ling techniques to study, which is of great significance to the integration of renewable energy, and the overall proportion of wind energy in the terminal energy structure has increased. China's installed wind power capacity has reached about 20 times that in 2016. Although large-scale wind power is installed in China, the proportion of wind power spillage has increased. This poses a severe threat to the safe and stable operation of high-penetration renewable energy power systems. From the perspective of power system operation and balancing high-penetration renewable energy, the problem of wind energy accommodation is proposed based on two indicators: loss of production and dispatchability, which is obtained by solving an optimization problem considering the factors of generator, transmission lines, and load demand in the form of economic dispatch and security.

Reference
[1] Evaluation of Wind Energy Accommodation
[2] Robust optimization problem with integer linear programming
[3] Economic and environmental benefits of renewable energy accommodation can improve the utilization rate of renewable energy generation.
[4] Large renewable energy accommodation is proposed based on two indicators: loss of production and dispatchability. Strong duality theory and envelope of wind power have been used to formulate the problem into a master problem and subproblem alternately. For the subproblem with constraints of the form of economic dispatch and security, the intractable optimization problem is transformed into a robust optimization problem with strong duality theory. Based on the benders algorithm, the envelope of wind power has been used to solve the master problem and subproblem alternately. Strong duality theory and envelope of wind power have been used to formulate the problem into a robust optimization problem with strong duality theory. Based on the benders algorithm, the envelope of wind power has been used to solve the master problem and subproblem alternately.

This research was funded by the Natural Science Foundation of China, the Department of Electrical Engineering, Shanghai 200093, China, and the Department of Control Science and Engineering, Shanghai 200093, China.
The solution methodologies proposed in Section III of this paper are based on the theory of electric power system dispatch production power of TG in real time stage. From the dispatch scheme and real time economic dispatching into the evaluation model, an assessment dispatchability model, which is the sequential production of TG in day time dispatch schemes, indicates the range of deviation of the system can accommodate. For the assessment of wind power accommodation, we first analyze the difference between flexibility of renewable energy and photovoltaic. Although a large number of studies have analyzed the possibility of load demand shedding and energy leakage with wind energy production [14], the authors introduce the evaluation framework of wind energy accommodation is that the former is the natural characteristic of power system dispatch, while the latter emphasizes the ability of accommodate renewable energy and photovoltaic. The difference between flexibility of renewable energy and photovoltaic is described in Section II. The framework provides a deterministic evaluation framework, which takes into account the problem of uncertainty of wind production and wind energy accommodation assessment is that the former is a real time economic operation of power system to deal with the uncertainty of wind production, while the latter emphasizes the ability of accommodate renewable energy and photovoltaic.

The numerical studies are conducted and the capability of wind power accommodation is analyzed in Section V based on the theory of electric power system. According to the Dispatch model and considering safety indicator, the authors introduce the evaluation framework of wind energy accommodation, which is the sequential production solution of TG in day time economic dispatching into the evaluation model.

The authors propose a real time dispatching dispatch production power of TG in real time stage. From the dispatch scheme and real time economic dispatching, the authors use the concept of robust optimization technology to improve the level of dispatchability constraints. Assuming that the allowable adjustment time. The authors have analyzed the dispatch process of TG in day time, and this constraint needs to be satisfied in order to avoid load curtailment. The authors solve to obtain the largest operating ranges of each WT. We take a simple system example to illustrate the process of power system dispatch.

The authors provide theoretical support for the economic operation of power system dispatch and wind energy accommodation is analyzed in Section V based on the theory of electric power system. The authors propose a real time dispatching dispatch production power of TG in real time stage. From the dispatch scheme and real time economic dispatching, the authors use the concept of robust optimization technology to improve the level of dispatchability constraints. Assuming that the allowable adjustment time. The authors have analyzed the dispatch process of TG in day time, and this constraint needs to be satisfied in order to avoid load curtailment. The authors solve to obtain the largest operating ranges of each WT. We take a simple system example to illustrate the process of power system dispatch.
The assessment of power system dispatchability is affected by various factors. The power system dispatchability is proportional to the tolerable level of prediction error. This paper proposes an evaluation framework of power system dispatchability, wind energy spillage and load demand curtailment.

The existing research on wind accommodation is based on economic dispatch, which is obtained by solving the SCUC problem. The assessment of wind accommodation based on the theory of robust optimization technology. Third, the re-power system aims to determine the production plan of wind power system from the perspective of TG, while the latter evaluates the maximum energy balance. The wind energy accommodation based on the theory of robust optimization technology.

The assessment of wind accommodation can be used to reduce the impact of wind power on the system operation. As the wind power system is dispersed and the capacity is limited, the system dispatch ability is limited. This paper proposes a method to evaluate the wind power system dispatch ability, and the metric indicator is the wind energy accommodation based on the theory of robust optimization technology. The former evaluates the maximum dispatching stage. If the deviation is less than the predetermined operation state in the future, the energy balance can be accommodated. The latter evaluates the maximum dispatching stage. If the deviation is less than the predetermined operation state in the future, the energy balance can be accommodated. If the deviation is less than the predetermined operation state in the future, the energy balance can be accommodated.
The minimum and profiles are given in Fig. 4. The time of each calculation is optimal, and the regulation capacity of TG is abundant, which reduces the generation cost of the power system. When wind power decreases and the ramping capacity is set as 30%, and the operation characteristic of the TG has significant curtailment. Besides, when wind power decreases and the load demand increases (i.e., at 11:00), TG needs to contribute to the predicted power of wind energy can be obtained by searching the extreme points of feasible regions. The economic load dispatch is given in Fig. 3. The wind farms with an installed capacity of 95295, 8651100, 1100, and 4904574 $(h)$ and ramping capacity are set as 300, 260, 280, and 150 MW, respectively. The wind farms are integrated into the modified test system at nodes 3, 10, 14, 16, and 500. The economic load demand increases. The data in the Fig. 3 show that the TG has similar characteristics to the load, which makes the predicted power of wind energy can be obtained.

The regulation capacity of TG is abundant, which makes the power system can be operated as the bilinear optimization as the bilinear term can be rewritten as the tractable MILP problem.

After theoretical derivation, the sub problems are obtained that is the optimality cuts (30
= (1 ) , , ,
pp
= (1 ) , , ,
, 0, , 
, , ,
, , ,
= (1 ) ,
, 0, ,
, , ,
, , ,
(1 ) 0,
(1 ) 0,
0,
0.
w t w t w w t
w t w t w w t
w t w t w w t
w t w t w w t
p M v
p M v
p M v
p M v



All TG are involved in the daily dispatch. TG located on nodes 30, 33, 34, and 35 are always in the turned-on state, and the other units have start-up and shut-down actions. Due to the limitation of the ramping capacity of TG, the excessive prediction deviation of wind power will lead to wind energy curtailment and load shedding. Applying the framework to assess the largest wind power interval that the power system can accommodate, the results are given in Section V-B.

### B. Assessment of Wind Energy Accommodation

In this section, the output deviation range of all WT nodes is calculated through the solution strategy in Section IV, which is the envelope band of wind power accommodation. To verify the influence of wind energy leakage and load shedding on wind power envelope that electric power system can be accommodated, we designed the following four cases:

- Case 1 is the most conservative ($\beta_u = 0\%$ and $\beta_d = 0\%$);
- Case 2 is load shedding only ($\beta_u = 0\%$ and $\beta_d = 5\%$);
- Case 3 is wind power leakage only ($\beta_u = 5\%$ and $\beta_d = 0\%$);
- Case 4 is the most radical ($\beta_u = 5\%$ and $\beta_d = 5\%$).

The hourly allowable wind power deviation in different cases is given in Fig. 5.

The data in Fig. 5 shows that there are some time periods with allowable wind power deviation of 0 in all four cases. The results mean that the ability of power system to deal with wind power fluctuations is different in temporal. Wind power continuously ramping-up or ramping-down will cause wind power leakage and load shedding, which will greatly consume the dispatchability resources of power system. Besides, the mathematical statistics indexes are used to evaluate the allowable deviation of wind power in each period of four cases, and the results are given in Table II.

| Index                  | Case 1 | Case 2 | Case 3 | Case 4 |
|------------------------|--------|--------|--------|--------|
| Maximum Value          | 198    | 960    | 596    | 960    |
| Minimum Value          | 0      | 0      | 0      | 0      |
| Average Value          | 84     | 305    | 153    | 335    |
| Standard Deviation     | 64     | 307    | 157    | 307    |

Note that the maximum adjusted output of all TG within the response time is 246 MW. Therefore, there is wind spillage and load curtailment in Case 2, Case 3, and Case 4. As the load demand is far greater than the installed capacity of WT, the allowable wind power deviation of Case 2 is greater than Case 3. Both wind power leakage and load shedding are allowed in Case 4, which makes the maximum allowable wind power deviation. The envelope band is given in Fig. 6.

The envelope band in Fig. 6 has such properties: for the realization of arbitrary wind power within the envelope, the amount of wind leakage or load shedding in the re-dispatch stage is acceptable through correcting the pre-dispatch scheme. Once the prediction deviation of wind power exceeds...
the range of wind accommodation envelope, wind leakage or load shedding will run out of predetermined constraints. The envelope band is similar to a metric and can provide early warning information. Furthermore, the hourly wind leakage or load shedding in Case 4 are given in Fig 7(a) and Fig. 7(b).

The total amount of wind spillage and load curtailments are 1316 MWh and 6223 MWh, respectively. Wind spillage occurs in 2nd, 5th, 13th, 15th, and 23rd periods, while the amount of load curtailment is zero. Note that the amount of load curtailment is both zero in 4th, 9th, 11th, 17th, and 21st periods. Reasonable wind power leakage and load shedding can significantly improve the ability of the system to withstand net load fluctuations.

VI. CONCLUSIONS

Based on the pre-dispatch and re-dispatch theory, the dispatchability of the power system is introduced, and the evaluation framework of wind energy accommodation is proposed. The results of numerical studies show that:

1. It is feasible to counterweight the deviation of wind power by correcting the pre-dispatch scheme. The effect of this method is related to the dispatchability resource of the electric power system.
2. Allowing certain wind spillage and load curtailment can greatly improve the ability of the grid to cope with wind power deviation. The results show that the reasonable wind spillage or load curtailment is beneficial to power system scheduling operation.
3. The envelope band of wind power accommodation represents the maximum range of wind power deviation for the power system, which can provide warning information (wind curtailment or load shedding) for decision-makers.

The envelope of wind power accommodation is affected by the electric power system pre-dispatching scheme. Therefore, the problem of co-optimization of the pre-dispatch scheme and envelope band of wind energy accommodation is worthy of attention in the future work. Besides, the deployment of energy storage to improve the envelope band of wind power accommodation is concerned.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] T. S. L. V. Ayyarao, “Modified vector controlled DFIG wind energy system based on barrier function adaptive sliding mode control”, Prot. Cont. Mod. Power Syst., vol. 4, article No. 4, 2019. DOI:10.1186/S14661-019-0119-3.
[2] C. Jung, D. Schindler, and J. Laible “National and global wind resource assessment under six wind turbine installation scenarios”, Energy Convers. Manage., vol. 156, pp. 463–415, Jan. 2018. DOI: 10.1016/J.ENERCONMAN.2017.11.059.
[3] H. Saber, M. Moeini-Aghtaie, M. Ehsan, and M. Fotuhi-Firuzabad “A scenario-based planning framework for energy storage systems with the main goal of mitigating wind curtailment issue”, Int. J. Electr. Power Energy Syst., vol. 104, pp. 414–422, Jan. 2019. DOI: 10.1016/J.JEPEPS.2018.07.020.
[4] X. Gou, Q. Chen, K. Hu, H. Ma, L. Chen, X. Wang et al., “Optimal planning of capacities and distribution of electric heater and heat storage for reduction of wind power curtailment in power systems”, Energy, vol. 160, pp. 763–773, Oct. 2018. DOI: 10.1016/J.ENERGY.2018.07.027.
[5] L. Ye, C. Zhang, H. Xue, J. Li, P. Lu, and Y. Zhao, “Study of assessment on capability of wind power accommodation in regional power grids”, Renew. energy, vol. 133, pp. 647–662, Apr. 2019. DOI: 10.1016/J.RENENE.2018.10.042.
[6] E. Lannoye, D. Flynn, and M. O’Malley, “Evaluation of power system flexibility”, IEEE Trans. Power Syst., vol. 27, no. 2, pp. 922–931, 2013. DOI: 10.1109/TPWRS.2011.2177280.
[7] J. Zhao, T. Zheng, and E. Litvinov, “A unified framework for defining and measuring flexibility in power system”, IEEE Trans. Power Syst., vol. 31, no. 1, pp. 339–347, 2015. DOI: 10.1109/TPWRS.2015.2390038.
[8] B. Mohandes, M. S. E. Moursi, N. Hatziargyriou, and S. E. Khatib, “A review of power system flexibility with high penetration of renewables”, IEEE Trans. Power Syst., vol. 34, no. 3, pp. 2457–2460, 2019. DOI: 10.1109/TPWRS.2019.2897727.
[9] H. Nosair and F. Bourfard, “Flexibility envelopes for power system operational planning”, IEEE Trans. Sustain. Energy, vol. 6, no. 3, pp. 800–809, 2015. DOI: 10.1109/TSTE.2015.2410760.
[10] W. Wei, F. Liu, and S. Mei, “Real-time dispatchability of bulk power systems with volatile renewable generations”, IEEE Trans. Sustain. Energy, vol. 6, no. 3, pp. 738–747, 2015. DOI: 10.1109/TSTE.2015.2413903.
[11] M. Zhou, M. Wang, J. Li, and G. Li, “Multi-area generation-reserve joint dispatch approach considering wind power cross-regional accommodation”, CSEE.J. of Power and Energy Syst., vol. 3, no. 1, pp. 74–83, 2017. DOI: 10.17775/CSEEJPS.2017.0010.
[12] L. F. Ochoa and G. P. Harrison, “Minimizing energy losses: Optimal accommodation and smart operation of renewable distributed generation”, IEEE Trans. Power Syst., vol. 26, no. 1, pp. 198–205, 2011. DOI: 10.1109/TPWRS.2010.2049036.
[13] G. Li, G. Li, and M. Zhou, “Model and application of renewable energy accommodation capacity calculation considering utilization level of inter-provincial tie-line”, Prot. Cont. Mod. Power Syst., vol. 4, article No. 1, 2019. DOI: 10.1186/S41601-019-00115-7.
[14] J. Zhao, T. Zheng, and E. Litvinov, “Variable resource dispatch through Do-Not-Exceed limit”, IEEE Trans. Power Syst., vol. 30, no. 2, pp. 820–828, 2015. DOI: 10.1109/TPWRS.2014.2333637.
[15] Z. Li, F. Qiu, and J. Wang, “Data-driven real-time power dispatch for maximizing variable renewable generation”, Appl. Energy, vol. 170, pp. 304–313, May. 2016. DOI:10.1016/J.APENGERY.2016.02.125.
[16] Y. Ding, M. Xie, Q. Wu, and J. Östergaard, “Development of energy and reserve pre-dispatch and re-dispatch models for real-time price risk and reliability assessment”, IET Gener. Transmiss. Distrib., vol. 8, no. 7, pp. 1338–1345, 2014. DOI: 10.1049/IET-GTD.2013.0822.
[17] A. S. Xavier, F. Qiu, F. Wang, and P. R. Thimmapuram, “Transmission constraint filtering in large-scale security-constrained unit commitment”, IEEE Trans. Power Syst., vol. 34, no. 3, pp. 2457–2460, 2019. DOI: 10.1109/TPWRS.2019.2897620.
[18] K. Tian, W. Sun, C. Yang, D. Han, W. Zhang, and P. Xi, “Evaluation method of power system flexibility for renewable energy accommodation”, in Proc. of 8th Renewable Power Generation
Conference, Shanghai, 2019. DOI: 10.1049/cp.2019.0387.

[19] A. G. Nahapetyan, “Bilinear Programming”, in Encyclopedia of Optimization. Springer, Boston, MA, 2008.

[20] T. Ding, S. Liu, W. Yuan, Z. Bie, and B. Zeng, “A two-stage robust reactive power optimization considering uncertain wind power integration in active distribution networks”, IEEE Trans. Sustain. Energy, vol. 7, no. 1, pp. 301–311, 2016. DOI: 10.1109/TSTE.2015.2494587.

[21] L. Baringo and A. Baringo, “A stochastic adaptive robust optimization approach for the generation and transmission expansion planning”, IEEE Trans. Power Syst., vol. 33, no. 1, pp. 792–802, 2018. DOI: 10.1109/TPWRS.2017.2713486.

[22] R. Zimmerman, C. Murillo-Sánchez, and R. Thomas, “MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education”, IEEE Trans. Power Syst., vol. 26, no. 1, pp. 12–19, 2011. DOI: 10.1109/TPWRS.2010.2051168.