

Security-constrained Economic Dispatch of Wind Power Integrated Power System based on Interval Optimization

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Abstract: The high penetration of wind power brings in new challenges for power system secure operation. As forecast error of wind power exists, system economic dispatch model needs to be enhanced to accommodate such uncertainty. Based on interval optimization theory, wind power and load uncertainties are described with intervals and turned into a security-constraint economic dispatch (SCED) model. The actual economic dispatch is set as the midpoint of the upper and lower bound value. Simulations on an IEEE 39-bus 10-generators system verified the presented linear interval optimization model.

Introduction

Renewable energy, especially wind power, is an effective way to reduce fossil fuel consumptions and environmental problems. Wind power is used in system to save the cost of energy. Intermittence and randomness are the main characteristics of wind power, which affects power system in many aspects such as voltage stability, load regulation and economic dispatch, raising the uncertainty level of power system.

SCED is a conventional scheduling problem to dispatch generation resources to supply the demand, subject to generation and transmission constraints. Fundamental work on SCED with wind power has been carried out. From statistical analysis, wind power forecast error is assumed to be following a Gaussian distribution with modest accuracy or a Beta distribution with higher accuracy by depicting its fat-tail effect [1]. The probability distribution functions created above are the basis of both unit commitment and economic dispatch models, either deterministic or probabilistic [2-4].

Although modern generation-control technologies are able to compensate for the fluctuations of demand, high-penetration wind power has a generally wider range of prediction error. Once wind power over-generates or under-generates (especially the latter one), excessive or insufficient power would cause an imbalance, imposing risks on system operation.

Interval optimization method is a way to address stochastic optimization problems [5-7]. Interval optimization does not need an approximated distribution function. Instead, intervals with upper and lower limits are used to bind the uncertainty. Interval optimization has been used in many areas, such as linear system analysis and power flow calculation [8].

The contribution of this paper can be summarized as proposed a SCED dispatch model with intervals and a decomposition method for solution.

Theory of Interval Optimization

Interval linear programming model has a general formulation, shown as

$$\max f^{\pm} = \sum_{j=1}^n c_j^{\pm} x_j \quad (1)$$

$$s.t. \quad a_{ij}^{\pm} x_j \leq b_i^{\pm} \quad (2)$$

$$x_j \geq 0 \quad (3)$$

where $c_j^\pm = [c_j^-, c_j^+]$; $a_{ij}^\pm = [a_{ij}^-, a_{ij}^+]$; $b_i^\pm = [b_i^-, b_i^+]$; $x_j \in \{R^\pm\}$; $\forall i = 1, 2, \dots, m, \forall j = 1, 2, \dots, n$

Theorem: Optimal solution calculated from (1) is a bounded interval, i.e. $f^\pm \in [f^-, f^+]$ where

$$f^- = \sum_{i=1}^n c_j^- x_j, f^+ = \sum_{i=1}^n c_j^+ x_j \quad (4)$$

Define f^- and f^+ as the best optimal solution and the worst optimal solution of the model, respectively. In the subsequent sections, economic dispatch model will be given accordingly as an interval set by the best and the worst optimal solutions.

SCED Model Formulation

SCED is a dispatch program which computes the generation output of online units. The objective of SCED maximizes social welfare. The security-constrained economic dispatch model with interval formulation is given in (5)-(11). Variables with the superscript ' \pm ' are the interval made up of two corresponding variables, representing the upper bound (or the superscript '+') and the lower bound (or the superscript '-').

$$\min \sum_{t=1}^T \left[\sum_{i=1}^N (a_i P_i^2(t) + b_i P_i(t) + c_i) \right] \quad (5)$$

$$s.t. \sum_{i=1}^N P_i(t) + P_w^\pm(t) = P_d^\pm(t) \quad \forall t \in T \quad (6)$$

$$P_w^\pm(t) = [P_f(t) - (1 - c_w) P_f(t), P_f(t) + (1 - c_w) P_f(t)] = [c_w P_f(t), (2 - c_w) P_f(t)] \quad (7)$$

$$\sum_{i=1}^N r_i(t) \geq p_r(t); \quad (8)$$

$$\underline{P}_i(t) \leq P_i(t) + r_i(t) \leq \overline{P}_i(t) \quad \forall t \in T; \quad (9)$$

$$-Sp_i(t) \leq P_i(t) - P_i(t-1) \leq Su_i(t) \quad \forall t \in T \quad (10)$$

$$\underline{P}_{ij}(t) \leq \sum_{k \in N_G} G_{ij-k1} P_{g,k1}(t) + \sum_{k \in N_W} G_{ij-k2} P_{g,k2}^\pm(t) - \sum_{k \in N_L} G_{ij-k3} P_{g,k3}(t) \leq \overline{P}_{ij}(t) \quad (11)$$

Where a_i, b_i, c_i are the quadratic cost function coefficients of unit i ; T the number of scheduled time slots; N the number of units; $P_i(t)$ the active power in time t generated from unit i . e_{ij}, f_{ij} are the piece-wise linear cost coefficients of the j th segment; L the number of segments. $P_i(t)$ is the output power of the generator i at time t ; $P_d(t)$ the total load at time t ; $P_w^\pm(t)$ the upper and lower bound of wind power at time t . $P_f(t)$ is the point-forecast value of wind power at time- t , c_w as the confidence coefficient, the interval of wind power output is formed as (7) by moving the forecasted wind power up and down $(1 - p_w)$ times the forecasted value. $r_i(t)$ is the spinning reserve available from unit i in time t ; $P_r(t)$ the spinning reserve requirement of the system at time t . $Sp_i(t)$ and $Su_i(t)$ are the hourly ramp down and up rate, respectively. N_G is the generator node set; N_W the wind farm nodes set; N_L the load nodes set. For the Generation Shift Factors (GSF) G_{ij-k} , whose subscript $ij-k$ means the flow shifted from bus k to branch $i-j$.

Decomposition and Solution Methodology

For notation brevity, we use simple notations to represent the objective and constraints of an interval linear programming (ILP) model. The formulation in section 3 can be represented as

$$\min f^\pm = c x_j^\pm, c \in \{R\}^{l \times n} \quad (13)$$

$$s.t. \quad Ax_j^\pm \leq B^\pm, A \in R^{m \times n}, B^\pm \in \{R^\pm\}^{m \times 1} \quad (14)$$

$$Kx_j^\pm = D^\pm, K \in R^{l \times n}, D^\pm \in \{R^\pm\}^{l \times 1} \quad (15)$$

$$x_j^\pm \geq 0 \quad (16)$$

where f is the objective function, x_j^\pm the interval decision variables, A, K, B^\pm and D^\pm the coefficients of the corresponding constraints.

It is observable that interval coefficients only exist on the right-hand side of the inequalities, i.e., only in B^\pm and D^\pm . This means that this model contains no multiplication between interval variables. Note that interval multiplication causes difficulty by extending the range of interval. In the scope of this paper, only the decomposition and solution of a general interval optimization model without multiplication is considered.

Objective Function Decomposition The optimal solution of the objective function (13) is an interval given by the optimal decision variable interval. Define two variable sets for the lower and upper bound of the optimal solutions.

$$\underline{Z} = \text{Min} \{Z \mid Z \in \Omega\} \quad (17)$$

$$\bar{Z} = \text{Max} \{Z \mid Z \in \Omega\} \quad (18)$$

Since it's a minimization problem, the lower bound has the minimum optimal value thus is termed the best optimal value; the upper bound has the maximum optimal value is termed the worst optimal. Linear characteristics guarantee the interval $[\underline{Z}, \bar{Z}]$ to be the optimal solution range.

For an arbitrary $x_j \in [x_j^-, x_j^+]$, the objective function has a characteristic function $Z^* = \sum_{j=1}^n cx_j^*$ that holds

$$\sum_{j=1}^n cx_j^* \leq (\geq) \sum_{j=1}^n cx_j. \quad (19)$$

which shows that for an arbitrary x_j , value of the objective is no less than or no more than the characteristic function. Such characteristic objective function is called the worst / best objective function of this ILP.

Using the characteristic objective function and the theorem proven in section 2, objective function is decomposed as:

$$\text{Best optimal} \quad \underline{Z} = \sum_{j=1}^n c_j x_j^- \quad (20)$$

$$\text{Worst optimal} \quad \bar{Z} = \sum_{j=1}^n c_j x_j^+ \quad (21)$$

Our goal is to solve the bounds of decision variables x^+ and x^- for each objective to find out the optimal interval.

Solving Optimal Interval of ILP The interval optimization model is decomposed into two sub-models, given the name of optimistic and pessimistic models, respectively. The models are summarized as follows:

Sub-model 1. Optimistic model

$$\text{Objective:} \quad \min f^- = \sum_{j=1}^n c_j x_j \quad (22)$$

s.t.

$$\sum_{j=1}^n a_{ij}x_j \geq b_i^- \quad (23)$$

$$\sum_{j=1}^n k_{ij}x_j \leq d_i^+ \quad \text{and} \quad \sum_{j=1}^n k_{ij}x_j \geq d_i^- \quad (24)$$

$$x_j \geq 0 \quad \forall j \quad (25)$$

Sub-model 2. Pessimistic Model

Objective:
$$\min \quad f^+ = \sum_{j=1}^n c_j x_j \quad (26)$$

s.t.
$$\sum_{j=1}^n a_{ij}x_j \geq b_i^+ \quad (27)$$

$$\sum_{j=1}^n k_{ij}x_j = d_i^+ \quad (28)$$

$$x_j \geq 0 \quad \forall j \quad (29)$$

The last step of model decomposition is to put together the solutions and optimal result. The lower bound of sub-model (1) and the upper bound of sub-model (2) are merged into a solution interval, Result of objective function is also an interval where $f^\pm = [f^-, f^+]$.

Case Study

The IEEE 39-bus10-generator system is used for simulation. Generator and system parameters are available in the Appendix.

Wind power data is set under 40% penetration rate, i.e. 600 MW rated wind power versus 1500 MW peak load. The wind power forecast Fig. 1 shows a reverse peak effect in terms of load curve. In order to test the effectiveness of the proposed method, wind power is assumed to be within the 80% confidence interval with the Beta distributed forecast error model [1].

To verify the model with basic constraints, the lossless model is investigated. This lossless model neglects the transmission active power loss and assumes the total generation output is exactly the same as the load level.

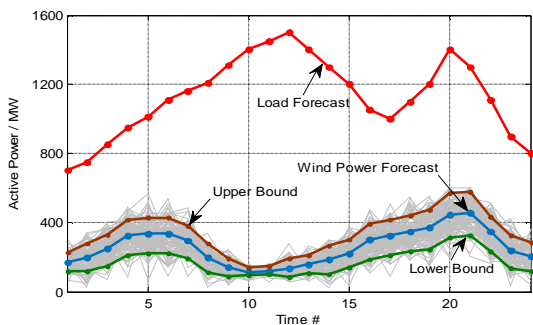


Fig. 1. Result of load forecast in 24 hours

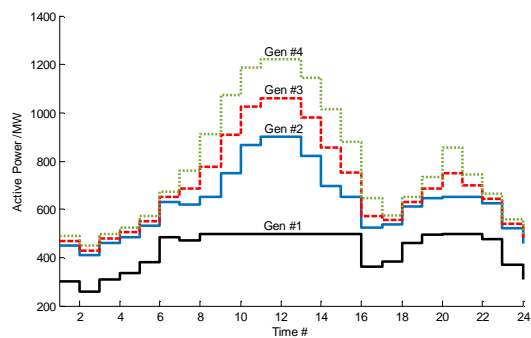


Fig.2. Economic dispatch result of Gen #1 to Gen #4 with accurate forecast

The dispatch result based on fixed load and accurate wind power forecast is first computed as a control group. Result shows that output of Gen #1, #2, #3 and #4 are actively changing in accordance with load curve shape in Fig.2.

Line flow through the transmission lines are shown in Fig. 3 with all lines in its limit. This is an indication that the system is tolerable to wind power with as high as 40% penetration with an accurate forecast.

Then, run the security constrained economic dispatch with wind power at the 80 percent confidence zone and load fluctuation within 5 percent. Result shows that unit dispatch remains

unchanged for unit #7 to unit #10, which means that those small capacity, quick response and high cost units should be continuously operating at its minimum output.

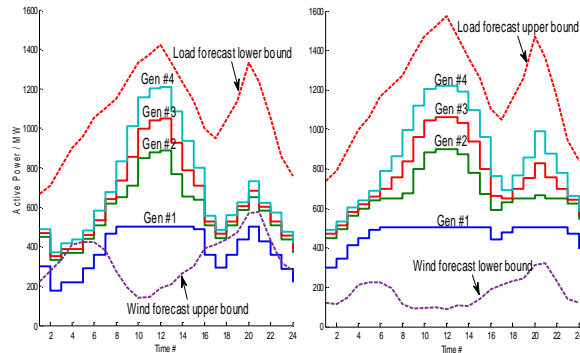
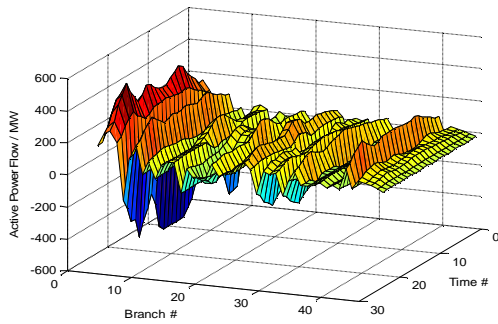


Fig. 3. Optimal power flow with accurate forecast uncertainty Fig. 4. Economic dispatch of Gen #1 to Gen #4

The economic dispatch of Gen #1 to Gen #4 is shown in Fig. 4. Power flow in the system is also changing as wind power and load varies. Shown in Fig. 5 is the maximum change of power flow for all the 46 lines across the whole time span.

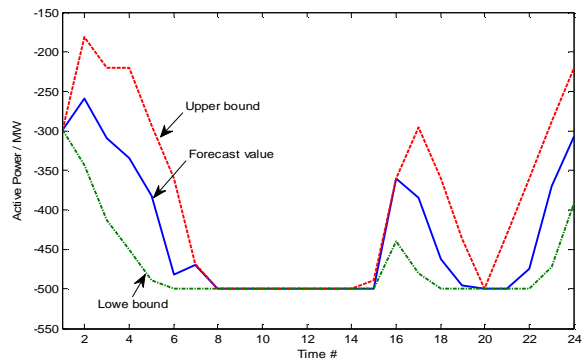
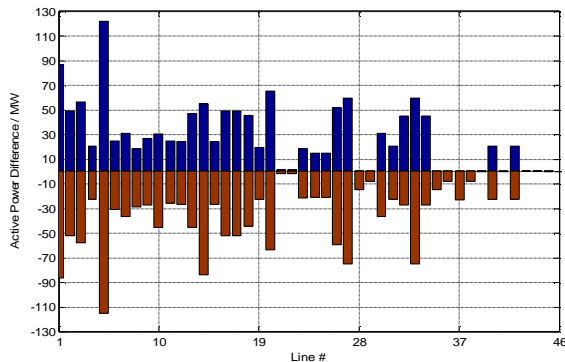


Fig. 5. Line flow change corresponding to the upper and lower, comparing with the accurate forecast scenario

Fig. 6. Flow on Line #5 with 80% bound confidence

The inter-temporal power flow on line #5, which has the maximum difference between the upper bound condition and the lower bound condition, is shown in Fig. 6. Line #5 power flow follows the shape of the pure load (load level minus wind forecast) and reaches the line flow limit during load peak hours. This also verifies the linear decomposition method proposed in this paper to optimize the upper and lower bound with LP and MIP, respectively.

Conclusion

This paper established interval optimization model considering wind power uncertainty based on SCED, and discussed the application of interval optimization method.

In this paper, the interval optimization method is used to deal with wind power uncertainty problem of power system, which overcomes the shortcoming of prior probability distribution of uncertain variables or fuzzy membership function estimation in traditional methods. With interval optimization method, upper and lower bounds can be acquired only through a small amount of information, which a new method to solve the uncertainty problem in power system.

The IEEE 39-bus 10-generator system is used in this paper. Simulation results verified the validity of the model. The effect of wind power prediction accuracy on optimization model is also studied, which provides a novel method for optimal scheduling of large scale wind power integrated systems.

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Appendix

App.Table 1. Modified IEEE 39-bus generator parameter

	unit1	unit2	unit3	unit 4	unit 5	unit 6	unit 7	unit 8	unit 9	unit 10
P_{\max}	500	400	160	160	162	80	85	55	55	55
P_{\min}	150	150	20	20	25	20	25	10	10	10
a	1000	970	700	680	560	370	480	660	650	670
b	16.19	17.21	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c	0.0004 8	0.0003 1	0.002	0.0021 1	0.0039 8	0.0071 2	0.0007 9	0.0041 3	0.0022 2	0.0017 3
Sp	2.6	2.6	1	1	1.2	0.8	0.9	0.5	0.4	0.3
Su	2.6	2.6	1	1	1.2	0.8	0.9	0.5	0.4	0.3