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A Bi-Level Model for the Bidding Strategy of an Inter-Regional Electricity Trading Aggregator Considering Reliability Requirements and Transmission Losses

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ABSTRACT In countries with large-scale power systems and nascent electricity markets, the inter-regional electricity trading aggregators (IRETAs) are in charge of participating in inter-regional electricity trading (IRET) on behalf of the generators and loads within the region except for operating the regional power systems (RPSs). As price makers in IRET and system operators of RPSs, IRETAs should make their bidding strategies considering both the RPSs' reliability requirements and the IRET's transmission losses to ensure both the safe operation of RPS and the profits in the IRET, which cannot be handled by the current methods. Therefore, this paper investigates an approach to help IRETAs make comprehensive bidding strategies in the IRET. Firstly, a hierarchical framework for an IRETA to participate in IRET is introduced. Then a bi-level model is proposed, in which the optimal operation of RPS and the market-clearing process of IRET are regarded as the upper and lower-level problems. Specifically, the upper-level problem is modeled as a two-stage stochastic optimization problem considering both the fault states and the reliability requirements of RPS. Moreover, the non-negligible losses from the inter-regional electricity transmission are internalized in the lower-level problem to consider their impacts on the IRETA's bidding strategy-making. The proposed bi-level model is nonlinear and transformed into a linear single-level one through the Karush-Kuhn-Tucker (KKT) conditions and the dual theory. Finally, simulations demonstrate that the bidding strategy formed by the proposed method reduces the number of buses exceeding the limit of reliability requirement by over 50% and cuts down the transmission loss by over 40% compared with the former works.

INDEX TERMS Inter-regional electricity trading aggregator, reliability modeling, bidding strategies, bi-level programming, inter-regional transmission.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Facing the unbalanced spatial distribution between electricity resources and demands, many countries (or regions) are opening their borders to a greater degree of competition in the market-orientied electricity transaction, resulting in a trend toward inter-regional electricity trading (IRET) [1], [2]. Compared to conventional electricity trading held within a specific region, IRET can better allocate the electricity resources and improve the operation efficiency of the whole industry in a larger scope. Several attempts on IRET have already been launched in Europe, where a competitive Internal Electricity Market (IEM) has been built to achieve a single inter-regional European electricity market [3]. In North America, the electricity interchanges between PJM and MISO are held through the Coordinated Transaction Scheduling (CTS) project [4]. Moreover, based on large-scale interconnected power systems, IRET shows a greater significance in China [5]. In 2019, the electricity traded through the IRET in China has reached 1061.9 billion kWh, accounting for nearly half of the total electricity trading volume across the country [6].

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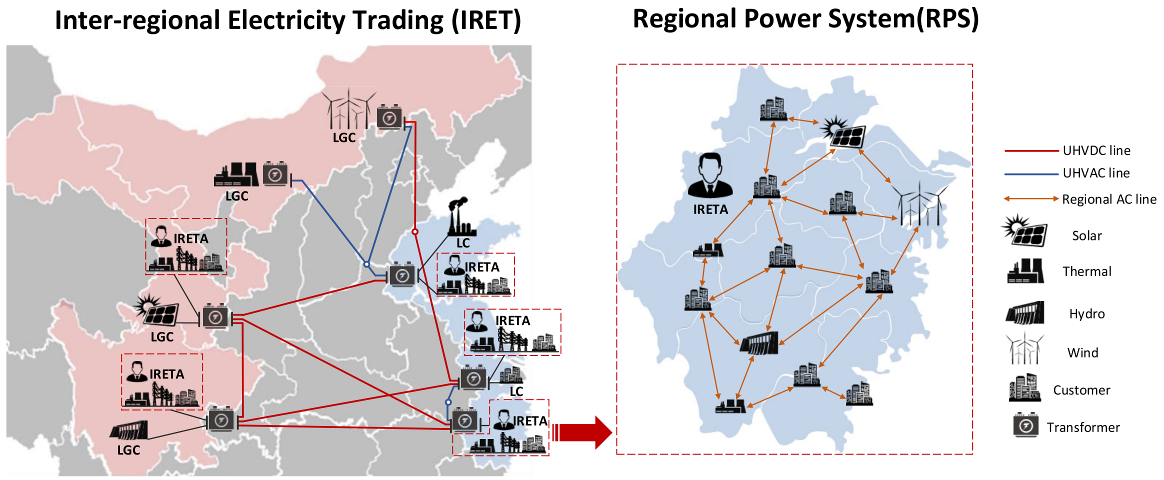

FIGURE 1. A Schematic Diagram of the relationship between IRET and RPS operated by the IRETA in China [9].

Ideally, each generator and load should be allowed to directly participate in IRET to ensure fairness. For example, the IEM allows the generators and loads to bid directly from each bidding zone. The market operator then determines the IRET results through a single centralized algorithm [3]. The generators and loads are allowed to give CTS bids for IRET between PJM and MISO. The trading results are given by the clearing of the corresponding regional electricity market [4].

However, for countries with large-scale power systems and nascent electricity markets, the clearing of IRET can be more complicated. Take China as an example, with the largest electricity generation and consumption around the world, the power system in China is divided into several regional (provincial) power systems (RPS) linked by multiple High Voltage Direct Current (HVDC) and Alternating Current (HVAC) lines. These HVAC/DC lines are independently operated by a National System Operator (NSO) rather than coordinately operated with RPSs [7]. Therefore, generators and loads within the regions cannot be directly dispatched by the NSO and thus are hard to participate in the IRET held through the HVAC/DC lines. On the other hand, the new round electricity market reform in China is just at the stage of start and the generation dispatch schedule in many regions is still planned by system operators rather than determined through market competition [6]. As a result, these generators are still incapable of making self-dispatch plans based on the market results. Under the above status, the current IRET in China is designed to be held among several eligible large generation companies (LGC), eligible large consumers (LC) and inter-regional electricity trading aggregators (IRETAs) [8], [9]. As shown in Fig.1, the eligible LGC and LC refer to the large generators and consumers that can be directly dispatched by the NSO and connect with the HVAC/DC lines [10]. Meanwhile, the IRETAs refer to the provincial power grid companies that act as system operators for RPSs and participate in IRET on behalf of the generators and loads within RPSs [11].

Considering that, the IRETA is not only in charge of the RPS operation, but also responsible to make effective bidding strategy in IRET as a market entity. Therefore, two main factors can influence the strategy made by the IRETA. The first factor is the operation reliability requirement of RPS. In order to ensure the transacted electricity can be successfully implemented, the clearing results of IRET have to be delivered physically, which will occupy a certain amount of generation resources in RPS [12]. When a certain fault among generators or converters within the RPS occurs, the IRETA may be short of abundant reserves to ensure the security of RPS. Under these circumstances, an increase in load shedding may be caused and the reliability of RPS can be reduced. The second factor is the market characteristic of IRET. Unlike the regional electricity market held based on AC lines spanning relatively shorter distance, the IRET is conducted though the long-distance HVAC/DC lines [13]. The non-negligible losses from long-distance HVAC/DC lines will significantly decrease the IRETA's economic benefits in IRET. Therefore, how to facilitate the IRETA makes an effective decision for its bidding strategy to ensure the operation security of the RPS and avoid necessary transmission losses in IRET becomes an imperative task to be solved.

B. LITERATURE REVIEW

The bidding strategy modeling for a market entity in a wholesale electricity market has been fully investigated in the previous literature. Generally, this type of problem can be cast as the Stackelberg game where the market entity and wholesale electricity market operator play as the role of leader and follower, respectively. Under this framework, bi-level programming is often used to formulate the optimal bidding strategy problem [14]–[18]. In [14], the optimal behaviors of retailers in wholesale and retail markets considering demand response are formulated by a two-stage bi-level model. Based on the bidding strategy of a wind power producer, the strategy behaviors of DR aggregators are modeled by a bi-level optimization approach in [15]. In [16], a bi-level approach for the optimal bidding strategies by electricity producers in day-ahead energy auctions with step-wise energy bid format is proposed. In [17], a bi-level optimal portfolio model is established for generation companies in the inter-regional electricity transaction considering the generation right trades. In [18], the strategic behavior of a distribution company (Disco) in energy and reserve markets is studied.

The above former works related to strategy modeling all have weak points in two aspects. On the one hand, the market entities in the former works mainly refer to producers, retailers or Discos. The power systems operated by these market entities are quite simple and thus their reliability requirements are ignored in the strategy modeling of former works. However, the RPS operated by the IRETA is quite complex and includes a large number of generators and loads. The reliability requirements of RPS are essential for the secure operation of the whole system and should be taken into account. On the other hand, the former works do not consider the transmission losses in their models. However, since the non-negligible transmission losses in IRET may have a significant effect on the economic benefits of the IRETA as aforementioned, they should also be included in the decision-making process. As a result, the above weakness of former works makes them incapable of enabling the IRETA to make effective bidding strategy in the IRET considering both the reliability requirements of RPS and transmission losses, which still leaves to be a knowledge gap for now.

C. CONTRIBUTIONS

In the light of the weak points of former works mentioned in the last subsection, this paper aims to bring a novel model to formulate the optimal bidding strategy of an IRETA in IRET with the reliability requirements of RPS and the inter-regional electricity transmission losses. The proposed model can better help the IRETA find an effective bidding strategy in the IRET compared to the state-of-art-model. Specifically, the main highlights of the proposed method are:

1) A hierarchical framework for an IRETA to participate in IRET is introduced, in which the IRETA submits its bids to the IRET based on the parameters of generators and loads as well as the network constants of RPS, then formulates the dispatch results according to the market-clearing results of IRET. The proposed framework enables the IRETA to make effective bidding decisions while ensuring the trading results to be physically implemented.

2) Under the hierarchical framework, a bi-level model is proposed to produce the optimal bidding strategy for the IRETA in the IRET. The proposed bi-level model considers the operation of RPS and the market-clearing process of IRET as the upper and lower-level problems. The proposed nonlinear bi-level problem is transformed into a linear single-level one through the KKT conditions and the dual theory.

3) In the bi-level model, reliability requirements of RPS are considered in the upper-level problem, in which the generator and converter fault states within RPS are modeled and the penalty costs for reliability indices out of range are regarded as part of the objective function. Besides, losses from HVAC/DC transmission are internalized in the lower-level problem by loss factors while maintaining the linear formulation of the problem.

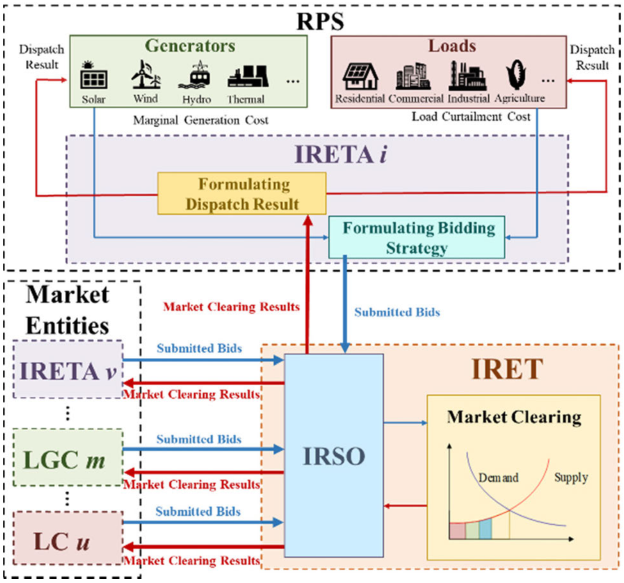

FIGURE 2. The hierarchical framework for an IRETA in the IRET.

D. ORGANIZATION OF THE PAPER

To better illustrate the proposed method, this paper is organized as follows: The hierarchical framework for an IRETA to participate in IRET is introduced in Section II. Section III deals with the formulation of the bi-level model. Section IV introduces the solving methodology of the proposed model. Section V reports numerical results. Finally, conclusions are given in Section VI.

II. DESCRIPTION OF THE FRAMEWORK

To facilitate the IRETA's bidding strategy in IRET on behalf of the generators (e.g. Solar, Thermal et.al) and loads (e.g.Residential, Comercial) within the region, a hierarchical framework is introduced in this section as shown in Fig.2.

Specifically, taking IRETA *i* as an example, it collects parameters such as ramping capabilities, output limits, marginal generation costs and load shedding costs from the generators and loads within RPS. Then based on the above parameters and the network constraints of RPS, IRETA *i* formulates its bids and submit it to the inter-regional system operator (IRSO), which is considered to be in charge of the IRET operation [12]. After that, the IRSO clears IRET based on the submitted bids from all market entities and transmits the market-clearing results to IRETA *i*. Finally, IRETA *i* acts as the system operator of corresponding RPS and produces the dispatch results for each generator and load within the RPS considering the market-clearing results of IRET.

In the above framework, IRETA *i* is a price-maker who has the autonomy to make its bidding decision. Besides,

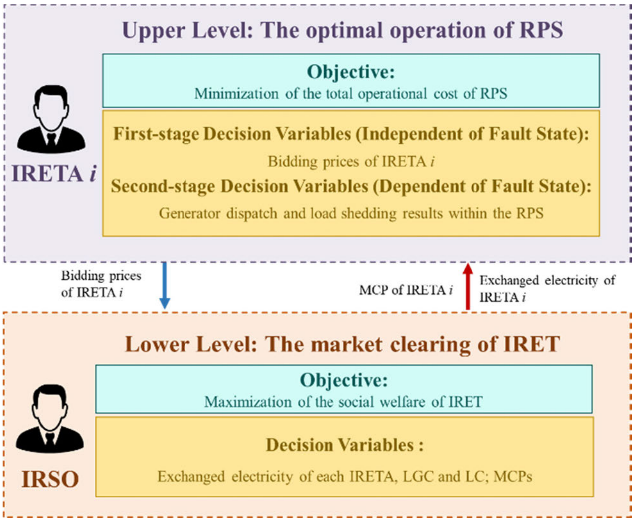

FIGURE 3. The bi-level model for IRETAs' bidding strategy-making.

the dispatch results of IRETA i are subject to the market profile reflected by the IRET's clearing result. To model this behavior, a bi-level optimization approach is adopted as shown in Fig.3.

The proposed bi-level model takes the operation problem of RPS as the upper-level problem while modeling the market clearing process of the IRET as the lower-level problem. The interaction decision variables between the upper and lower-level problems are the biding price of IRETA i in the IRET as well as the market-clearing results of IRET including the market-clearing prices (MCPs) and the exchanged electricity. Meanwhile, the RPS operation problem in the upper-level considers the fault states of generator and converters within the RPS as well as the corresponding probabilities and is modeled as a two-stage stochastic optimization problem. Specifically, the bidding price of IRETA i in the IRET is considered as the first-stage variable and is independent of the fault states. The generators dispatch and load shedding results within the RPS depend on the realization of each fault state and are considered as the second-stage variables.

III. MATHEMATICAL FORMULATION OF THE BI-LEVEL MODEL

In this section, the bidding strategy of an IRETA in the IRET is mathematically formulated as a bi-level optimization problem. For this purpose, some assumptions are considered in this paper as follows:

1) The RPS operated by the studied IRETA is assumed to connect with the inter-regional HVAC/DC power system through several points of common coupling (PCC) buses. Besides, the whole RPS is considered as an equivalent bus in the market-clearing model of IRET, in which the network constraints of RPS are neglected.

2) Each LGC and LC is assumed to directly connect with the inter-regional HVAC/DC power system and considered as an equivalent generator or load in the market-clearing model of IRET.

3) The uncertainties associated with the bidding strategies of other market entities are not considered in this paper. They are assumed to be deterministic and can be obtained through the prediction of the studied IRETA.

A. FAILURE STATE MODELING OF RPS

In this paper, the generator within RPS is considered as a two-state component (available state $s_{a,g}$ with 100% capacity and unavailable state $s_{u,g}$ with 0% capacity). Therefore, the corresponding state probabilities $p_{sa,g}$ and $p_{su,g}$ of generator g can be expressed as:

$$p_{sa,g} = R_g(t) \tag{1}$$

$$p_{su,g} = 1 - R_g(t) \tag{2}$$

where $R_g(t)$ is the reliability function of generator g. In this paper, it's assumed that the generators' life spans are all exponentially distributed and their failure rates are constant. Therefore, $R_g(t)$ can be defined in the form as:

$$R_g(t) = e^{-\lambda_g t} \tag{3}$$

where λ_g is the constant failure rate of generator g.

Meanwhile, converters are considered to link the PCC buses and inter-regional HVDC lines. Each converter can be regard as a three-state component (available state $s_{a,c}$ with 100% capacity, derated state $s_{d,c}$ with 50% capacity and unavailable state $s_{u,c}$ with 0% capacity). The corresponding state probabilities $p_{sa,c}$, $p_{sd,c}$ and $p_{su,c}$ of converter c can be calculated based on the method introduced in [19].

Considering all the potential failures among generators and converters, the RPS can be represented by an equivalent multi-state system with a fault state set $\mathbf{S}$ and state probability set $\mathbf{P}$. Given that the RPS has N_G generators and N_C converters, the probability p_s of state s can be calculated by:

$$p_s = \prod_{g=1}^{O_G} p_{su,g} \prod_{g=O_G+1}^{N_G} p_{sa,g} \prod_{c=1}^{O_{C1}} p_{su,c} \prod_{c=O_{C1}+1}^{O_{C1}+O_{C2}} p_{sd,c} \times \prod_{c=O_{C1}+O_{C2}+1}^{N_C} p_{sa,c} \tag{4}$$

where O_G is the number of failed generators during state s. O_{C1} and O_{C2} are the number of failed and derated converters,.

Combining the state probabilities and corresponding load shedding results under all failure states, the typical reliability indices such as Expect Energy Not Supply (EENS) can be calculated by the method in [20], [21]. Generally, the reliability requirement is often reflected by setting constraints for typical reliability indices during the system operation model [22]. Therefore, in this paper, to integrate the reliability constraints of RPS in the IRETA's strategy model, the expected load curtailment exceeding the EENS requirement are regarded as a penalty term in the objective function of the upper-level RPS's problem and will be detailed formulated in the next subsection.

B. THE RPS PROBLEM FORMULATION: UPPER-LEVEL MODELING

Still take IRETA i as an example, the objective function of the upper-level model is to minimize total operation costs the RPS managed by IRETA i considering all the potential fault states$s$, shown as:

$$\begin{cases} Min\ TOC = \sum_{t=1}^{T}(EDC_t + \eta PC_t) \\ EDC_t = \sum_{s=1}^{\mathbf{S}} p_s(\sum_{k=1}^{\mathbf{K}} c_k P_{k,t,s} + \sum_{l=1}^{\mathbf{L}} c_l \Delta P_{l,t,s} + \rho_{i,t} P_{i,t}^{exc}) \\ PC_t = \sum_{s=1}^{\mathbf{S}} p_s \sum_{l=1}^{\mathbf{L}} \Delta P_{l,t,s} - EENS^T/8760 \end{cases} \tag{5}$$

where TOC is the total operation cost of RPS, which includes the expected dispatch cost EDC_t and the penalty cost PC_t for the EENS out of range at interval t. p_s is the probability of fault state s, which is constant at a specific interval t based on Eq.(1)-(4). $\Delta P_{l,t,s}$ is the load shedding of load l under fault state s during interval t and η is the penalty coefficient. $EENS^T$ is the threshold EENS required by the RPS operation. As a result, the formuation of PC_t is linear. $P_{k,t,s}$ is the dispatched results of generator k under fault state s during interval t. c_k is the marginal dispatch cost of generator k. c_l is the load shedding cost of load l. $P_{i,t}^{exc}$ is the total exchange electricity of IRETA i in the IRET during interval t, where the positive value refers to the cleared electricity purchased from the IRET and the negative value refers to the cleared electricity sold to the IRET. $\rho_{i,t}$ is the MCP of IRETA i in IRET during interval t. **K** and **L** is the set of generators and loads within the RPS, respectively.

The above objective function is restricted by the following constraints shown as:

$$\sum_{k=1}^{\mathbf{K}} P_{k,t,s} + P_{i,t}^{exc} - \sum_{l=1}^{\mathbf{L}} (P_{l,t} - \Delta P_{l,t,s}) = 0 \tag{6}$$

$$P_{i,t}^{exc} = \sum_{z=1}^{\mathbf{Z}} P_{z,t}^{exc} \tag{7}$$

$$\sum_{k=1}^{\mathbf{K}} f_{b-k} P_{k,t,s} + \sum_{z=1}^{\mathbf{Z}} \gamma_{z,s} f_{b-z} P_{z,t,s}^{exc} - \sum_{l=1}^{\mathbf{L}} f_{b-l}(P_{l,t} - \Delta P_{l,t,s}) = F_{b,t,s} \tag{8}$$

$$-ATC_{b,s} \le F_{b,t,s} \le ATC_{b,s} \tag{9}$$

$$\underline{P_{k,s}} \le P_{k,t,s} \le \overline{P_{k,s}} \tag{10}$$

$$P_{k,t,s} - P_{k,t-1,s} \le RU_k \tag{11}$$

$$P_{k,t-1,s} - P_{k,t,s} \le RD_k \tag{12}$$

$$P_{l,t} - \Delta P_{l,t,s} \ge 0 \tag{13}$$

$$\underline{a_{i,t}} \le a_{i,t} \le \overline{a_{i,t}} \tag{14}$$

where constraints (6) refers to the power balance constraints of RPS under fault state s. $P_{l,t}$ is the demand of load l during interval t. Constraints (7) refers to the equation between the total exchanged electricity $P_{i,t}^{exc}$ and the exchanged electricity $P_{z,t}^{exc}$ in PCC bus z. **Z**is the set of the PCC buses in RPS. Constraints (8) refers to the power flow equations of line b under fault state s during interval t. Here, the Power Transfer Distribution Factor (PTDF) method is used to formulate the constraints [23]. f_{b-k},f_{b-l} and f_{b-z} are the PTDFs between line b and generator k, load l and PCC bus z, respectively. $\gamma_{z,s}$ is the capacity ratio of the converter at PCC bus z under fault state s. $\gamma_{z,s} = 0$, 0.5 and 1 correspond to unavailable, derated and available states of the converter, respectively. $F_{b,t,s}$ is the power flows of line b under fault state s. Constraints (9) refers to the power flow limit of line b under fault state s. $ATC_{b,s}$ is the available transmission capacity (ATC) of line b under fault state s. Constraints (10) and (11) refer to the ramping limits of generators. RU_k and RD_k are the ramp up and ramp down rate of generator k. Constraints (12) and (13) refer to the output limits of generators and shedding limit of load. $\overline{P_{k,s}}$ and $\underline{P_{k,s}}$ are the upper and lower bounds of generator output under fault state s. Constraints (14) refers to the limit of bidding prices of IRETA i in IRET and $a_{i,t}$ is the bidding price of the IRETA i during interval t.

The above upper-level model receives the MCP $\rho_{i,t}$ and the exchanged electricity $P_{z,t}^{exc}$ generated from the lower-level model and gives the bidding prices $a_{i,t}$ to the lower-level model during each iteration.

C. THE IRET PROBLEM FORMULATION: LOWER-LEVEL MODELING

The objective function of the lower-level model is to minimize the minus (maximize) IRET social welfare, which refers to the most efficient allocation of power resources and shown as:

$$Min - BF = \sum_{t=1}^{T}(\sum_{m=1}^{\mathbf{M}} a_{m,t} P_{m,t}^{sell} - \sum_{r=1}^{\mathbf{R}} a_{r,t} P_{r,t}^{pur} - a_{i,t} P_{i,t}^{exc} - \sum_{v=1}^{\mathbf{V}} a_{v,t} P_{v,t}^{exc}) \tag{15}$$

where BF is the social welfare of IRET. $a_{i,t}$ is treated as an input parameter obtained from the upper-level problem. $a_{m,t}$, $a_{r,t}$ and $a_{v,t}$ are the bidding prices of LGC m, LC r and IRETA v, respectively, which are assumed to be deterministic and regarded as constants in the model. $P_{m,t}^{sell}$ is the electricity sold by LGC m in IRET during interval t. $P_{r,t}^{pur}$ is the electricity purchased by LC r in the IRET during interval t and $P_{v,t}^{exc}$ is the exchange electricity of IRETA v in IRET during interval t. **M**, **R** and **V** are the set of LGC, LC and other IRETAs.

The above objective function is restricted by the following constraints shown as:

$$-P_{i,t}^{exc} + P_{i,t}^{loss} + \sum_{m=1}^{\mathbf{M}} (P_{m,t}^{sell} + P_{m,t}^{loss}) + \sum_{r=1}^{\mathbf{R}} (-P_{r,t}^{pur} + P_{r,t}^{loss}) + \sum_{v=1}^{\mathbf{V}} (-P_{v,t}^{exc} + P_{v,t}^{loss}) = 0, \quad \lambda_t \tag{16}$$

$$\begin{aligned}&f_{x-i}(-P_{i,t}^{exc}+\sum_{y=1}^{\mathbf{Y}}\eta_{y-i}F_{y,t}+P_{i,t}^{loss})+\sum_{m=1}^{\mathbf{M}}f_{x-m}(P_{m,t}^{sell}\\&\quad+\sum_{y=1}^{\mathbf{Y}}\eta_{y-m}F_{y,t}+P_{m,t}^{loss})+\sum_{u=1}^{\mathbf{R}}f_{x-r}(-P_{r,t}^{pur}\\&\quad+\sum_{y=1}^{\mathbf{Y}}\eta_{y-r}F_{y,t}+P_{r,t}^{loss})+\sum_{v=1}^{\mathbf{V}}f_{x-v}(-P_{v,t}^{exc}\\&\quad+\sum_{y=1}^{\mathbf{Y}}\eta_{y-v}F_{y,t}+P_{v,t}^{loss})=F_{x,t}\end{aligned}\tag{17}$$

$$-ATC_y\le F_{y,t}\le ATC_y,\quad \overline{\mu_{y,t}},\ \underline{\mu_{y,t}}\tag{18}$$

$$-ATC_x\le F_{x,t}\le ATC_x,\quad \overline{\mu_{x,t}},\ \underline{\mu_{x,t}}\tag{19}$$

$$-\overline{P_i^{sell}}\le P_{i,t}^{exc}\le\overline{P_i^{pur}},\quad \overline{\mu_{i,t}},\ \underline{\mu_{i,t}}\tag{20}$$

$$-\overline{P_v^{sell}}\le P_{v,t}^{exc}\le\overline{P_v^{pur}},\quad \overline{\mu_{v,t}},\ \underline{\mu_{v,t}}\tag{21}$$

$$0\le P_{m,t}^{sell}\le\overline{P_m^{sell}},\quad \overline{\mu_{m,t}},\ \underline{\mu_{m,t}}\tag{22}$$

$$0\le P_{r,t}^{pur}\le\overline{P_r^{pur}},\quad \overline{\mu_{r,t}},\ \underline{\mu_{r,t}}\tag{23}$$

where constraint (16) refers to the power balance constraint of the inter-regional power system.$P_{i,t}^{loss}$, $P_{m,t}^{loss}$, $P_{r,t}^{loss}$ and $P_{v,t}^{loss}$ are the transmission losses of IRETA i, LGC m, LC r and IRETA v, respectively. They can be determiend based on their relationship with power flows decribed in the next section. Constraint (17) refers to the power flow equation of AC line x. $F_{x,t}$ and $F_{y,t}$ are the power flows of the inter-regional HVAC line x and HVDC line y, respectively. $f_{x-i}, f_{x-m}, f_{x-v}$ and f_{x-u} are the PTDFs between each market participant and inter-regional HVAC line x. η_{y-i}, η_{y-m}, η_{y-u} and η_{y-v} are the incidence coefficients between market entities and inter-regional HVDC line y, defined as :

$$\eta_{y-n}=\begin{cases}1 & \text{entity } n \text{ is the sending-end of HVDC line } y\\ -1 & \text{entity } n \text{ is the receiving-end of HVDC line } y\\ 0 & \text{otherwise}\end{cases}\tag{24}$$

Constraint (18) and (19) refer to the power flow limits of the inter-regional lines. ATC_x and ATC_y are the ATC of the HVDC line y and HVAC line x, respectively. Constraint (20) and (21) refer to the limits of the exchanged electricity of IRETA i and IRETA v in the IRET, respectively. $\overline{P_i^{pur}}$ and $\overline{P_v^{pur}}$ are the upper bound of the electricity purchased by IRETA i and IRETA v in the IRET. $\overline{P_i^{sell}}$ and $\overline{P_v^{sell}}$ are the upper bound of the electricity sold by IRETA i and IRETA v in the IRET. Constraint (22) refers to the limit of the electricity sold by LGC m in the IRET. Constraint (23) refers to the limit of the electricity purchased by LC r in the IRET. λ_t, $\overline{\mu_{y,t}}$, $\underline{\mu_{y,t}}\overline{\mu_{x,t}}$, $\underline{\mu_{x,t}}$, $\overline{\mu_{i,t}}\underline{\mu_{i,t}}$,.$\overline{\mu_{m,t}}$, $\underline{\mu_{m,t}}\overline{\mu_{r,t}}$, $\underline{\mu_{r,t}}$, $\overline{\mu_{v,t}}$ and $\underline{\mu_{v,t}}$ are dual variables associated with the corresponding constraints. Based on the above model, the MCP of IRETA i in IRET $\rho_{i,t}$ is computed as follows:

$$\rho_{i,t}=\lambda_t-f_{x-i}(\underline{\mu_{x,t}}-\overline{\mu_{x,t}})\tag{25}$$

D. INCLUSION OF TRANSMISSION LOSSES IN THE IRET'S PROBLEM

Traditionally, the transmission losses are ex-ante determined using offline models and regarded as invariable parameters in the market-clearing problem [as shown in Eq. (15)-(23)]. However, for IRET, the electricity transmission distance can reach hundreds or even thousands of kilometers long and the transmission losses should be simultaneously optimized in the market-clearing process.

The transmission losses in IRET can be divided into two parts: HVAC losses and HVDC losses. HVAC losses include losses from cables and transformers, which can be expressed by [24]:

$$P_{x,t}^{loss}=R_x^{eq}\left|F_{x,t}\right|^2\tag{26}$$

where R_x^{eq} is the equivalent resistance of cables and transformers in inter-regional HVAC line x. Meanwhile, HVDC losses include losses from cables and converters, which can be expressed by [24]:

$$P_{y,t}^{loss}=(R_y+A_y)\left|F_{y,t}\right|^2+B_y\left|F_{y,t}\right|+C_y\tag{27}$$

where R_y is the resistance of cables in HVDC line y. A_y, B_y and C_y are the quadratic, linear as well as constant loss coefficients of the converter stations linked with HVDC line y, respectively.

To avoid excessive complexity and ensure the market-clearing results can be given online, the transmission loss constraints need to be convex [25]. Here, the piecewise linear function with K segments is adopted to approximate the nonlinear transmission loss, the loss of line $lP_{l,t}^{loss}$ becomes:

$$P_{l,t}^{loss}=\begin{cases}\alpha_{1,l}\left|F_{l,t}\right|+\beta_{1,l},0\le\left|F_{l,t}\right|\le F_{l,t}^1\\ \cdots\\ \alpha_{K,l}\left|F_{l,t}\right|+\beta_{K,l},F_{l,t}^{K-1}\le\left|F_{l,t}\right|\le F_{l,t}^K\end{cases}\tag{28}$$

where $\alpha_{1,l}$, $\alpha_{K,l}$ and $\beta_{1,l}$, $\beta_{K,l}$ are parameters of linear loss function that can be estimated by approaches such as the least squares approach and Taylor expansion, etc. $F_{l,t}^1$, $F_{l,t}^{K-1}$ and $F_{l,t}^K$ are the critical values of power flow in the linear loss function.

Although the above approach can linearize transmission loss functions, the existence of the absolute value operator makes the whole problem still non-linear. To lineralize the the absolute value operator, the loss fuction in segment z can be recast as:

$$\begin{cases}P_{l,t}^{loss}\ge\alpha_{z,l}F_{l,t}+\beta_{z,l}, & \forall z\in[1,\ldots K],\mu_{z,l}^{1,+}\\ P_{l,t}^{loss}\ge-\alpha_{z,l}F_{l,t}+\beta_{z,l}, & \forall z\in[1,\ldots K],\mu_{z,l}^{1,-}\end{cases}\tag{29}$$

where $\mu_{z,l}^{1,+}$, $\mu_{z,l}^{1,-}$ are dual variables associated with the corresponding constraints. Based on Eq. (28)-(29), the transmission loss $P_{x,t}^{loss}$ and $P_{y,t}^{loss}$ can be linearlized. Then the transmission losses of market entity n can be written as:

$$P_{n,t}^{loss}=\sigma_{x-n}P_{x,t}^{loss}+\sigma_{y-n}P_{y,t}^{loss}\tag{30}$$

where σ_{x-n} and σ_{y-n} are the loss distribution factors defined as follows:

$$\sigma_{l-n} = \begin{cases} 0.5, & \text{if line } l \text{ is connected to entity } n \\ 0, & \text{otherwise} \end{cases} \tag{31}$$

Through considering transmission losses, the MCP of IRETA i in the IRET $\rho_{i,t}$ is reformulated as:

$$\rho_{i,t} = \lambda_t - \sum_{x=1}^{X} f_{x-i}\left[\underline{\mu_{x,t}} - \overline{\mu_{x,t}} - \sum_{z=1}^{K} \alpha_{z,x}(\mu_{z,x}^{1,+} - \mu_{z,x}^{1,-})\right] \tag{32}$$

IV. SOLVING METHODOLOGY

By combining Eq. (28)-(30) with Eq. (15)-(23), the transmission losses can be calculated based on the power flow generated in the IRET's problem while maintaining convex. Then the bi-level model for IRETAs' bidding strategy-making is formulated with upper-level model containing Eq.(5)-Eq.(14) and lower-level model containing Eq.(15)-(23) and Eq. (28)-(30). In practice, the bi-level optimization problem is usually solved after converting them into single-level Mathematical Programs with Equilibrium Constraints (MPEC), through replacing the lower-level problem with its equivalent KKT optimality conditions [26]. In this paper, since the lower-level IRET's problem is convex, the KKT optimality conditions are also applicable. Therefore, KKT optimality conditions can be adopted to replace the IRET's problems to reform the proposed bi-level model into a single level MPEC.

A. FORMULATION OF THE SINGLE-LEVEL MPEC

If we set $K = 1$, then the lagrange function L of the lower-level IRET's problems can be calculated as:

$$L = \left[\begin{array}{l} \sum_{t=1}^{T}(\sum_{m=1}^{\mathbf{M}} a_{m,t}P_{m,t}^{sell} - \sum_{r=1}^{\mathbf{R}} a_{r,t}P_{r,t}^{pur} - a_{i,t}P_{i,t}^{exc} \\ - \sum_{v=1}^{\mathbf{V}} a_{v,t}P_{v,t}^{exc}) + \lambda_t \cdot [-P_{i,t}^{exc} + P_{i,t}^{loss} \\ + \sum_{m=1}^{\mathbf{M}}(P_{m,t}^{sell} + P_{m,t}^{loss}) + \sum_{r=1}^{\mathbf{R}}(-P_{r,t}^{pur} + P_{r,t}^{loss}) \\ + \sum_{v=1}^{\mathbf{V}}(-P_{v,t}^{exc} + P_{v,t}^{loss})] + \underline{\mu_{y,t}} \cdot (F_{y,t} - \underline{ATC_y}) \\ + \overline{\mu_{y,t}} \cdot (\overline{ATC_y} - F_{y,t}) + \underline{\mu_{x,t}} \cdot (F_x - \underline{ATC_x}) \\ + \overline{\mu_{x,t}} \cdot (\overline{ATC_x} - F_x)) + \mu_y^{1,+} \cdot (P_{loss,y,t} + \alpha_y F_{y,t} - \beta_y) \\ + \mu_y^{1,-} \cdot (P_{loss,y,t} - \alpha_y F_{y,t} - \beta_y) + \mu_x^{1,+} \\ \cdot (P_{loss,x,t} + \alpha_x F_x - \beta_x) + \mu_x^{1,-} \\ \cdot (P_{loss,x,t} - \alpha_x F_x - \beta_x) + \underline{\mu_{i,t}}.(-\overline{P_{i,t}^{sell}} - P_{i,t}^{exc}) \\ + \overline{\mu_{i,t}} \cdot (P_{i,t}^{exc} - \overline{P_{i,t}^{pur}}) + \underline{\mu_{v,t}} \cdot (-\overline{P_{v,t}^{sell}} - P_{v,t}^{exc}) \\ + \overline{\mu_{v,t}} \cdot (P_{v,t}^{exc} - \overline{P_{v,t}^{pur}}) \underline{-\mu_{m,t}} \cdot P_{i,t}^{exc} \\ + \overline{\mu_{m,t}} \cdot (P_{m,t}^{sell} - \overline{P_{m,t}^{sell}}) - \underline{\mu_{r,t}} \cdot P_{r,t}^{pur} + \overline{\mu_{r,t}} \\ \cdot (P_{r,t}^{exc} - \overline{P_{r,t}^{pur}}) \end{array}\right] \tag{33}$$

Then the KKT optimality conditions for the lower-level IRET's problems are constructed as follows:

$$\begin{aligned} \frac{dL}{dP_{i,t}^{exc}} &= -a_{i,t} - \lambda_t + \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} - \overline{\mu_{x,t}})f_{x-i} \\ &- (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x f_{x-i}] - (\underline{\mu_{i,t}} - \overline{\mu_{i,t}}) = 0 \end{aligned} \tag{34}$$

$$\begin{aligned} &\frac{dL}{dP_{r,t}^{pur}} - a_{u,t} - \lambda_t + \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} - \overline{\mu_{x,t}})f_{x-r} \\ &- (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x f_{x-r}] - (\underline{\mu_{r,t}} - \overline{\mu_{r,t}}) = 0 \end{aligned} \tag{35}$$

$$\begin{aligned} \frac{dL}{dP_{v,t}^{exc}} &= -a_{v,t} - \lambda_t + \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} - \overline{\mu_{x,t}})f_{x-v} \\ &- (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x f_{x-v}] - (\underline{\mu_{v,t}} - \overline{\mu_{v,t}}) = 0 \end{aligned} \tag{36}$$

$$\begin{aligned} \frac{dL}{dP_{m,t}^{pur}} &= a_{m,t} + \lambda_t - \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} - \overline{\mu_{x,t}})f_{x-m} \\ &- (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x f_{x-m}] - (\underline{\mu_{m,t}} - \overline{\mu_{m,t}}) = 0 \end{aligned} \tag{37}$$

$$\begin{aligned} \frac{dL}{dP_{loss,y,t}} &= \lambda_t - (\mu_{y,t}^{1,+} + \mu_{y,t}^{1,-}) + \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} \\ &- \overline{\mu_{x,t}}) - (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x](f_{x-i}\sigma_{y-i} \\ &+ \sum_{r=1}^{\mathbf{R}} f_{x-r}\sigma_{y-r} + \sum_{v=1}^{\mathbf{V}} f_{x-v}\sigma_{y-v} + \sum_{m=1}^{\mathbf{M}} f_{x-m}\sigma_{y-m}) = 0 \end{aligned} \tag{38}$$

$$\begin{aligned} \frac{dL}{dP_{loss,x,t}} &= \lambda_t - (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) + \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} \\ &- \overline{\mu_{x,t}}) - (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-}) \times \alpha_x](f_{x-i}\sigma_{x-i} \\ &+ \sum_{u=1}^{\mathbf{R}} f_{x-r}\sigma_{x-r} + \sum_{v=1}^{\mathbf{V}} f_{x-v}\sigma_{x-v} + \sum_{m=1}^{\mathbf{M}} f_{x-m}\sigma_{x-m}) = 0 \end{aligned} \tag{39}$$

$$\begin{aligned} \frac{dL}{dF_{y,t}} &= (\overline{\mu_{y,t}} - \underline{\mu_{y,t}}) - \alpha_x(\mu_{y,t}^{1,+} - \mu_{y,t}^{1,-}) - (f_{x-i}\eta_{y-i} \\ &+ \sum_{r=1}^{\mathbf{R}} f_{x-r}\eta_{y-r} + \sum_{v=1}^{\mathbf{V}} f_{x-v}\eta_{y-v} + \sum_{m=1}^{\mathbf{M}} f_{x-m}\eta_{y-m}) \\ &\times \sum_{x=1}^{\mathbf{X}}[(\underline{\mu_{x,t}} - \overline{\mu_{x,t}}) \\ &- (\mu_{x,t}^{1,+} - \mu_{x,t}^{1,-})\alpha_x] = 0 \end{aligned} \tag{40}$$

$$0 \leq \underline{\mu_{y,t}} \perp (F_{y,t} - \underline{ATC_y}) \geq 0 \tag{41}$$

$$0 \leq \overline{\mu_{y,t}} \perp (\overline{ATC_y} - F_{y,t}) \geq 0 \tag{42}$$

$$0 \leq \underline{\mu_{x,t}} \perp (F_x - \underline{ATC_x}) \geq 0 \tag{43}$$

$$0 \leq \overline{\mu_{x,t}} \perp (\overline{ATC_x} - F_x)) \geq 0 \tag{44}$$

$$0 \leq \mu_y^{1,+} \perp (P_{loss,y,t} + \alpha_y F_{y,t} - \beta_y) \geq 0 \tag{45}$$

$$0 \leq \mu_y^{1,-} \perp (P_{loss,y,t} - \alpha_y F_{y,t} - \beta_y) \geq 0 \tag{46}$$

$$0 \leq \mu_x^{1,+} \perp (P_{loss,x,t} + \alpha_x F_x - \beta_x) \geq 0 \tag{47}$$

$$0 \le \mu_x^{1,-} \perp (P_{loss,x,t} - \alpha_x F_x - \beta_x) \ge 0 \tag{48}$$

$$0 \le \underline{\mu_{i,t}} \perp (-\overline{P_{i,t}^{sell}} - P_{i,t}^{exc}) \ge 0 \tag{49}$$

$$0 \le \overline{\mu_{i,t}} \perp (P_{i,t}^{exc} - \overline{P_{i,t}^{pur}}) \ge 0 \tag{50}$$

$$0 \le \underline{\mu_{v,t}} \perp (-\overline{P_{v,t}^{sell}} - P_{v,t}^{exc}) \ge 0 \tag{51}$$

$$0 \le \overline{\mu_{v,t}} \perp (P_{v,t}^{exc} - \overline{P_{v,t}^{pur}}) \ge 0 \tag{52}$$

$$0 \le \underline{\mu_{m,t}} \perp - P_{i,t}^{exc} \ge 0 \tag{53}$$

$$0 \le \overline{\mu_{m,t}} \perp (P_{m,t}^{sell} - \overline{P_{m,t}^{sell}}) \ge 0 \tag{54}$$

$$0 \le \underline{\mu_{r,t}} \perp (-P_{r,t}^{pur}) \ge 0 \tag{55}$$

$$0 \le \overline{\mu_{r,t}} \perp (P_{r,t}^{exc} - \overline{P_{r,t}^{pur}}) \ge 0 \tag{56}$$

$$\begin{aligned}&\lambda_t, \overline{\mu_{y,t}}, \underline{\mu_{y,t}}, \overline{\mu_{x,t}}, \underline{\mu_{x,t}}, \overline{\mu_{i,t}}, \underline{\mu_{i,t}}, \overline{\mu_{v,t}},\\ &\underline{\mu_{v,t}}, \overline{\mu_{m,t}}, \underline{\mu_{m,t}}, \overline{\mu_{r,t}}, \underline{\mu_{r,t}}, \mu_x^{1,+}, \mu_x^{1,-}, \mu_y^{1,+}, \mu_y^{1,-} \ge 0\end{aligned} \tag{57}$$

The above KKT optimality conditions contain stationary (34)–(40), complementary slackness (40)–(56), primal feasibility (16)-(23), and dual feasibility (57). As a result, the proposed bi-level model is replaced with (5)–(14), (16)-(23) and (35)–(57) as a single-level MPEC.

B. LINEARIZATION OF THE NON-CONVEX MPEC

The non-convexity of the single-level MPEC comes from two parts: the complementary slackness conditions in lower-level KKT equivalent constraints (40)–(56) and the IRETA's bidding result in Eq.(5) of the upper-level model $\rho_{i,t}P_{i,t}^{exc}$.

To linearize $\rho_{i,t}P_{i,t}^{exc}$, the strong duality method is applied [27] and the linearized term of $\rho_{i,t}P_{i,t}^{exc}$ is given as Eq. (58).

$$\rho_{i,t}P_{i,t}^{exc} = \left[\begin{aligned}&\sum_{y=1}^{\mathbf{Y}}(\underline{\mu_{y,t}ATC_y} - \overline{\mu_{y,t}}\overline{ATC_y})\\ &+\sum_{y=1}^{\mathbf{Y}}(\mu_{y,t}^{1,+} + \mu_{y,t}^{1,-})\beta_y\\ &+\sum_{x=1}^{\mathbf{X}}(\underline{\mu_{x,t}}\underline{ATC_x} - \overline{\mu_{x,t}}\overline{ATC_x})\\ &+\sum_{x=1}^{\mathbf{X}}(\mu_{x,t}^{1,+} + \mu_{x,t}^{1,-})\beta_x\\ &+(\underline{\mu_{i,t}}\underline{P_i} - \overline{\mu_{i,t}}\overline{P}_i) - (\underline{\mu_{i,t}}\overline{P_i^{sell}} + \overline{\mu_{i,t}}\overline{P_i^{pur}})\\ &-\sum_{v=1}^{\mathbf{V}}(\underline{\mu_{v,t}}\overline{P_v^{sell}} + \overline{\mu_{i,t}}\overline{P_v^{pur}}) - \sum_{m=1}^{\mathbf{M}}\overline{\mu_{m,t}}\overline{P_m^{sell}}\\ &-\sum_{r=1}^{\mathbf{R}}\overline{\mu_{r,t}}\overline{P_r^{pur}} - \sum_{m=1}^{\mathbf{M}}a_{m,t}P_{m,t}^{sell} + \sum_{r=1}^{\mathbf{R}}a_{r,t}P_{r,t}^{pur}\\ &+\sum_{v=1}^{\mathbf{V}}a_{v,t}P_{v,t}^{exc} - (\underline{\mu_{i,t}} - \overline{\mu_{i,t}})P_{i,t}^{exc}\end{aligned}\right] \tag{58}$$

The complementary slackness constraints (40)–(56) can be linearized as Eq. (59), where M_1 and M_2 are large enough values and U is a binary variable.

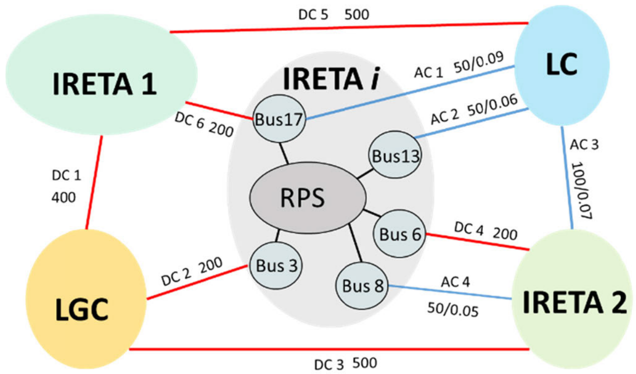

FIGURE 4. IRET through the inter-regional power system.

TABLE 1. Loss factors for inter-regional lines.

Inter-regional Line	α	β
DC 1	0.0248	0.0082
DC 2	0.0176	0.0010
DC 3	0.0393	0.0100
DC 4	0.0153	0.0095
DC 5	0.0453	0.0110
DC 6	0.0168	0.0054
AC 1	0.0618	-0.0335
AC 2	0.0576	-0.0306
AC 3	0.0782	-0.0213
AC 4	0.0721	-0.0103

$$0 \le A \perp B \ge 0 \Rightarrow M_1 \cdot U \ge A \ge 0, \quad M_2 \cdot (1-U) \ge B \ge 0 \tag{59}$$

Through the above method, the non-convex single-level MPEC becomes a MILP problem that can be effectively solved by commercial solver such as CPLEX.

V. NUMERICAL RESULTS

To validate the proposed model, an IRET market with five participants is established for study as illustrated in Fig.4. The inter-regional power system for IRET is composed of 6 HVDC lines and 4 HVAC lines. The ATC of each HVDC line, the ATC and impedance of each AC line are also given in Fig 4. In this section, the IRETA i is selected as the objective for bidding strategy-making in IRET. The IEEE RTS-24 test system is used to model the corresponding RPS operated by IRETA i, where bus 3, 6, 8, 13 and 17 of RPS are selected as the PCC buses linked with the inter-regional power system. The detailed network data, generation cost and reliability parameters of generators and converter within RPS are shown in [19], [28], where only the states with single or simultaneous failure are considered in this paper. The $EENS^T$ is set to be 500000 MWh/yr and the penalty coefficient η is set to be 1000.

Loss factors are introduced for inter-regional HVAC/DC lines as shown in Table 1, which is proposed in [29].

Meanwhile, the maximum exchanged electricity of IRETA 1, IRETA 2, IRETA i, LGC and LC in IRET are

TABLE 2. Bidding price ($/MWh) of each market entity in IRET.

Time	IRETA 1	IRETA 2	LGC	LC
1	50	32	28	69
2	63	76	31	87
3	67	52	42	56
4	48	42	21	52
5	43	79	49	89
6	78	48	26	74
7	40	24	17	70
8	57	38	18	60
9	59	41	18	90
10	42	29	35	74
11	47	79	34	72
12	52	27	39	78
13	55	77	37	51
14	33	53	10	79
15	33	72	20	74
16	58	43	22	61
17	37	66	29	66
18	40	63	47	58
19	46	59	43	57
20	46	53	11	80
21	43	69	35	90
22	53	40	22	75
23	57	33	20	66
24	41	77	45	90

TABLE 3. Interruption cost for different customers.

Load Type	Location (bus)	Interruption costs ($/unserved MWh)
Residential	1,3,4,6,8,9,10,13,14,18,20	243
Commercial	7,15	2990
Industrial	16,19	2951
Agricultural	2,5	295

set to be 800MW, 600MW. 500MW, 550MW and 400MW, respectively. The minimum unit of bidding price is set to be 1 $/MWh and the bidding prices of IRETA 1, IRETA 2, LGC and LC in IRET are assumed to be deterministic and predicted by IRETA i as shown in Table 2.

The loads within the RPS are divided into agricultural, industrial, commercial and residential, whose interruption costs [30] are presented in Table 3.

Three subsections are presented below to show the effectiveness of the proposed model. The simulation in the following subsections is all implemented on a PC with Intel 3 GHz 4-core processor (6 MB L3 cache), 8 GB memory.

A. SIMULATION RESULTS OF THE IRETA'S BIDDING STRATEGY IN IRET

In this subsection, the bidding strategy of IRETA i and the market-clearing results of IRET obtained through the proposed bi-level model in the 24-hour horizon are given in Fig 5, where the positive exchanged electricity means selling while the negative exchanged electricity means purchasing.

It can be seen from the market-clearing results that the IRETA i purchases electricity from the IRET during most intervals due to the reliability requirement of the corresponding RPS. Meanwhile, the IRETA i only sells electricity to IRET in interval 3h. It may because that under this interval the IRETA 1 submit a bid with relatively larger exchangeable electricity and a higher bidding price over other market entities (800MW, 67$/MWh), which makes the IRETA i get higher benefits through selling electricity to the IRETA 1 in IRET than purchasing electricity to improve the RPS's reliability. Meanwhile, the market-clearing results of other IRETAs in purchasing or selling electricity are varied over time. Specifically, the IRETA 1 purchases electricity during 1h, 3h, 4h, 6h-10h, 12h, 16h, 22h and 23h with relatively higher bidding prices and sells electricity during other intervals with relatively higher bidding prices. Meanwhile, the IRETA 2 purchases electricity during 2h, 5h, 11h, 13h-15h, 17h-21h and 24h with relatively higher bidding prices and sells electricity during other intervals with relatively lower bidding prices.

B. IMPACT OF RELIABILITY REQUIREMENTS ON THE IRETA'S BIDDING STRATEGY

In this subsection, in order to effectively illustrate the impact of reliability requirements on the IRETA's bidding strategy, three cases with different reliability requirements are given as follows:

Case 1: The bidding strategy of IRETA i is obtained through the proposed bi-level model without considering any fault states of the generators and converters within RPS.

Case 2: The bidding strategy of IRETA i is obtained through the proposed bi-level model considering each fault state of the generators within RPS and the corresponding fault probability.

Case 3: The bidding strategy of IRETA i is obtained through the proposed bi-level model with only the worst fault state considered (two 400MW generators are simultaneously failed in RPS).

The bidding prices of IRETA i under different cases are shown in Fig.6. Obviously, the bidding prices of IRETA i varies with different reliability requirements during most of the intervals in 24-hour horizon except for 17h-20h. In detail, compared with the bidding prices under Case 3 and Case 1, it can be seen that the IRETA i will give a much higher price with only the worst generator fault state considered. Especially, during interval 4 the price of IRETA i in Case 3 is 81$/MWh while in Case 1 the price of IRETA i is only 43$/MWh. Meanwhile, with each generator fault state and correspond probability considered, the bidding prices given by the IRETA i in Case 2 are between Case 1 and Case 3. Specifically, during 1h-2h, 5h, 7h-8h, 11h, 13h, 21h and 23h, the bidding prices in Case 2 are consistent with those in Case 3 and higher than those in Case 1. While only during 3h and 14h the bidding prices in Case 2 are consistent with those in Case 1 and lower than those in Case 3. It can be concluded from the above results that with the promotion of the reliability requirements, the bidding prices of the IRETA will be increased. In this way, the IRETA may achieve a higher purchase of electricity in IRET to improve the system reliability.

The EENS of RPS in 24-hour horizon under different cases are given in Table 4. Apparently, with no reliability

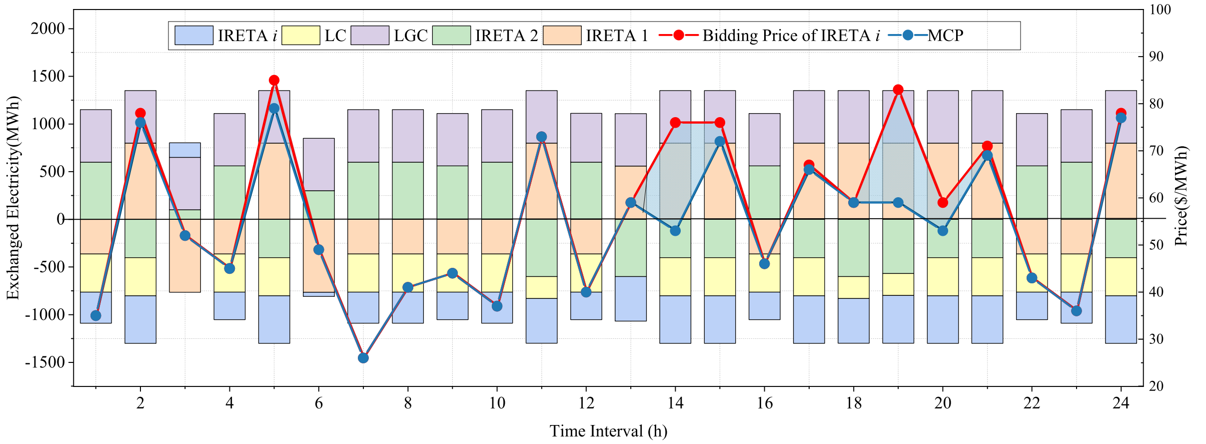

FIGURE 5. The bidding prices of IRETA *i* and the market results of IRET.

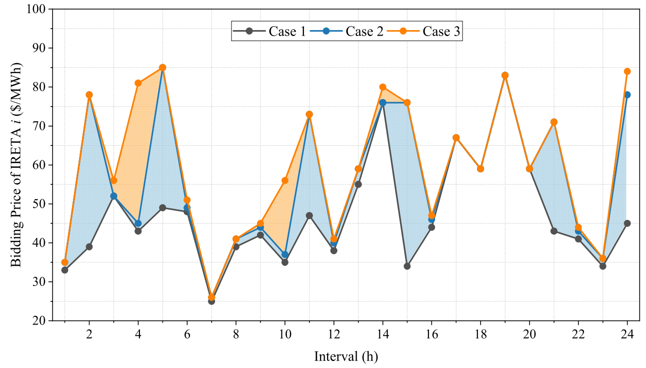

FIGURE 6. The bidding prices of IRETA *i* with different reliability requirements.

requirement, the EENS of RPS in Case 1 is much higher than those in Case 2 and Case 3. Besides, during most intervals, the EENS of RPS in Case 1 is even higher than that when IRETA *i* no participating in IRET (EENS equals to 107533 MWh/yr when IRETA *i* does not participate in IRET). It seems that the reliability of the RPS will be harmed if the IRETA *i* making its bidding strategy in IRET without considering the reliability requirement. Meanwhile, it can be seen from the EENS in Case 2 that the bidding strategy of IRETA *i* in Case 2 can ensure the EENS of RPS does not beyond the $EENS^T$ (500000 MWh/yr) during most intervals.

Moreover, to illustrate the economic impact on the RPS operation from the IRETA's bidding strategy under different reliability requirements. The expected dispatch cost EDC_t of RPS under different cases are shown in Fig.7.

Compared both the EENS and EDC_t of the RPS between Case 2 and Case 3, the EENS in Case 2 is quite close to that in Case 3 while the EDC_t in Case 2 is much lower than that in Case 3. It can be concluded from the above results that through considering the probability characteristic of each fault state, the IRETA's bidding strategy can effectively reduce the operating costs while ensuring the reliability of RPS.

TABLE 4. EENS (MWh/yr) of RPS with different reliability requirements.

Time	Case 1	Case 2	Case 3
1	61583	0	0
2	5037625	23860	23860
3	438009	438009	0
4	61583	0	0
5	2918370	23860	23860
6	438009	61583	0
7	61583	0	0
8	61583	0	0
9	61583	0	0
10	247944	0	0
11	2749199	590357	590357
12	828750	0	0
13	2749199	590357	590357
14	23860	23860	23860
15	2588776	23860	23860
16	61583	0	0
17	23860	23860	23860
18	590357	590357	590357
19	23860	23860	23860
20	23860	23860	23860
21	2749199	23860	23860
22	61583	0	0
23	61583	0	0
24	2918370	23860	23860

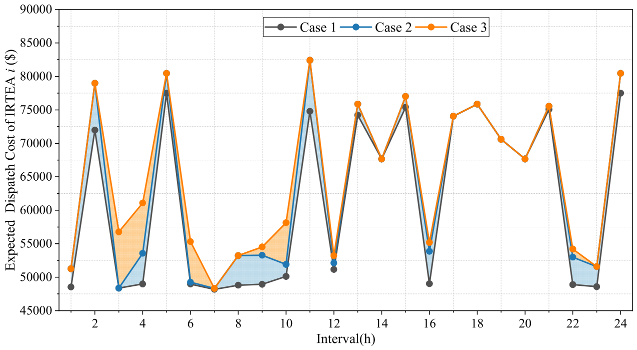

FIGURE 7. The *EDCt* of *RPS* with different reliability requirement.

C. IMPACT OF TRANSMISSION LOSSES ON THE IRETA'S BIDDING STRATEGY

In this subsection, in order to effectively illustrate the impact of transmission losses on the IRETA's bidding strategy, two cases with different loss settlement are given as follows:

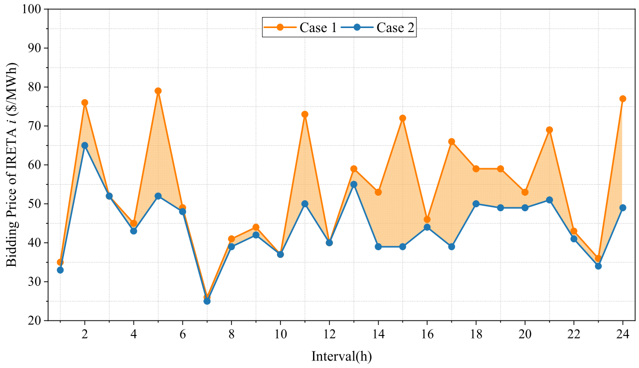

FIGURE 8. The bidding prices of IRETA i with different loss settlement.

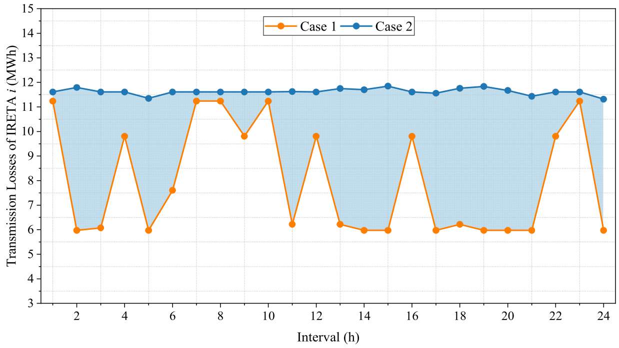

FIGURE 9. Transmission losses of IRETA i with different loss settlement.

Case 1: The bidding strategy of IRETA i is obtained through the same bi-level model with Case 2 in Subsection B internalized with the transmission losses.

Case 2: The bidding strategy of IRETA i is obtained through the same bi-level model with Case 2 in Subsection B without considering the transmission losses (α and β in Table. 2 are set to be zero).

The bidding prices of IRETA i under different cases are shown in Fig.8.

It can be seen that with the inclusion of transmission losses, the bidding prices of IRETA i are increased during most of the intervals. The result shows that the IRETA i needs to give higher prices to purchase electricity from IRET during most situations when the transmission losses are considered. Meanwhile, the transmission losses of IRETA i under different cases are illustrated in Fig.9.

It can be seen that the transmission losses of IRETA i in Case 2 are almost consistent while those in Case 1 vary during different intervals. Moreover, compared the results with Case 2, the losses of IRETA i in Case 1 drops significantly when transmission losses are internalized in the model. Specifically, during 14h the transmission losses of IRETA i decreases from 11.69 MWh to 5.97 MWh when changed from Case 2 to Case 1. The results show that by considering the inter-regional transmission losses in the bidding strategy-making process, the IRETA can effectively reduce its transmission losses in the IRET.

VI. CONCLUSION

In this paper, a bi-level model is proposed for the IRETA to find the optimal bidding strategy in IRET, in which the operation of RPS operated by the IRETA and the market-clearing of IRET are regarded as the upper and lower-level models, respectively. The random fault states and reliability requirements of RPS and inter-regional transmission losses are considered in the upper and lower-level models, respectively. KKT conditions and strong dual theory are used to transform the proposed bi-level model into a linear single-level MPEC. Numerical results show the findings that:

1) The proposed reliability-based bi-level model enables the IRETA to make effective bidding strategies in IRET to reduce the operating costs of RPS while ensuring its reliability. Specifically, compare with the former works, the proposed method reduces the number of buses exceeding the limit of reliability requirement by over 50% while reduce the operating costs of RPS by over 20% considering all intervals.

2) By internalizing inter-regional transmission losses, the proposed model can help the IRETA make bidding strategies to avoid excessive transmission losses. Specifically, compare with the former works, the proposed method cuts down the transmission loss by over 40% considering all intervals.

With the development of IRET in countries with nascent power markets, more and more IRETAs will change their roles from sole RPS operators to comprehensive decision-makers of IRET participation and RPS operation. The bidding strategy model proposed in this paper can help IRETAs better adapt to the role change and make effective bidding decisions.

REFERENCES

[1] A. Karimi, M. K. Sheikh-El-Eslami, and H. Seifi, "Market-based mechanism for multi-area power exchange management in a multiple electricity market," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 13, pp. 1662–1671, Oct. 2015.

[2] Y. Liu, M. Liu, and H. Chen, "Decentralized day-ahead market clearing in multi-area interconnected electricity market with variable wind generation," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Nov. 2018, pp. 755–762.

[3] L. H. Lam, V. Ilea, and C. Bovo, "European day-ahead electricity market coupling: Discussion, modeling, and case study," *Electric Power Syst. Res.*, vol. 155, pp. 80–92, Feb. 2018.

[4] PJM. *PJM/MISO Joint & Common Market Initiative*. Accessed: Oct. 1, 2020. [Online]. Available:https://www.pjm.com/committees-and-groups/stakeholder-meetings/pjm-miso-joint-common.aspx

[5] E. Gnansounou and J. Dong, "Opportunity for inter-regional integration of electricity markets: The case of Shandong and Shanghai in East China," *Energy Policy*, vol. 32, no. 15, pp. 1737–1751, Oct. 2004.

[6] Beijing Power Exchange Center, "Annual report of electricity market 2019," Beijing Power Exchange Center, Beijing, China, Tech. Rep., Apr. 2020. [Online]. Available: http://shoudian.bjx.com.cn/html/20200402/1060461.shtml

[7] M. S. Ho, Z. Wang, and Z. Yu, "China's power generation dispatch," RFF, Washington, DC, USA, Tech. Rep., Apr. 2017. [Online]. Available: https://media.rff.org/documents/RFF-Rpt-ChinaE lectricity.pdf

[8] H. Wang, B. Su, H. Mu, N. Li, B. Jiang, and X. Kong, "Optimization of electricity generation and interprovincial trading strategies in Southern China," *Energy*, vol. 174, pp. 696–707, May 2019.

[9] L. Guo, Y. Ding, M. Bao, and D. Zen, "An optimal power purchase model of inter-provincial traders in two-level electricity market considering risk management," *Power Syst. Technol.*, vol. 43, no. 8, pp. 2726–2733, Aug. 2019.

[10] National Energy Administration. *Basic Rules for Inter-Province Electricity Trading*. Accessed: Oct. 1, 2020. [Online]. Available: http://zfxxgk.nea.gov.cn/au-to79/201307/t20130708_1649.htm

[11] L. Guo, Y. Ding, D. Zeng, and L. Liu, "A mechanism for two-level power market in China: Promoting cross regional consumption of renewable energy," *Energy Procedia*, vol. 159, pp. 255–260, Feb. 2019.

[12] Z. Tan, H. Zhong, Q. Xia, and J. Yang, "Bi-level electricity market design with boundary equivalence of interior security constraints," in *Proc. 15th Int. Conf. Eur. Energy Market (EEM)*, Jun. 2018, pp. 1–5.

[13] K. Loh, "Proportioning inter-regional losses to regions," AEMO, Melbourne, VIC, Australia, Tech. Rep., Sep. 2009. [Online]. Available: https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/loss_factors_and_regional_boundaries/2009/0170-0003-pdf.pdf

[14] W. Wei, F. Liu, and S. Mei, "Energy pricing and dispatch for smart grid retailers under demand response and market price uncertainty," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1354–1374, May 2015.

[15] N. Mahmoudi, T. K. Saha, and M. Eghbal, "Modelling demand response aggregator behavior in wind power offering strategies," *Appl. Energy*, vol. 133, pp. 347–355, Nov. 2014.

[16] A. G. Bakirtzis, N. P. Ziogos, A. C. Tellidou, and G. A. Bakirtzis, "Electricity producer offering strategies in day-ahead energy market with step-wise offers," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1804–1818, Nov. 2007.

[17] N. Shang, C. Ye, Y. Ding, T. Tu, and B. Huo, "Risk-based optimal power portfolio methodology for generation companies considering cross-region generation right trade," *Appl. Energy*, vol. 254, Nov. 2019, Art. no. 113511.

[18] S. Bahramara, M. Yazdani-Damavandi, J. Contreras, M. Shafie-Khah, and J. P. S. Catalao, "Modeling the strategic behavior of a distribution company in wholesale energy and reserve markets," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3857–3870, Jul. 2018.

[19] L. Guo, Y. Ding, M. Bao, C. Shao, P. Wang, and L. Goel, "Nodal reliability evaluation for a VSC-MTDC-Based hybrid AC/DC power system," *IEEE Trans. Power Syst.*, vol. 35, no. 3, pp. 2300–2312, May 2020.

[20] B. Wang, X. Wang, Z. Bie, P. D. Judge, X. Wang, and T. C. Green, "Reliability model of MMC considering periodic preventive maintenance," *IEEE Trans. Power Del.*, vol. 32, no. 3, pp. 1535–1544, Jun. 2017.

[21] P. Wang, Y. Ding, and Y. Xiao, "Technique to evaluate transmission reliability indices and transmission prices of restructured power systems," *IEE Proc. Gener., Transmiss. Distrib.*, vol. 152, no. 3, pp. 390–396, May 2005.

[22] K. Okada, H. Asano, R. Yokoyama, and T. Niimura, "Reliability-based impact analysis of independent power producers for power system operations under deregulation," in *Proc. Eng. Solutions Next Millennium. IEEE Can. Conf. Electr. Comput. Eng.*, May 1999, pp. 1325–1330.

[23] X. Cheng and T. J. Overbye, "PTDF-based power system equivalents," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1868–1876, Nov. 2005.

[24] C. Coffrin, P. Van Hentenryck, and R. Bent, "Approximating line losses and apparent power in AC power flow linearizations," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–8.

[25] All NEMOs Comittee. (Apr. 2019). *EUPHEMIA Public Description: Single Price Coupling Algorithm*. [Online]. Available: http://www.nemo-committee.eu/assets/files/190410 Euphemia%20Public%20Description%20version%20NEMO%20Committee.pdf

[26] Y. Ye, D. Papadaskalopoulos, J. Kazempour, and G. Strbac, "Incorporating non-convex operating characteristics into bi-level optimization electricity market models," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 163–176, Jan. 2020.

[27] C. Ruiz and A. J. Conejo, "Pool strategy of a producer with endogenous formation of locational marginal prices," *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1855–1866, Nov. 2009.

[28] P. Subcommittee, "IEEE reliability test system," *IEEE Trans. Power App. Syst.*, vol. PAS-98, no. 6, pp. 2047–2054, Nov. 1979.

[29] E. Fingrid and S. K. Statnett, "Analyses on the effects of implementing implicit grid losses in the Nordic CCR," Fingrid, Energinet, Statnett, Svenska Kraftnät, Helsinki, Finland, Tech. Rep., Apr. 2018.

[30] G. Wacker and R. Billinton, "Customer cost of electric service interruptions," *Proc. IEEE*, vol. 77, no. 6, pp. 919–930, Jun. 1989.

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