2	G 2	10	1.3	136.5
	G 3 of ISO 1	G 1	11	0.4	40.4
	G 1 of ISO 1	G 1	12	4.9	504.7
	G 1 of ISO 1	G 1	13	10.4	1029.6
D	–	–	–	–	–

A in Fig. 4(b), although the supportive energy from the GENCO 2 of neighbor ISO 2 is the cheapest at time slot 4, the power flow at time slot 4 is from the host ISO to neighbor ISO 2. Thus, recall the explanation of Case 3 in Section 2.2, the power flow from the host ISO to neighbor ISO 2 should be reduced to zero, and then the supportive energy from the GENCO 2 of neighbor ISO 2 can be purchased. On the contrary, since in time slot 4 of Case A, the power flow is from neighbor ISO 1 to the host ISO, the supportive energy from the GENCO 2 of neighbor ISO 1 can be purchased directly. Consequently, although the supportive energy from the GENCO 2 of neighbor ISO 1 is more expensive than that from the GENCO 2 of neighbor ISO 2, the total cost for obtaining 0.4 GW·h from GENCO 2 of neighbor ISO 1 is cheaper.

IBMM suggests for Cases A to D to perform 4, 5, 5, and 4 maintenance actions respectively, see Fig. 6. NBMM suggests only 3 maintenance actions for Cases A to D. With IBMM, the time slots in which the maintenance actions will be performed are different from those of NBMM. Furthermore, in Table 3, it can be observed that the GENCOs

Table 4

Amount of reduced energy for Cases A to D.

Case	From	Time slot	Reduced energy (GW h)
A	ISO 2	8	0.4
	ISO 2	9	0.4
	ISO 2	12	1.3
B	ISO 1	3	3
	ISO 2	8	0.4
	ISO 2	12	2
C	ISO 1	8	0.4
	ISO 1	8	0.4
	ISO 2	9	0.4
D	ISO 2	10	4.9
	ISO 2	11	0.4
	ISO 1	12	2.9
	ISO 2	12	2
	ISO 2	12	2

of the host ISO purchase the supportive energy and pay the penalty fee for reducing the transmission energy to the neighbor ISOs. Thus, IBMM can provide more opportunities for GENCOs of the host ISO to obtain their preferred maintenance time slots. Furthermore, the reliability of the power system can be ensured.

4.3. Influences of bid prices on the bidding results

From Case A and Case C, see Fig. 6, when the bid prices of the GENCOs of the host ISO increase, more GENCOs of the host ISO can obtain their preferred maintenance slots. For example, in Case C, the maintenance action bid by GENCO 1 in the host ISO can be performed from time slots 11 to 13, while in Case A the maintenance action cannot be performed. Besides, as observed from Table 3, more supportive energy is purchased, especially from time slots 11 to 13. Thus, the increase of the bid prices of the GENCOs of the host ISO can be leveraged to purchase more supportive energy so that more preferred maintenance actions can be obtained.

When comparing Case B with Case D, it can be observed that maintenance action bid by GENCO 2 of the host ISO can no longer be obtained in Case D, as in that case, the bid prices for supportive energy are larger than the penalty fees for reducing transmitted energy. Thus, the GENCOs of the host ISO pay more penalty fees for reducing the transmitted energy instead of purchasing supportive energy. The increase of the bid prices of the supportive energy may result in fewer preferred maintenance actions to be obtained.

According to the analysis, the first advantage of using IBMM is that the reliability of the power system can be ensured. The second advantage of IBMM is that the GENCOs of the host ISO can obtain their preferred time slots by purchasing the supportive energy from the GENCOs of the neighbor ISOs participating in the bidding process and paying the penalty fee for reducing the transmitted energy to the neighbor ISOs. Furthermore, both the bid prices of the GENCOs of the host ISO and the bid prices for the supportive energy can influence the bidding results.

5. Discussions

5.1. Bidding organization schemes for large grids

In the proposed bidding mechanism, the ISOs should periodically start bidding processes as the host ISO to determine the maintenance schedule of their GENCOs considering the participation of the GENCOs of their neighbor ISOs. For a grid with multiple ISOs, the organization of the bidding processes, e.g., when an ISO can be the host ISO, should be explained. Thus, this paper proposes that the bidding processes can be organized, e.g., in a centralized way or a distributed way. For the distributed ways, this paper discusses two possible organization schemes. The first one is to determine a priority of being the host ISO for ISOs in this large grid. In the second one, any ISO who intends to schedule the MGU actions, can be the host ISO at any time if it intends so. Thus, one centralized and two distributed schemes to organize the bidding processes for a grid with multiple ISOs will be considered and analyzed in this paper, called centralized bidding, priority bidding, and impromptu bidding respectively.

5.1.1. Centralized bidding

In a centralized bidding process, all the GENCOs of all the ISOs participate in one process. The centralized bidding processes will be started periodically, e.g., once every half year. Then the GENCOs of the ISOs who intend to determine their MGU actions will participate. In the centralized bidding, the decision making problem formulated is different from the problem (1)–(12) in Section 3.2, because the set of maintenance actions is the union of the sets of maintenance actions of all the GENCOs of all the ISOs participating in the centralized bidding process, and supportive energy suppliers are all the GENCOs of all the ISOs. In the centralized bidding process, all the GENCOs of all the ISOs in the grid can participate, while for priority bidding and impromptu bidding, only the neighbor ISOs can participate. Therefore, the centralized market environment is the most competitive among the three bidding organization schemes considered in this paper. However, there are two major drawbacks of centralized bidding.

Firstly, when delivering supportive energy among two non-neighbor ISOs, the energy must be delivered through other ISOs. The delivery of the supportive energy may face more strict tie line conditions for transmission. Thus, the capacities of all the tie lines on the path between the supporting ISO and the receiving ISO should be considered. As a result, the transmission process will face more constraints; hence, the centralized bidding will be less practical.

Secondly, if the number of GENCOs in the grid is large, there will be computational complexity issues. Indeed if all the GENCOs of all the ISOs join the centralized bidding process to purchase or sell energy, the large computational complexity for solving the bidding programming problem for a large number of ISO participants is a drawback of the centralized bidding.

5.1.2. Priority bidding

Another way to organize the bidding processes for a grid with multiple ISOs is the priority bidding. In each bidding process only one ISO can be the host ISO. The host ISO will gather the GENCOs of the neighbor ISOs with the host ISO and start the bidding process, and then it is the turn for another ISO to be the host ISO. In priority bidding, the host ISO solves (1)–(12) when it starts a bidding process. The priority of being the host ISO can be determined by negotiation among the ISOs, e.g., the ISOs agree to be the *host ISO* in turn. Being the host ISO in turn implies that, e.g., when there are two connected ISOs in one grid, and in the current period, ISO 1 is the host ISO firstly, and then, at the next period, ISO 2 will be the host ISO firstly. If there are no GENCOs of the neighbor ISO that participate in the bidding process, the host ISO will start the bidding process without participation of GENCOs of the neighbor ISOs. In this scenario, during the bidding process, no supportive energy will be purchased.

In priority bidding, the delivery between two non-neighbor ISOs is avoided. Furthermore, if only the GENCOs of the neighbors ISOs are considered, the number of GENCOs can be kept relatively low and thus the computational complexity for solving the bidding problems will be limited. The disadvantage of priority bidding is its reduced competitiveness compared with centralized bidding. The definition of fairness of the ranking method can also be challenging.

5.1.3. Impromptu bidding

Impromptu bidding is another way to organize the bidding process. Any ISO can be the host ISO at any time if it intends so, by gathering the GENCOs of its neighbor ISOs to participate in the bidding process. If there are multiple ISOs that intend to be the host ISO at the same time, the ISO who first claims its intention of being the host ISO will be the host ISO. Then after that ISO has finished its bidding process, other ISOs can announce their intention to be the host ISO and so on. If there is no GENCOs of the neighbor ISOs that participates in the bidding process, the host ISO will start the bidding process only with its GENCOs, and during the bidding process, no supportive energy will be purchased.

In impromptu bidding, the ISOs can get rid of both the drawbacks of the centralized bidding. Besides, the starting times of the bidding processes are more flexible than with priority bidding. In impromptu bidding, the host ISO solves (1)–(12) when it starts a bidding process.

In impromptu bidding, whether the GENCOs of the neighbor ISOs can join the bidding is determined by the network conditions of the neighbor ISOs. It is not required that all the neighbor ISOs of the host ISO should join the bidding and supply their energy; so they can choose to join or not.

5.2. Implementation of the proposed bidding strategy

Since different ISOs in different countries may have different power market mechanisms, the bidding mechanism proposed in this paper may not be applicable in some of the deregulated power systems, e.g., in situations where the ISOs do not interconnect to other ISOs.

For deregulated power systems interconnecting with other ISOs, the reserved energy of the neighbor ISOs decreases when the GENCOs of the neighbor ISOs support the energy to the host ISO. Consequently, the marginal price of the neighbor ISO may increase. Thus, it is crucial to analyze the influence on the marginal price and to set regulation mechanisms to the amount of supportive energy the GENCOs of the neighbor ISO can bid. This can be implemented, for instance, via a threshold that defines the maximum support energy that a GENCO can provide, as included in (12) with the parameter $q_G^{\max}(m, n, k)$.

Furthermore, the bidding problem formulated in this paper includes the case when the reduction of the energy transmitted from the host ISO to some neighbor ISOs is not allowed. In that case, the parameter $C_{\text{pen}}(m, k)$ can be set equal to a huge value. Additionally, the case when the bid prices of the supportive energy are too high is also considered in the proposed formulation. In that case, the bid prices of the GENCOs

of the host ISO are not sufficient for paying the prices of the supportive energy, so the GENCOs of the host ISO may not choose to change their scheduled time slots. The GENCOs of the host ISO should follow the ISO-wide optimal scheduling results.

5.3. Discussion of a larger scheduling period of maintenance

The case study of this paper sets the scheduling period (i.e., the period over which the maintenance actions are scheduled) as 13 weeks. If the scheduling period is set to a larger value, the number of the time slots to be considered will increase. The IBMM proposed in this paper can handle the longer period of maintenance by increasing the cardinality of set $\mathcal{K}$ in the formulated bidding problem Section 3.2.

However, a too-long scheduling period will increase the uncertainty in the predictions of failure rates, which means that in practice, the risk of sudden failure occurring during the scheduling period may increase. Thus, in practice, the scheduling period should not be set too long.

Furthermore, a longer scheduling period implies that the GENCOs of the host ISO and the GENCOs of the neighbor ISOs should predict their bids for a longer period. However, the profits for a long period are more difficult to predict. Thus, the participants of the bidding may not welcome a longer scheduling period.

6. Conclusions

This paper has proposed a novel bidding mechanism for maintenance of generation units in transmission power systems. In this mechanism, the GENCOs of the host ISO can bid to change their scheduled maintenance actions and to achieve their own benefits. The GENCOs can use their bid price to purchase supportive energy from the GENCOs of the neighbor ISOs, to pay the penalty fee caused by reducing the energy transmitted from the host ISO to the neighbor ISOs w.r.t. the long-term power exchange transactions, or both. Besides, three possible schemes, including centralized bidding, priority bidding, and the impromptu bidding, to organize the bidding processes in a grid associated with multiple ISOs have been discussed. As indicated by the simulations for a case study, this interchangeable bidding mechanism for maintenance implies that more GENCOs can obtain their preferred time slots, and the reliability of the power system can be ensured. The results imply that the inter-ISO power exchange will give more flexibility to the GENCOs for maintaining their generation units and ensure the reliability of the power systems.

As for future work, the proposed bidding strategy will be tested on larger-scale and real-life cases. Furthermore, to avoid the scenario that the GENCOs of the neighbor ISOs raise their bid prices for supportive energy to any high level, a truthful bidding mechanism (Vickrey–Clarke–Groves mechanism), can be developed. In addition, distribution companies will be considered in our proposed bidding strategy. Moreover, methods to quantify the positive impacts of the bidding mechanism on, e.g., the reserved energy levels of the power systems and health conditions of the generation units, will be developed.

CRedit authorship contribution statement

Jianfeng Fu: Conceptualization, Methodology, Software. **Alfredo Núñez:** Supervision. **Bart De Schutter:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jianfeng Fu reports financial support was provided by China Scholarship Council.

Data availability

No data was used for the research described in the article.

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