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Wind Power Economic Dispatch for Steady-State Secure Region Using GSIP

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***Abstract*— In this paper, an economic dispatch model considering a flexible generation dispatch is proposed for managing the wind power variability in electric power systems. The model considers the base case operation cost as well as the steady-state secure region for the variable wind energy. The generation schedule in the secure region provides grid operators with the boundary for absorbing wind power. The proposed model is formulated as a generalized semi-infinite programming (GSIP) problem and the corresponding solution is presented. The impact of flexible thermal resources and transmission capacity on the calculation of the wind power secure region is also discussed.**

***Index Terms*— Variable wind power utilization, steady-state secure region, economic dispatch, generalized semi-infinite programming (GSIP)**

A. Sets and Index

gi	Index of generators
i	Index of load buses
j,k	Index of grid constraints and extreme wind power conditions
K	Set of grid constraints
l	Index of transmission lines
wi	Index of wind farms

B. Parameters

$a_{gi,k}$	Coefficients in grid constraints
$b_{wi,k}$	Coefficients in grid constraint
c_l	Cost coefficient of load curtailment
c_w	Cost coefficient of wind spillage
d_i	Load power at Bus i
F_l	Transmission capacity of Line l
m_k	Coefficients in grid constraints

Nomenclature

NL	Number of transmission lines
$p_{gi,\max}$	Maximal output of Generator gi
$p_{gi,\min}$	Minimal output of Generator gi
R_{gi}	Ramping rate of Generator gi
$rw_{wi,\max}$	Upper bound of the secure region of Wind Farm wi
$rw_{wi,\min}$	Lower bound of the secure region of Wind Farm wi
T_a	Allowed generation adjustment time duration
$w_{wi,\max}$	Real maximal power output of Wind Farm wi
$w_{wi,\min}$	Real minimal power output of Wind Farm wi
t	Timeslot duration
$_{i,l}$	Power flow distribution factor of load
$_{gi,l}$	Power flow distribution factor of generation
$_{wi,l}$	Power flow distribution factor of wind power

C. Variables and Functions

INTRODUCTION

WIND power has been experiencing a rapid deployment across the world. The large integration of wind power could help reduce emissions and alleviate the dependence on fossil fuels. However, the deployment also imposes significant challenges on the power system operation because of the variable nature of wind power. In such cases, the flexible generation capacity should be properly reserved to manage the variations in the real-time generation availability caused by the wind power uncertainty.

A large volume of research has been devoted to dealing with the economics and the security of variable wind power in the power grid operation [1]-[8]. In such cases,

stochastic and robust programming methods are widely adopted under the framework of unit commitment (UC) and economic dispatch [1]-[4]. In the former

, the wind power variability is usually modeled by considering possible scenarios. The scenario reduction is essential to decrease the number of scenarios for computational efficiency. And an economic generation schedule is obtained, which satisfies the prevailing constraints in all or parts of the scenarios. However, it is often difficult to determine whether the proposed schedule is secure or can be secured in practice because the probability information is modified in the scenario generation and reduction process.

The robust optimization methods describe the wind power by a deterministic uncertainty set rather than the accurate probability distribution. It takes the worst-case realization into consideration which can guarantee that the obtained schedule is always secure for the given uncertainty set. Compared with the robust optimization, the adaptive robust optimization (ARO) method appears to be less conservative [5]-[8]. Accordingly, the operation decisions are made in two or more stages. Based on the operation plan made at the first stage, the extreme realization is studied in the subsequent stages. In addition, the adaptive generation dispatch or adjustment is considered, which makes the solution less conservative.

Although robust schedules can be obtained via ARO, the region where the wind power can be completely absorbed by the power system is not provided. The wind power will be curtailed in an ex-post fashion at the re-dispatch stage, if the wind power demonstrates significant variations or flexible resources in the power grid are scarce. The wind power spillage causes the uncertainty set to be different than the absorbable region of wind power.

According to [9]- [12], the same problem exists in the ISOs' operation practice. For instance, the ISO New England dispatches conventional generators to satisfy a very short-term load forecast and the predicted level of wind power. In the meantime, the system operator continuously monitors the network security. If a security violation caused by wind power is witnessed, then excessive wind will be curtailed via a manual process by the system operator. That's to say only corrective actions are carried out on wind farms once the power system has already experienced security violations.

The concept of steady-state secure region is defined as a set of power injections which satisfy static operating constraints. In the secure region, the security violation can always be eliminated by the proper re-dispatch. When projected onto the space of wind power, it becomes the region in which the wind power can be absorbed completely, which is referred to as the *steady-state secure region for wind power*. In [13], a secure region is obtained and expressed in terms of the power injection limits at different buses. Based on the DC power flow solution, an expanding region method is proposed in [14] to obtain the maximum steady-secure region. Recently, a method for calculating the dispatchable region of wind power is proposed in [15] as a special case of the steady-state secure region projected onto the wind power space. In essence, the do-not-exceed (DNE) dispatch limit proposed in [9] is the corresponding boundary of a special hyper-box secure region for the wind power.

Compared with conventional methods for calculating the power system secure region presented in [13] and [14], it is more difficult to calculate the wind power secure region in power systems, from which the generation re-dispatch should be separated. It is possible to apply a fast DC optimal power flow (OPF) to determine whether a wind power dispatch solution is secure. However, an enormous number of DC OPF calculations, which is a time-consuming process, are needed to get the ex-ante wind power secure region.

It is of vital necessity and importance to co-optimize the grid base-case operation point and the secure region. Accordingly, the operation economics and the wind power integration would be considered and balanced closely. In addition, dispatch signals for conventional units and variable wind power can be produced simultaneously. The work in [16] has made an effort on co-optimization via a two-stage model. However, only one group of AGC participation factors is used for accommodating wind power variations. As shown in [9], such limited solutions could result in conservative regions of security in power systems.

In this paper, an economic dispatch model is proposed which would consider the steady-state secure region for variable wind power. The base-case operation cost and the wind power integration are balanced via the introduction of secure regions. The proposed model differs from the existing ARO methods in the following respects. First, a variable secure region rather than a deterministic set is considered for managing the wind power variability. In ARO, the uncertainty set is predefined according to wind power forecasts while in this paper the secure region is obtained and optimized via properly setting the base-case operation point. Second, the proposed model finds a secure region in which wind power can be completely absorbed (i.e., wind curtailment is not allowed). For the given uncertainty set, there are no feasible solutions for ARO if flexible resources in the power grid are limited and wind spillage is prohibited.

The contributions of this paper include the following. First, the secure region for wind power is considered in the economic dispatch model which provides a tradeoff between operation cost and security. Second, the secure region for wind power is obtained by solving the proposed generation scheduling model. The secure region boundary (DNE limit) of wind power can serve as dispatch signals for power grid operators when scheduling the variable wind power. Proactive actions are adopted based on the proposed method in order to retain variable wind power in the secure region. Third, the proposed economic dispatch model is formulated as a generalized semi-infinite programming (GSIP) problem and the corresponding solution is introduced. In addition, the impact of several operation factors such as the availability of flexible resources and transmission capacity on the secure region of variable wind power is discussed in the case studies.

The rest of this paper is organized as follows. The steady-state secure region for wind power is illustrated in Section II. Section III formulates the proposed model and Section IV provides the algorithm. The case studies and conclusions are presented in Sections V and VI respectively.

III. Secure Region for Wind Power

A. Steady-state secure region

The use of OPF model in economic dispatch calculations minimizes the generation cost (1) subject to power generation and network constraints.

$$\min \sum_{gi} f_{gi}(p_{gi}) \quad (1)$$

Here, static operation constraints including power balance (2), power flow (3), generation dispatch (4), and ramping constraints (5) for the last dispatch period are calculated because the steady-state secure region alone is of interest.

$$\sum_{gi} p_{gi} \quad \sum_{i} d_i \quad \sum_{wi} w_{wi} \quad (2)$$

$$F_l \quad \sum_{gi} \lambda_{gi,l}\, p_{gi} \quad \sum_{wi} \lambda_{wi,l}\, w_{wi} \quad \sum_{i} \lambda_{i,l}\, d_i \quad F_l \quad (3)$$

$$p_{gi,\min} \quad p_{gi} \quad p_{gi,\max} \quad (4)$$

$$R_{gi}\, t \quad p_{gi} \quad p^{0}_{gi} \quad R_{gi}\, t \quad (5)$$

The optimal power flow model (1)-(5) is a parameterized programming problem, given load and wind power forecasting errors, in which the possibility of a secure operation plan depends on load and wind power values. Thus, the steady-state secure region is defined as the set S where a feasible solution of (2)-(5) exists for $\{\boldsymbol{d}, \boldsymbol{w}\}$ S. Given a base case operation point, the re-dispatch plan must satisfy adjustment ranges of generation resources (6), as well as (2)-(5). Here, T_a represents the adjustment time duration.

$$R_{gi} T_a \quad p_{gi} \quad p_{gi,b} \quad R_{gi} T_a \quad (6)$$

We label the region defined by (2)-(5) as the *secure dispatch region* and the one defined by (2)-(6) as the *secure re-dispatch region* where the base- case operation point $\{\boldsymbol{p_{gi,b}}\}$ is considered. In the short-term grid operation, the base-case schedule plays an important role so that the latter should be considered while the former can apply to mid/long term planning problems.

B. Secure region for wind power

The wind power secure region, in which the wind power variability is considered, is a projection of the steady-state secure region of power systems where load is assumed to be deterministic. In this case, the preceding regions are reduced to a set of wind power injections and the secure dispatch region for the variable wind power is derived from (2)-(5), while the re-dispatch region is obtained by (2)-(6).

The steady-state secure region is expressed by bus power injection limits. Similarly, the secure region for variable wind power corresponds to wind power generation limits. The secure region is a convex polyhedral [13]. However, according to [14], the hyper box subset is easier to obtain for power system operation. Thus a secure hyper box for wind power is considered in this paper which is shown in Fig.1. The secure region is in the same form as the DNE limit [9].

$$S_w \{\boldsymbol{w} | rw_{wi,\min} \quad w_{wi} \quad rw_{wi,\max}\} \quad (7)$$

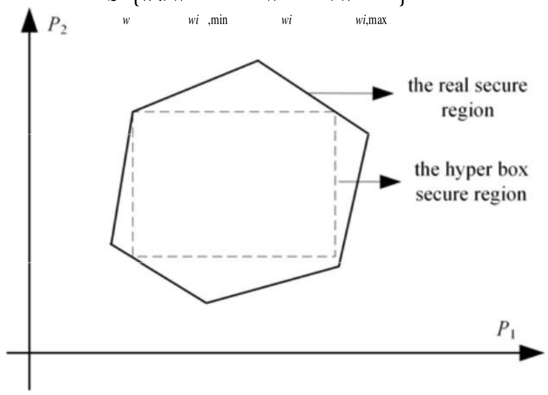

Fig. 1. Illustration of the hyper box secure region of wind power

IV. Model Formulation

$$\min \sum_{gi} f_{gi}(p_{gi,b}) \quad \sum_{wi} f_{wi}(rw_{wi,\min}, rw_{wi,\max}) \quad (8)$$

A. Objective Function

The objective function (8) consists of the base-case generation fuel cost and the additional cost of maintaining the secure region for variable wind power.

$[w_{wi,\min}, w_{wi,\max}]$ is assumed to be the range for the wind power forecast of the Wind Farm wi. $[rw_{wi,\min}, rw_{wi,\max}]$ is the absorbable wind power region. Thus, there will be wind spillage in $[rw_{wi,\max}, w_{wi,\max}]$. Considering the probability density function of wind power, the expectation cost for wind spillage is calculated as,

$$f_{wi}(rw_{wi,\max}) \quad c_{w\,rw} \int_{w_{wi,\max}}^{W_{wi,\max}} pdf_{wi}(w_{wi})(w_{wi} \quad rw_{wi,\max})\, dw_{wi}\,. \quad (9)$$

If wind power is uniformly distributed on $[w_{wi,\min}, w_{wi,\max}]$,

$$pdf(w_{wi}) \quad \frac{1}{w_{wi,\max} \quad w_{wi,\min}}\,. \quad (10)$$

We conclude

$$f_{wi}(rw_{wi,\max}) \quad \frac{c_w(rw_{wi,\max} \quad w_{wi,\max})^2}{2(w_{wi,\max} \quad w_{wi,\min})}. \tag{11}$$

Similarly, the expectation of load curtailment in [$w_{wi,\min}$, $rw_{wi,\min}$] is calculated as a function of $rw_{wi,\min}$. The total additional cost related to considering a secure region is formulated as

$$f_{wi}(rw_{wi,\min}, rw_{wi,\max}) \quad \frac{1}{2(w_{wi,\max} \quad w_{wi,\min})} \tag{12}$$
$$[\, c_w (rw_{wi,\max} \quad w_{wi,\max})^2 \quad c_l (rw_{wi,\min} \quad w_{wi,\min})^2 \,]$$

Other probability distributions such as a Gaussian function may also be considered for the wind power forecast. Accordingly, the related cost terms will be formulated similar to (9)-(12).

The minimization of objective function is considered, thus $rw_{wi,\min}$ and $rw_{wi,\max}$ tend to be $w_{wi,\min}$ and $w_{wi,\max}$ to minimize f_{wi}. The latter term in (8) not only takes wind spillage and load curtailment costs into consideration, but also helps maximize the secure region. In addition, a trade-off is made between the base-case generation cost and the operation security by properly selecting c_w and c_l.

B. Base-case Constraints

The base-case operation constraints (13)-(19) are similar to those in (2)-(5) which provide a general framework for OPF. In (13)-(19), the base -case variables are indexed by subscript *b*. The secure region is placed within the wind power variation range by (17) and (18) . In (19), the wind power in the base-case operation is restricted to the secure region. Here, the base-case wind power is considered as variable so that its most optimistic operation plan is obtained.

$$\sum_{gi} p_{gi,b} \quad \sum_{i} d_i \quad \sum_{wi} w_{wi,b} \tag{13}$$

$$F_l \quad \sum_{gi} \ldots_{lgi,l}\, p_{gi,b} \ldots_{wi,l}\, w_{wi,b} \ldots_{i,l}\, d_i \quad F_l \tag{14}$$

$$p_{gi,\min} \quad p_{gi,b} \quad p_{gi,\max} \tag{15}$$

$$R_{gi}\, t \quad p_{gi,b} \quad p^{0}_{gi} \quad R_{gi}\, t \tag{16}$$

$$w_{wi,\min} \quad rw_{wi,\min} \tag{17}$$

$$rw_{wi,\max} \quad w_{wi,\max} \tag{18}$$

$$rw_{wi,\min} \quad w_{wi,b} \quad rw_{wi,\max} \tag{19}$$

Here, $rw_{wi,\min}$ and $rw_{wi,\max}$ will naturally be $w_{wi,\min}$ and $w_{wi,\max}$, if the following secure region constraints are not considered.

C. Secure region Constraints

For the ease of presentation, we restate the grid constraints (13)-(14) as those in (20) where *K* is the set for grid constraints and *k*=1,2,…,2*NL*+2.

$$g_k(\boldsymbol{p},\boldsymbol{w}) \quad \sum_{gi} a_{gi,k}\, p_{gi} \quad \sum_{wi} b_{wi,k}\, w_{wi} \quad m_k \quad 0, \quad k \quad K \tag{20}$$

The feasible region of generation unit is defined by

$$G(\boldsymbol{p}_b) \quad \boldsymbol{p} \left| \begin{array}{l} p_{gi,\min} \quad p_{gi} \quad p_{gi,\max} \\ R_{gi}\, t \quad p_{gi} \quad p^{0}_{gi} \quad R_{gi}\, t. \\ RT_{gi\,a} \quad p_{gi} \quad p_{gi,b} \quad RT_{gi\,a} \end{array} \right. \tag{21}$$

Thus the secure region constraints are described in (22) by a set of the secure region boundaries. Because of the arbitrary nature of $\boldsymbol{w}$, a large set of constraints can be generated accordingly. In addition, the boundaries of $\boldsymbol{w}$ are considered variable which make the proposed economic dispatch model a GSIP problem [17].

$$U \quad \{(\boldsymbol{rw}_{\min}, \boldsymbol{rw}_{\max}) \,|\, g_k(\boldsymbol{p}, \boldsymbol{w}) \quad 0, \boldsymbol{p} \quad G(\boldsymbol{p}_b), \tag{22}$$
$$\text{for all } k \quad K, \boldsymbol{rw}_{\min} \quad \boldsymbol{w} \quad \boldsymbol{rw}_{\max}\}$$

D. Relation to ARO Model

The proposed two-stage structure is an extension of ARO. If $rw_{wi,\min}$ and $rw_{wi,\max}$ are fixed at $w_{wi,\min}$ and $w_{wi,\max}$ respectively, the constraints stated in (22) are reduced to

$$g_k(\boldsymbol{p}, \boldsymbol{w}) \; 0, \; \boldsymbol{p} \; G(\boldsymbol{p}_b) \text{ for } k \; K, \; \boldsymbol{w} \; [\boldsymbol{w}_{\min}, \boldsymbol{w}_{\max}], \tag{23}$$

which are the same as those in ARO. The model is reduced to a special ARO model considering robust intervals. The wind spillage and load curtailment are not allowed in wind power intervals. Accordingly, this is a standard semi-infinite programming (SIP) problem [17].

From the physical system perspective, the proposed model is also an extension of ARO. If the grid flexible resource is abundant and the punishment factors c_w and c_l are large enough, the solution of $rw_{wi,\min}$ and $rw_{wi,\max}$ will naturally be $w_{wi,\min}$ and $w_{wi,\max}$. The proposed model fills the gap when the preceding conditions are not satisfied. There will be no solution for the ARO model if flexible resources in the power grid are scarce and the wind power curtailment is not allowed in the uncertainty set. However, the proposed model can provide a feasible operation plan by shrinking the uncertainty set to the secure region for wind power.

V. Proposed Algorithm

A. Explicit Formulation

The problem formulation stated in (22) is not in an explicit form as required. Since the constraints in (20) are stated for an arbitrary $\boldsymbol{w}$, for each *k* there exists

$$\max_{\boldsymbol{w}} g_s(\boldsymbol{p}, \boldsymbol{w}) \quad 0. \tag{24}$$

in which the following constraints would have to be satisfied in the maximization problem. The corresponding positive dual multipliers are also included.

$$g_j(\boldsymbol{p}, \boldsymbol{w}) \quad 0, j \quad K \text{ and } j \quad k : \; _{j,k} \tag{25}$$

$$w_{wi} \quad rw_{wi,\max}, \quad wi : \; _{wi,k} \tag{26}$$

$$rw_{wi,\min} \quad w_{wi}, \quad wi : \; _{wi,k} \tag{27}$$

$$\boldsymbol{p} \quad G(\boldsymbol{p}_b) \tag{28}$$

According to the KKT conditions, the set of constraints in (29) -(32) hold for the best wind power solution $w_{k,wi}$.

$$0 \quad g_j(\boldsymbol{p}_k, \boldsymbol{w}_k)_{j,k} 0, j \quad K \text{ and } j \quad k \tag{29}$$

$$0 \quad rw_{wi,\max} \quad w_{wi,k} \quad _{wi,k} \quad 0, \quad wi \tag{30}$$

$$0 \quad w_{wi,k} \quad rw_{wi,\min} \quad _{wi,k} \quad 0, \quad wi \tag{31}$$

$$_{wi,k} \quad \sum_{j \; K, j \; k} {}_{wi,j}\; _{j,k} \; b_{wi,k} \tag{32}$$

Meanwhile, the corresponding $\boldsymbol{p}_k$ should also be in its feasible region, so

$$\boldsymbol{p}_k \quad G(\boldsymbol{p}_b) \tag{33}$$

As the constraints in (25)-(28) are linear and convex, the preceding conditions are sufficient and necessary, which is consistent with the general discussions on GSIP [18]. Used in this way, the large set of constraints can be replaced by (2*NL*+2) set of variables and the complementarity constraints (29)-(33).

B. Line-screening Method

As shown, the computation scale of the proposed model depends on the number of transmission lines. Thus a line-screening method is introduced here to detect a transmission line with a redundant capacity, which can reduce the model scale and improve the calculation efficiency.

For transmission lines, the problem in (34) provides a relaxation of that defined by (24)-(28), where only the power balance and generation output constraints are considered and the re-dispatch of generation units to minimize the violation is not included. Thus the objective function mv_k in (34) is not smaller than that in (24)-(28). If mv_k is less than 0, the constraint in (24) will be satisfied naturally and constraints in (24)-(28) will be redundant which will be excluded from the model for the corresponding *k*.

$$\max_{\boldsymbol{w},\boldsymbol{p}} g_k(\boldsymbol{p}, \boldsymbol{w})$$
$$s.t. \; \underset{gi}{p_{gi,k}} + \underset{wi}{w_{wi,k}} \quad \underset{i}{a_i} \qquad (34)$$
$$w_{wi,\min} \quad w_{wi,k} \quad w_{wi,\max}$$
$$p \quad p \quad p$$

The problem in (34) is solved efficiently by the merit-order method [23] because g_k is a linear combination of $p_{gi,k}$ and $w_{wi,k}$ as shown in (20), and only one coupling equality constraint is considered, The transmission lines with redundant capacity can be detected quickly by the line-screening method and removed from the original model.

C. Linearization

Our economic dispatch model is formulated as a complementarity problem [15] stated in (35). For the compact one, only the no-redundant transmission lines are included.

$$\min \underset{gi}{f}(p_{gi,b}) \quad \underset{wi}{f}(rw_{wi,\min}, rw_{wi,\max})$$
$$s.t. \quad Constraints(13) \;\; (19) \qquad (35)$$
$$Constraints\,(29) \;\; (33), \;\; k \;\; K$$

The complementary slackness constraints in (29)-(31) make the proposed model non-convex and computationally challenging. A straightforward method is applied, introducing integer variables to linearize the proposed formulation. We use the *Big-M* method for linearizing the constraints in (29)-(31) as

$$0 \quad g_j(\boldsymbol{p}_k, \boldsymbol{w}_k) \quad Mx_{j,k}, j \;\; K \text{ and } j \;\; k \qquad (36)$$
$$0 \quad {}_{j,k} \quad M(1 \;\; x_{j,k}), j \;\; K \text{ and } j \;\; k \qquad (37)$$
$$0 \;\; rw_{wi,\max} \quad w_{wi} \quad My_{wi,k}, \;\; wi \qquad (38)$$
$$0 \quad {}_{wi,k} \quad M(1 \;\; y_{wi,k}), \;\; wi \qquad (39)$$
$$0 w_{wi,k} \quad rw_{wi,\min} \quad Mz_{wi,k}, \;\; wi \qquad (40)$$
$$0 \quad {}_{wi,k} \quad M(1 \;\; z_{wi,k}), \;\; wi \qquad (41)$$

where $x_{j,k}$, $y_{wi,k}$, $z_{wi,k}$ are the integer variables for complementary constraints.

Thus, the proposed model is transformed into an MIQP model which is solved by CPLEX. If other types of generation cost functions or distribution functions for wind power are considered for large-scale problems, the objective function in (8) will be presented using the piecewise linearization of the corresponding MILP problem. The procedure for formulating and solving the proposed model is presented in Fig. 2.

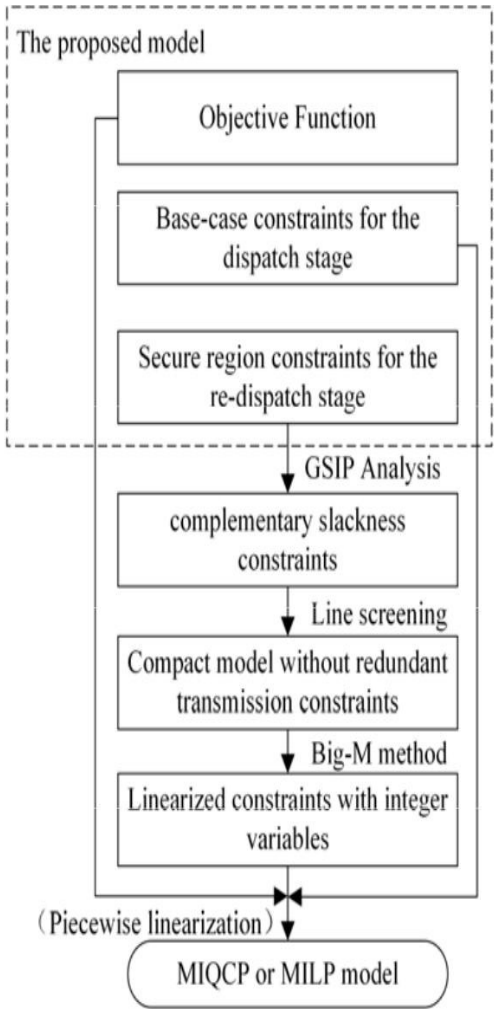

Fig.2 Procedure to formulate and solve the proposed model

VI. Case Studies

A. Case Study on IEEE-RTS78

The first case study is carried out on the modified IEEE-RTS78 [20]-[21]. The 300MW hydro generation is replaced by two wind farms located at Buses 7 and 23. The initial power range of wind farms are provided by the probabilistic or interval-based wind power forecast. Here the power range is assumed as that in Table I, where 20% variations in wind power are considered. The allowable adjustment duration T_a is set to be 1 minute. It is assumed that nuclear units will not be re-dispatched. The total grid load is 2,850 MW and bus loads are calculated by the ratio stated in
[20]. Because the thermal generation cost in IEEE-RTS is within 20-25$/MWh, the coefficients c_w and c_l are set at 20$/MWh and 1000$/MWh, respectively. The proposed model is solved by CPLEX in GAMS [22] on a computer with an Intel Core i7 3.60GHz CPU and 8 GB of memory. The economic power generation scheme and the secure region for wind power are obtained by solving the proposed model. The cost and the secure region are shown in Table II and Fig. 3, respectively.

TABLE I
POWER RANGE OF WIND FARMS (MW)

Wind Farm	Lower Bound $w_{wi,\min}$	Upper Bound $w_{wi,\max}$
#1	95.25	142.87
#2	190.50	285.74

TABLE II
COST OF GENERATION ($)

Index	Cost
Fuel	34456.09
Wind Spillage	81.09
Load Curtailment	51.80
Total	34588.98

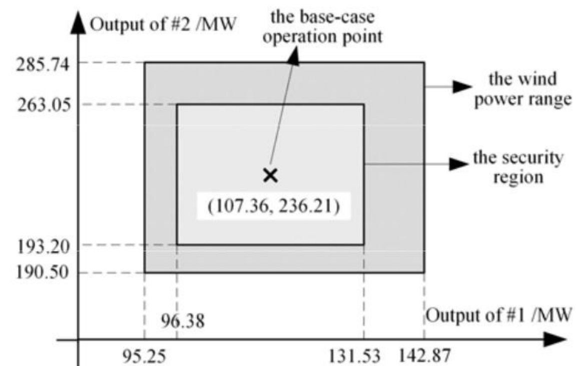

Fig.3 Secure region of variable wind power (T_a=1 min)

The base-case operation point of wind farms is chosen as (107.36MW, 236.21MW) and the uncertainty within the secure region is managed by a proper generation re-dispatch. However, the limitations on T_a and flexible resources could result in wind spillage and load curtailment, which are signified by the dispatch cost and secure region boundaries. The calculation time is 0.344s.

Here a normal distribution truncated at ±3 of the forecasted wind power is also considered, where and are the expectation and the standard deviation respectively. The results are presented in Tables III and IV. Compared with the uniform distribution results, the secure region for Wind Farm #1 becomes smaller while that for #2 does not change much, and the overall operating region for wind power is reduced. However, the total cost is smaller which makes the proposed method more significant with the use of uniformly distributed wind power. It is because higher wind power capacity (larger than) has a lower probability under the normal distribution. So the power system operator tends to disregard the low-probability wind power generation to control the cost of the base-case operation or avoid any load curtailments.

TABLE III
COST OF GENERATION SCHEME USING A NORMAL DISTRIBUTION ($)

Index	Cost
Fuel	34541.43
Wind Spillage	28.86
Load Curtailment	0
Total	34570.29

TABLE IV
SECURE REGION OF WIND FARMS USING A NORMAL DISTRIBUTION (MW)

Wind Farm	Lower Bound $rw_{wi,\min}$	Upper Bound $rw_{wi,\max}$
#1	95.25	127.31
#2	190.50	263.43

B. Impact of Flexible Resource

T_a is set to be 1 min, 2 min and 5 min, respectively to analyze the impact of flexible resources. The scale of flexible resource increases with the extension of duration for allowable adjustments. Here the size of secure region is defined for the ease of comparison.

$$s_{wi} \quad rw_{wi,\max} \quad rw_{wi,\min} \tag{42}$$

The secure region size is compared in Table V. As shown, the size of the secure region becomes larger with a larger T_a. When more flexible resources are provided, the re-dispatch is carried out in a larger feasible region with a larger wind power variability. However, a larger T_a also indicates the longer time period for restoring a secure state in which the grid will be at risk. In operation practice, a proper T_a is chosen according to the reliability requirements.

TABLE V
COMPARISON OF SECURE REGIONS AS A FUNCTION OF T_a (MW)

T_a	Secure Region of Wind Farm #1	Secure Region of Wind Farm #2
1 min	35.15	69.86
2 min	46.67	92.93
5 min	47.44	94.42

Table VI shows the base-case operation points of the wind farms which are shifted towards the upper bound of the secure region. This is because the operation security can be guaranteed by utilizing flexible resources and proper generation re-dispatch even for a small wind power output. Table VII shows that the total operation cost, especially the fuel cost, has decreased dramatically.

TABLE VI
COMPARISON OF BASE-CASE OPERATIONS AS A FUNCTION OF T_A (MW)

T_a	Base-Case Output of Wind Farm #1	Base-Case Output of Wind Farm #2
1 min	107.36	236.21
2 min	117.56	277.54
5 min	142.87	285.74

TABLE VII
COST COMPARISON AS A FUNCTION OF T_A ($)

T_a	Fuel	Wind Spillage	Load Curtailment	Total
1 min	34456.09	81.09	51.80	34588.98
2 min	33591.56	0	35.04	33626.60
5 min	32612.15	0	4.02	32616.17

C. *Impact of Transmission Capacity*

The transmission capacity in IEEE-RTS is decreased at 10% increments in order to analyze its impact on generation dispatch and the size of the wind power secure region. It is considered that the wind power secure region will be narrowed if the transmission capacity is decreased. This condition is more apparent when the base-case generation scheme is fixed. However, Table VIII shows that in the transmission capacity interval [0.5,1], the change in the secure region is rather minimal. This is because, as wind power is dispatched, there are conventional generators with enough flexibility which are located at Buses 7 and 23.

TABLE VIII
SECURE REGIONS AS A FUNCTION OF TRANSMISSION CAPACITY (MW)

Transmission Capacity	Secure Region of Wind Farm #1	Secure Region of Wind Farm #2
40%	Infeasible	Infeasible
50%	[96.38,130.86]	[193.23,263.06]
60%	[96.36, 131.53]	[193.22, 263.06]
70%	[96.37, 131.53]	[193.21, 263.05]
80%	[96.37, 131.53]	[193.21, 263.05]
90%	[96.38, 131.53]	[193.20, 263.05]
1	[96.38, 131.53]	[193.20, 263.05]

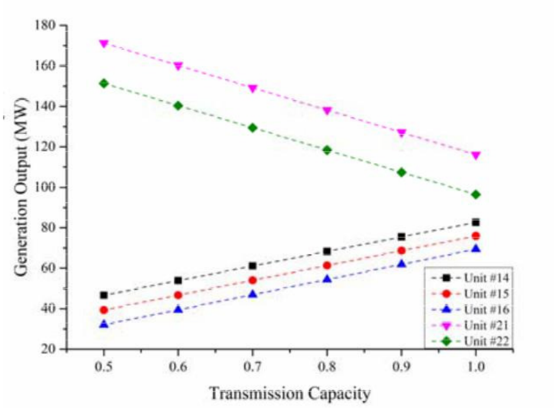

Fig. 4 Generation dispatch for different transmission capacity

As we optimize the base-case operation scheme and the security region simultaneously in this paper, the base-case plan is properly adjusted and enough transmission capacity is spared for managing the wind power variability. Accordingly, the use of available transmission capacity for integrating the wind power capacity is also verified in Fig. 4 by applying the optimal economic power generation. Here, the generation unit dispatch is increased monotonically to adapt to a lower transmission capacity. Correspondingly, Table IX shows that the dispatch cost, especially the fuel cost, increases as we lower the transmission capacity. In this interval, the transmission capacity would mainly have an impact on the base-case economic generation schedule while the secure region for wind farms is rather unchanged.

Table X captures the solution details in the transmission capacity interval [0.4, 0.5]. In this case, the secure wind power region will shrink, as we lower the transmission capacity available for the wind power dispatch, until the economic dispatch problem gets to be infeasible. The secure region for the power system is also influenced by the location of wind farms. The results shown in Table XI indicate that when wind farms are located at Buses 4 and 16, the secure regions in the interval [0.6, 1] are barely influenced by the transmission capacity. In [0.45,0.6], the secure region for the Wind Farm #1 increases while that for the Wind Farm #2 decreases. The secure region for both farms will be smaller as we lower the transmission capacity is to be below 42%. However, secure regions demonstrate uneven patterns as we lower the transmission capacity in power systems.

TABLE IX
COST COMPARISON USING THE ARO METHOD ($)

Transmission Capacity	Fuel	Wind Spillage	Load Curtailment	Total
40%	Infeasible	infeasible	infeasible	infeasible
50%	34998.60	83.56	52.64	35134.80
60%	34884.02	81.07	52.02	35017.11
70%	34772.19	81.07	51.96	34905.23
80%	34663.60	81.08	51.91	34796.59
90%	34558.23	81.08	51.86	34691.17
1	34456.09	81.09	51.80	34588.98

TABLE X
SECURE REGIONS AS A FUNCTION OF TRANSMISSION CAPACITY (MW)

Transmission Capacity	Secure Region of Wind Farm #1	Secure Region of Wind Farm #2
47%	infeasible	infeasible
48%	[96.49, 124.81]	[193.79, 255.22]
49%	[96.43, 128.01]	[193.38, 258.32]

TABLE XI
SECURE REGIONS AS A FUNCTION OF TRANSMISSION CAPACITY (MW)

Transmission Capacity	Secure Region of Wind Farm #1 (Bus 4)	Secure Region of Wind Farm #2 (Bus 16)
42%	[104.91,142.87]	[192.30,212.81]
45%	[96.41,141.28]	[192.80,224.09]
50%	[96.40,141.31]	[192.80,226.94]
60%	[96.60, 131.60]	[193.20, 263.20]
80%	[96.59, 131.59]	[193.18, 263.18]
1	[96.59, 131.59]	[193.18, 263.18]

In general, the influence of available transmission capacity on secure region will depend on transmission line and wind farm locations. However, if the available transmission capacity is sufficiently large, a proper secure region can be maintained by the optimal economic dispatch of power generation. In comparison, wind power integration is significantly influenced by limitations on operation cost and generation flexibility. Accordingly, the proposed co -optimization approach can fully exploit the potentials offered by the transmission capacity for enhancing the wind power integration.

D. Comparison of Methods

First, the proposed model is compared with the conventional economic dispatch solution, in which the secure region cost and physical constraints are not considered. The base-case wind power output is set at its expected value. Table XII shows that although the fuel cost is lower in this case, the total cost is higher which corresponds to a higher wind spillage and load curtailment cost. The larger cost for secure region implies a smaller secure region. This point is also reflected in the secure region comparison presented in Fig. 5. In the conventional economic dispatch solution, the secure region for wind power is calculated by minimizing the secure region cost based on the operation plan determined by the optimal economic dispatch. The corresponding secure region would be much smaller than that of the proposed model. Furthermore, in the conventional economic dispatch calculation, the system flexibility is often sacrificed as we minimize the generation fuel cost without considering the secure region constraints and cost. In contrast, the proposed model offers a better tradeoff of the power system operation cost and security.

TABLE XII
COMPARISON WITH CONVENTIONAL ECONOMIC DISPATCH ($)

Index	Proposed Method	Conventional Economic Dispatch
Fuel	34456.09	33948.55
Wind Spillage	81.09	117.74
Load Curtailment	51.80	6008.67
Total	34588.98	41054.96

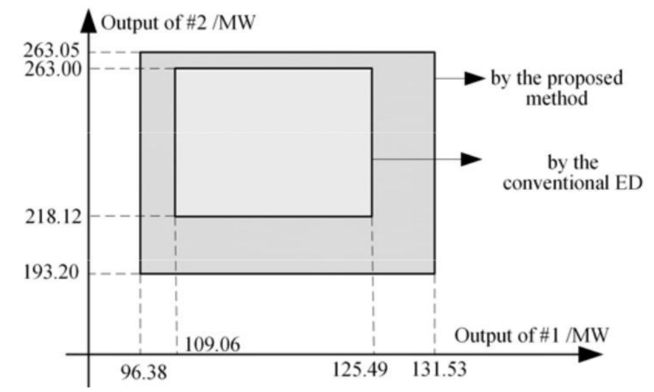

Fig. 5 Secure region comparison using the conventional economic dispatch

We discussed earlier that, when $rw_{wi,\min}$ and $rw_{wi,\max}$ are fixed as $w_{wi,\min}$ and $w_{wi,\max}$ respectively, the proposed model is reduced to ARO in which neither the wind spillage nor the load curtailment is allowed. In Table XIII, the proposed method is compared with the ARO method in which the proposed method without any potential for load curtailment is also considered. As shown, there will be no solutions for ARO when the flexible generation resource is limited, while the other two methods can provide feasible generation schemes (load curtailment) via a proper wind spillage.

When the flexible generation resource is sufficiently large, the proposed method can offer the same generation plan as that in ARO without considering any load curtailments. In fact, the same solution can be obtained by the proposed method if the coefficient c_w is large enough. Generally, the cost obtained by the proposed method is always the lowest. It is safe to indicate that the proposed method is an extension of ARO which is quite effective when the wind power variations are significant or the power grid flexibility is limited.

TABLE XIII
COST COMPARISON USING THE ARO METHOD ($)

T_a	Proposed	Proposed (no load curtailment)	ARO
1 min	34588.98	34641.821	Infeasible
5min	33626.60	33661.64	33661.64
7 min	32616.17	32620.21	32620.21

The method in [16] is also analyzed, which considers a two-stage economic dispatch solution. However, identical AGC participation factors are adopted in [16], for several variations of power at the re-dispatch stage, which are in line with considering optimal participation factors in [9]. The approach in [9] is rather inflexible which can reduce the secure region. In contrast, the proposed method in this paper considers a fully adaptive re-dispatch strategy for the wind power variability. In Table XIV and Fig. 6, the secure region obtained by the proposed method is larger and the operation cost is less than that obtained by the method presented in [16]. These results are consistent with those in [9] where the given base-case operation point is considered. The proposed method is more efficient in obtaining a secure and economic generation schedule plan for power systems.

TABLE XIV
COST COMPARISON USING THE METHOD IN [16] ($)

Index	Proposed Method	Method in [16]
Fuel	34456.09	35513.24
Wind Spillage	81.09	642.29
Load Curtailment	51.80	90.69
Total	34588.98	36246.22

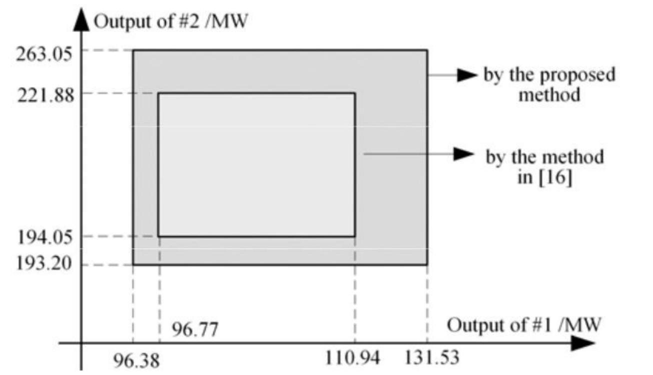

Fig. 6 Secure region comparison using the method given in [16]

E. Case Study on IEEE-119

The case study is also carried out on the modified IEEE-119[24], in which three wind farms are added at Buses 10, 62 and 87, respectively. The original power range of the added units is the same as that of Wind Farm #2 in the modified IEEE-RTS. The corresponding cost is shown in Table XV while the base-case operation point and secure region of wind power is presented in Table XVI. There are 54 generators and 186 branches in the modified problem.

The calculation times for different models are shown in Table XVII in which the calculation efficiency is greatly improved to an acceptable level via the line screening and linearization method. In IEEE-119, there are (186×2－45 = 327) redundant transmission capacity constraints that can be detected and removed to formulate the proposed compact model. The time consumed for the line-screening process is 0.036s. For larger systems, a parallel multi-area solution method can be considered.

Tables XVIII and XIX show the impact of flexible resources and transmission capacity, respectively using the proposed method for the modified IEEE-119system. These results are consistent with those in the IEEE-RTS case. The changing patterns of secure wind power regions can be observed in Table XIX for various wind farms and transmission capacity intervals.

TABLE XV
COST OF GENERATION IN IEEE-119 ($)

Index	Cost
Fuel	57963.81
Wind Spillage	851.89
Load Curtailment	103.34
Total	58919.04

TABLE XVI
BASE-CASE OPERATION POINT AND SECURITY REGION (MW)

Wind Farms	Base-Case	Secure Region
#1	219.15	[193.07, 243.85]
#2	227.76	[193.07, 243.81]
#3	198.17	[193.07, 217.92]

TABLE XVII
CALCULATION TIME OF COMPARATIVE MODELS (S)

Model	Calculation time
Original MIQP Model	42.719
Compact MIQP Model	2.907
Linearized Compact Model	0.453

TABLE XVIII
SECURE REGION AS A FUNCTION OF T_A IN IEEE-119(MW)

T_a	Wind Farm #1	Wind Farm #2	Wind Farm #3
1 min	60.78	60.74	24.85
4 min	87.23	89.36	61.08
9 min	91.97	91.97	91.97

TABLE XIX
SECURE REGIONS AS A FUNCTION OF TRANSMISSION CAPACITY (MW)

Transmission Capacity	Wind Farm #1	Wind Farm #2	Wind Farm #3
68%	Infeasible	Infeasible	Infeasible
69%	[192.72, 245.00]	[192.71, 263.14]	[192.41, 195.00]
88%	[192.84, 246.22]	[192.83, 257.28]	[192.53, 200.00]
95%	[193.03, 239.57]	[193.03, 246.94]	[193.00, 217.86]

VII. CONCLUSIONS

A novel economic dispatch model is proposed in this paper for managing the wind power variability. In the two-stage model, both the base-case generation scheme and the secure re-dispatch region for wind power are considered. The proposed method is deemed as an extension of the existing ARO method, in which variable secure regions rather than the predefined uncertainty sets are considered. The proposed model is formulated as a GSIP problem and the corresponding algorithm is introduced. The case studies on the modified IEEE-RTS 1979 and IEEE-119 have illustrated the effectiveness of the proposed model. The proposed method offers a better trade-off between operation cost and security in which a feasible operation plan and the corresponding secure boundaries of wind power are obtained. In addition, according to the sensitivity analyses, the corresponding size of secure regions depends on the volume of grid flexible resources and the transmission capacity. And the influence of transmission capacity is related to the location of wind farms. The authors will consider in their future studies the application in unit commitment of the proposed model.

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