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An Optimal Generation Scheduling Approach Based on Linear Relaxation and Mixed Integer Programming

YUNKAI LEI[1], (Member, IEEE), FANG LIU[1], AO LI[1], YUNCHE SU[1], XINTING YANG[1], AND JIEHUI ZHENG[2], (Member, IEEE)

[1]State Grid Sichuan Economic Research Institute, Chengdu 610000, China
[2]School of Electric Power Engineering, South China University of Technology, Guangzhou 510640, China

Corresponding author: Jiehui Zheng (zhengjh@scut.edu.cn)

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ABSTRACT This paper proposes an optimal generation scheduling approach based on linear relaxation and mixed integer programming, which is used to solve the generation dispatch problem. The quadratic transmission loss constraint of each transmission line is converted into linear constraints by using the linear relaxation and mixed integer programming technique. Consequently, the original optimal generation scheduling problem is formulated as a quadratic programming or mixed integer quadratic programming problem that can be solved by commercial optimization solver. In order to improve the efficiency of algorithm, this paper further analyses the generation scheduling model and deletes the redundant variables and constraints. Three test systems, including IEEE 30-node system, IEEE 118-node system, and Polish 2746-node system, are employed to examine the effectiveness of the proposed method. The comparative results obtained by the proposed method, quadratically constrained quadratic programming method (QCQP), and solving constraint integer programs solver (SCIP) verify the effectiveness of the proposed method in solving the optimal generation scheduling problem.

INDEX TERMS Optimal generation scheduling, transmission losses, quadratic programming, mixed integer programming, linear relaxation, prosumer energy management.

I. INTRODUCTION

As a major energy consumer, the power industry's slight improvement in generation scheduling will have a significant impact on the national economy and social environment. The energy distribution in China has obvious regional characteristics [1]. High-voltage long-distance transmission plays an important role in the transmission structure, and transmission loss becomes a key factor of generation scheduling. On the other hand, one important direction of renewable energy utilization-power generation and grid connection, has a growing proportion in the traditional power system, which brings great challenges to optimal the generation scheduling problem [2]. The growing penetration of DERs has made it possible for traditional passive consumers to evolve into active prosumers. Compared with traditional consumers, prosumers are capable of managing their energy generation, storage and consumption simultaneously. In China, the centralized dispatching strategy is still the main dispatching method, when dispatching the generation plan, the dispatching department simply converts network losses into forecasted loads in a certain proportion, but lacks of accurate network loss model [3]. In order to determine an accurate generation scheduling plan, it is necessary to take network losses into account in the generation scheduling model [4], [5].

Many researches have been done on the generation scheduling of traditional power grids considering renewable energy generation and grid connection [6]–[11]. In this paper, the above problems will be classified and explained from two aspects: model and algorithm. In terms of generation scheduling optimization models, the DC optimal power flow model and the AC optimal power flow model are often used. (1) The first scheduling model is focus on reasonably arrange the power generation of different power plant generators on the premise of satisfied the load demand to achieve the effect of allocating electricity and saving energy and reducing emissions [7], [8], [10]. However, this model lacks consideration of the influence of network topology on

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the scheduling scheme. For this scheduling model, the commonly used optimization methods include equal increment rate criterion, dynamic programming, linear and quadratic programming methods [11]. (2) The DC optimal power flow model is a simple and efficient generation scheduling model [12], [13]. This model considers the transmission constraints of each line, but the model is based on a lossless network and lacks consideration of transmission loss constraints of each transmission line on the generation scheduling plan. Therefore, this scheduling plan often has a large deviation. (3) The AC optimal power flow model is a more comprehensive and widely used generation scheduling model [14], [15], which aims at minimizing total power generation cost, total coal consumption, or network loss, the constraints the transmission capacity and voltage amplitude of each line are taken into consideration. However, it is difficult to accurately predict the reactive load in the day-ahead scheduling of generation plan, which limits the application of the AC optimal power flow model to a certain extent [16]. Moreover, the model often needs to be solved by non-linear programming methods such as the interior point method which the efficiency and robustness still need to be strengthened.

In view of the influence of the network loss of renewable energy generation on the generation scheduling problem, [17] and [18] used the Kron formula to calculate the network loss, but this method can only roughly calculate the value of the network loss, and the transmission loss coefficient of Kron formula needs to be recalculated as the operating conditions of the system change. Reference [4] proposed a dynamic linear segment method to solve the problem of generation scheduling considering network loss. This method linearizes the transmission loss curve of each transmission line in a dynamic way until the mismatch satisfies the convergence conditions. Reference [5] relaxed the transmission line loss constraints with quadratic equality to the quadratic inequality constraints based on the relaxation technique. For the transmission line loss constraints that do not satisfied the equality constraints, the corresponding transmission line loss variables are dealt with by adding the terms of penalty. By employing of the terms of penalty, this method tends to minimize network loss, which changes the nature of the original problem [19].

With the proportion of renewable energy generation increasing, in order to effectively solve the generation scheduling problem considering network losses, this paper proposes an optimal generation scheduling approach based on linear relaxation and mixed integer programming. Three test systems, including IEEE 30-node system, IEEE 118-node system, and Polish 2746-node system, are employed to test the effectiveness of the proposed method. The comparative results obtained by the proposed method, quadratically constrained quadratic programming method (QCQP), and solving constraint integer programs solver (SCIP) verify the effectiveness of the proposed method in solving the optimal generation scheduling problem.

II. GENERAL FRAMEWORK

The real power leaving out of a node by using DC power flow can be shown as (1).

$$\begin{cases} P_{l_{ij}} = V_i^2 G_{ij} - V_i V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \\ P_{l_{ji}} = V_j^2 G_{ij} - V_j V_i \left(G_{ij} \cos\theta_{ji} + B_{ij} \sin\theta_{ji} \right) \end{cases} \tag{1}$$

where l_{ij} is the end bus i and j of a transmission line, V_i and V_j are voltage magnitudes of bus i and j while $\theta_{ij} = \theta_i - \theta_j$ and θ_i and θ_j are voltage angles of bus i and j. G_{ij} and B_{ij} are the conductance and susceptance of a transmission line, respectively.

However, in real engineering, the injection active power flow of the line is should be calculated as follows:

$$\begin{aligned} P_{l_{ij}} - P_{l_{ji}} &\approx -2V_{ij,N}^2 B_{ij} \sin\theta_{ij} \\ &\approx 2V_{ij,N}^2 \frac{x_{ij}}{r_{ij}^2 + x_{ij}^2} \sin\theta_{ij} \approx 2\frac{V_{ij,N}^2 \theta_{ij}}{x_{ij}} \end{aligned} \tag{2}$$

where $V_{ij,N}$ is rated voltage, r_{ij} and x_{ij} are the resistance and reactance of the transmission line, respectively and $r_{ij} \ll x_{ij}$. However, the real power flow of transmission line l_{ij} can be approximately expressed as the average of the real power difference between the two ends of the transmission line that can be expressed as (3). The transmission loss can be calculate by adding the both ends of a transmission line l_{ij}, which is show as (4). When we introduce a transmission loss variable $P_{l_{ij}}$ into the (4) that can be expressed as (5).

$$P_{l_{ij}}^f \approx \frac{P_{l_y} - P_{l_{ji}}}{2} \approx \frac{V_{ij,N}^2 \theta_{ij}}{x_{ij}} \tag{3}$$

$$\begin{aligned} P_{l_{ij}} + P_{l_{ji}} &\approx G_{ij} \left(V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij} \right) \\ &\approx V_{ij,N}^2 G_{ij} \theta_{ij}^2 \end{aligned} \tag{4}$$

$$P_{l_{ij}}^l = V_{ij,N}^2 G_{ij} \theta_{ij}^2 \tag{5}$$

III. PROBLEM STATEMENT

A. OBJECTIVE FUNCTIONS

The generator cost curve $F_i(P_i)$ are represented by quadratic function and the total fuel cost FT that can be expressed as (6) and (7)

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{6}$$

$$\min \quad FT = \sum_{i=1}^{N} F_i(P_i) \tag{7}$$

$F_i(P_i)$ is ith generator cost, a_i, b_i and c_i are the cost coefficients of the ith generator, and P_i is the real power output of the ith generator, where N is the number of generators.

B. CONSTRAINTS

1) EQUALITY CONSTRAINTS

These constraints represent typical load flow equations as follows [1].

$$\sum\nolimits_{g \in G_i} P_g - \sum\nolimits_{j \in \mathrm{L}_i} P_j^f = \sum\nolimits_{k \in D_i} P_k^d + \frac{1}{2} \sum\nolimits_{j \in \mathrm{L}_i} P_j^l \qquad i = 1, 2, \cdots, N_{\mathrm{B}} \tag{8}$$

$$P_l^f = \frac{V_{l,N}^2 \theta_l}{x_l} \quad l = 1, 2, \cdots, N_{\mathrm{L}} \tag{9}$$

$$P_j^l = V_{l,N}^2 G_l \theta_l^2 \quad l = 1, 2, \cdots, N_{\mathrm{L}} \tag{10}$$

$$\theta_{\mathrm{ref}} = 0 \tag{11}$$

while (8) and (9) represent the balance limits of real power and the constraint of the DC power flow. G_i, L_i and D_i are the sets of generators, transmission lines and loads. P_g is the real power output of the gth generator, P_j^d is the real power of the kth consumer, P_j^f and P_j^l denote the real power flow and the transmission loss of the line. $\theta_l = \theta_i - \theta_j$, is the phase difference between the voltages at both ends of the transmission line l. N_B is the total number of buses whereas the total number of transmission lines is defined by N_L. The transmission loss constraint of the transmission line l can be illustrated in (10), where G_l is conductance of transmission line l. The reference bus voltage phase angle constraint is presented by (13).

2) INEQUALITY CONSTRAINTS

These constraints represent the system operating constraints as follows.

For secure operation, the transmission line loading P_l^f is restricted by its upper limit as:

$$\underline{P}^l \leq P_l^f \leq \bar{P}^l \quad l = 1, 2, \cdots, N_{\mathrm{L}} \tag{12}$$

The node voltage phase difference constraint at both ends of the transmission line l is shown in the following formula:

$$\theta_{l,\min} \leq \theta_l \leq \theta_{l,\max} \tag{13}$$

The ramp-up/down rate of the ith generator limited by its physical characteristics [20]. It must satisfy the following constraint:

$$-\mathrm{DR}_i \leq P_i - P_i^0 \leq \mathrm{UR}_i \quad i = 1, 2, \cdots, N \tag{14}$$

The ith generator real power output P_i is restricted by its lower and upper limits as follows:

$$P_{i,\min} \leq P_i \leq P_{i,\max} \quad i = 1, 2, \cdots, N \tag{15}$$

IV. PROPOSED APPROACH

A. LINEARIZATION RELAXATION FOR TRANSMISSION LOSS CONSTRAINT

Let $m_{l_{ij}}$ is the total number of points that are taken on the network loss curve of the transmission line l_{ij}, which is show in Figure 1. The kth point is linearized to obtain the following relaxed linear inequality:

$$P_{l_{ij}}^l \geq K_{l_{ij}}^k \theta_{ij} + B_{l_{ij}}^k \quad k = 1, 2, \ldots, m_{l_{ij}} \tag{16}$$

where $K_{l_{ij}}^k$ and $B_{l_{ij}}^k$ can be calculate as follows:

$$\begin{cases} K_{l_{ij}}^k = 2V_{ij,N}^2 G_{ij} \theta_{ij}^k \\ B_{l_{ij}}^k = P_{l_{ij}}^{l,k} - K_{l_{ij}}^k \theta_{ij}^k \end{cases} \tag{17}$$

After performing the above-mentioned linear relaxation processing on the transmission line loss constraints of each line, the quadratic equation constraints are relaxed into a series of linear inequality constraints, thereby mathematically transforming the original optimization scheduling problem into a quadratic convex programming problem, which is expressed as:

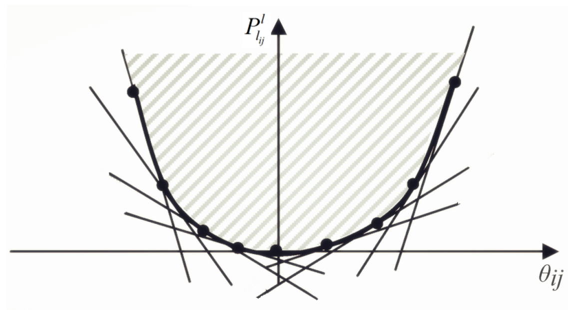

FIGURE 1. Linear relaxation technique for transmission loss of each line.

$$\begin{aligned} \min_x \quad & \frac{1}{2} x^T H x + f^T x \\ \text{s.t.} \quad & Ax \leq b \\ & A_{\mathrm{eq}} x = b_{\mathrm{eq}} \\ & l_{\mathrm{b}} \leq x \leq u_{\mathrm{b}} \end{aligned} \tag{18}$$

where H and f are the coefficient matrix and coefficient vector of the objective function. A and b represent the coefficient matrix and coefficient vector of the linear inequality constraints. A_{eq} and b_{eq} represent the coefficient matrix and coefficient vector of the linear equality constraints. l_b and u_b are upper and lower bound of the independent variable, respectively.

B. MIXED INTEGER PROGRAMMING FOR TRANSMISSION LINE LOSS

In order to deal effectively with the situation that the marginal cost of negative nodes exists in power grid, independent variables, the relaxed linear inequality constraints, which do not satisfied the given threshold after solving by quadratic programming, the following linear processing is further carried out in this paper.

The network loss constraints of each transmission line treated is handled by linear approximation, i.e. transmission line loss constraints in the form of quadratic equations is transformed into linear constraints as shown in Figure 2. The linearized transmission line loss constraints are as follows:

$$P_{l_{ij}}^l = V_{ij,N}^2 G_{ij} \sum_{r=1}^{R_{l_{ij}}} \left(U_{ij,r} \theta_{ij,r} + W_{ij,r} Z_{ij,r} \right) \tag{19}$$

$R_{l_{ij}}$ represents the number of linear segments of the voltage phase difference between the node i and j at the transmission line l_{ij}. $U_{ij,r}$ and $W_{ij,r}$ are the slope and intercept of the linear segment r, respectively. $Z_{ij,r}$ is the binary variable that corresponding to the continuous sub-variable $\theta_{ij,r}$.

$$\begin{cases} U_{ij,r} = V_{ij,N}^2 G_{ij} \left(\theta_{ij,r}^{\mathrm{ub}} + \theta_{ij,r}^{\mathrm{lb}} \right) \\ W_{ij,r} = V_{ij,N}^2 G_{ij} \left(\theta_{ij,r}^{\mathrm{lb}} \right)^2 - U_{ij,r} \theta_{ij,}^{\mathrm{lb,}} \end{cases} \tag{20}$$

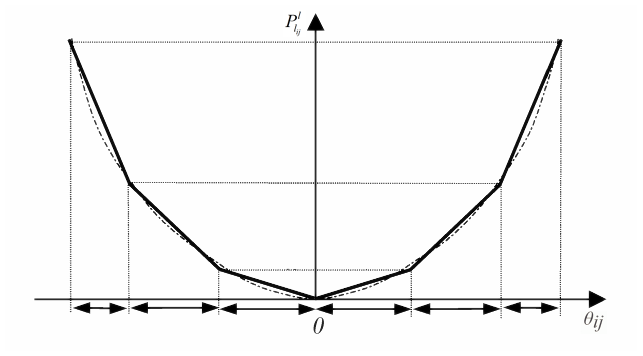

FIGURE 2. Linear relaxation technique for transmission loss of each line.

$\theta^{\mathrm{lb}}_{ij,r}$ and $\theta^{\mathrm{ub}}_{ij,r}$ represent the lower and upper bounds of the voltage phase difference of linear segment r, respectively.

After linearizing the transmission line loss constraints, since the voltage phase difference between the nodes at both ends of the transmission line can only be located in one of the linear segments, binary variables need to be introduced and the following constraints are added:

$$\sum_{r=1}^{R_{l_{ij}}} Z_{ij,r} = 1 \tag{21}$$

Constrained by (21), when the voltage phase difference between the two ends of the line is in a linear segment, the continuous sub-variable corresponding to the other linear segments is set to zero as follows:

$$\theta^{\mathrm{lb}}_{ij,r} Z_{ij,r} \le \theta_{ij,r} \le \theta^{\mathrm{ub}}_{ij,r} Z_{ij,r} \tag{22}$$

Constrained by (21) and (22), the voltage phase difference between the two ends of the transmission line should be the sum of each continuous sub-variable $\theta_{ij,r}$, which can be expressed as follows:

$$\theta_{ij} = \sum_{r=1}^{R_{lj}} \theta_{ij,r} \tag{23}$$

If some transmission line loss constraints solving by the quadratic programming do not satisfy the constraints or exceed the threshold values after relaxing the transmission line loss constraints, we need to modify the transmission line loss constraints into (19), (20) and (22) forms to obtain a mixed integer quadratic programming problem.

C. DELETION METHOD OF MODEL VARIABLES AND CONSTRAINTS

According to (9), the real power flow of each transmission line is expressed as a function of the voltage phase difference between the nodes at both ends of the transmission line. Therefore, the real power flow P^f_l $(l = 1, 2, \cdots, N_{\mathrm{L}})$ of each transmission line is not taken as an independent variable in the real power optimal scheduling model in this paper. Accordingly, the security transmission capacity constraints (10) of each transmission lines can be deleted. Moreover, the real power flow of each transmission line can be rewritten by correcting the voltage phase difference between the nodes at both ends of each line, which is shown below:

$$\max\left\{\frac{P^l x_l}{V^2_{l,N}}, \theta_{l,\min}\right\} \le \theta_l \le \min\left\{\frac{\bar{P}^l x_l}{V^2_{l,N}}, \theta_{l,\max}\right\} \tag{24}$$

By merging the DC power flow constraint (9) into the node power balance constraint (8) to remove the DC power flow constraint, and the following node power balance constraint is obtained as follows:

$$\sum_{g\in G_i} P_g - \sum_{j\in L_i} \frac{V^2_{j,N}\theta_j}{x_j} = \sum_{k\in D_i} P^d_k + \frac{1}{2}\sum_{j\in L_i} P^l_j \tag{25}$$

After the above processing, the real power flow variables, the DC power flow constraint of the network and the security transmission capacity constraint are deleted, so the efficiency of the algorithm can be effectively improved.

D. PROCEDURE SOLVING FOR GENERATION SCHEDULING PROBLEM

As a consequence, according to the description stated in the previous section, the procedure for the generation dispatch problem is summarized as follows:

- **Step1**: Simplify the real optimal scheduling model by using the deletion method to reduced model variables and constraints of the network.
- **Step2**: Linearize the relaxed transmission line loss constraints and use a commercial optimization solver to solve the quadratic convex programming model. If all transmission line loss constraints satisfy the equality constraints or a given threshold valves, and go to **step5**; otherwise, go to **step3**.
- **Step3**: The mixed integer programming technique is used to deal with the transmission line loss constraints that do not satisfy the equality constraints or given thresholds, then employ a commercial optimization solver solve this mixed integer quadratic programming model.
- **Step4**: If all transmission line loss constraints meet the equality constraints or a given threshold, and go to **step5**; otherwise, skip to **step3**;
- **Step5**: Stop and output the results.

It is noteworthy that the mixed integer quadratic programming model needs to be handled only when the marginal cost of negative nodes exists in network. In most cases, in the process of optimizing the unit's power generation cost, the transmission loss is also minimized, and the transmission loss constraint usually satisfies the equality constraints or less than a given threshold, so there is only a quadratic programming problem needs to be solved.

V. SIMULATION STUDIES

In this paper, MATLAB R2017b is used and the MIP optimizer of CPLEX software is used to solve the proposed quadratic programming model and mixed integer quadratic programming model [21]. All methods in this paper are implemented on a computer with 4G memory and 3.10-GHz. The examine time is averaged by 30 independent operations.

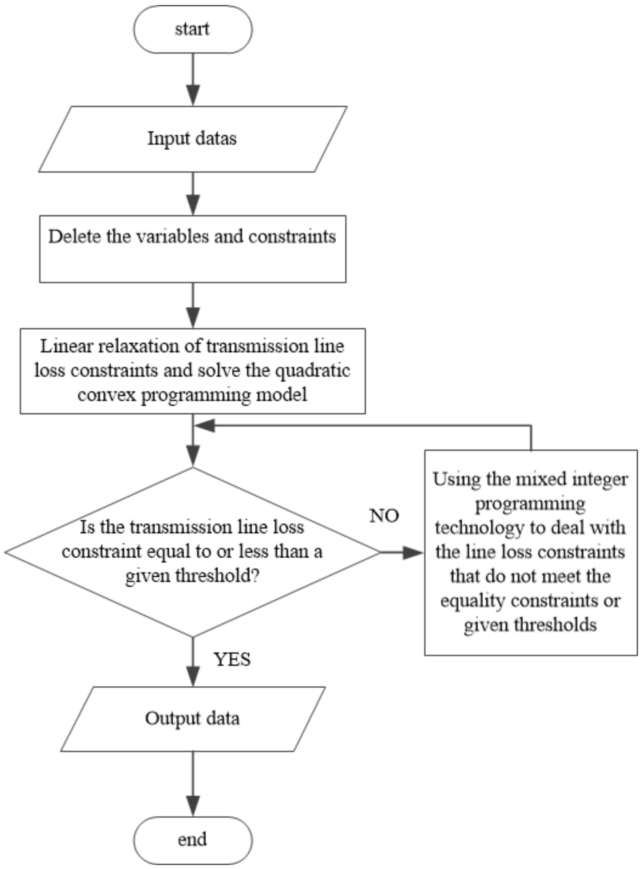

FIGURE 3. Flowchart of the proposed method.

TABLE 1. Essential characteristics of three test systems.

Test system	Number of generators	Number of buses	Number of lines
IEEE30	6	30	41
IEEE118	54	118	186
PL2746	520	2746	3514

A. TEST SYSTEMS DESCRIPTION

Three test systems, including IEEE 30-node system, IEEE 118-node system, and Polish 2746-node system, are employed to verify the effectiveness of the proposed method in this paper, which is shown in Table 1. In order to examine the effectiveness of the proposed approach, the following two representative algorithms are selected for comparison:

1) QCQP: The transmission loss constraint is mathematically relaxed into a quadratic constraint with convex. In the process, the transmission line loss variables which do not satisfy the equality constraints are added to the objective function by the term of penalty factor, and that will be solved by solving the quadratic constraint quadratic programming problem [5].
2) SCIP: This is a commercial optimization solver for solving optimization problems with quadratic constraints, and it solver can find a global optimal solution quickly [22].

B. CASE 1: IEEE 30- AND 118-NODE SYSTEMS

In order to verify the effectiveness of the propose approach in this paper, we first tests in IEEE30-node system and IEEE 118-node system. These system-related datas, IEEE30-node system and IEEE118-node system are come from Matpower5.1.

TABLE 2. Comparison of results obtained by three methods on IEEE 30- and 118-node systems.

Approach	Total cost /($)	Transmission loss /(MW)	time /(s)
33 -node system			
QCQP	8,880.61	11.3038	0.10
SCIP	8,880.62	11.3037	0.14
Proposed. method	8,866.36	11.4633	0.09
118 -node 'system			
QCQP	129,695.54	78.2215	1.70
SCIP	129,695.54	78.2226	6.68
Proposed. method	129,643.23	78.3091	0.78

TABLE 3. Comparison of results obtained by three methods on polish 2746-node system.

Approach	Total cost /($)	Transmission loss /(MW)	time(s)
QCQP	1,587,414.05	437.0690	33.88
SCIP	1,587,414.23	437.0747	120.57
Proposed method	1,578,162.50	431.5289	23.47

The results obtained by QCQP, SCIP and the proposed approach in this paper is show in Table 2. As shown in this table, from the perspective of solution quality, both QCQP and SCIP have the same global optimum solution on the two test systems. Due to the proposed approach in this paper solving the line loss constraints in a linear relaxation technique, there are little minor differences in the total generator cost and network loss. However, from the point of view of total generation cost and network loss, the simulation comparison with QCQP and SCIP shows that the solution obtained by proposed approach is close to the global optimum within the range of error tolerance.

In terms of the time, for small-scale system, like IEEE30-node test system, QCQP, SCIP and the proposed approach all can obtain satisfactory solutions efficiently, and there is little difference in the calculating time Compared with the IEEE30-node system, the time of the IEEE118-node system of the three methods increases. As a sequence, it can conclude that the calculation time of the proposed approach in this paper is much better that the QCQP and SCIP. Compared with QCQP and SCIP, the advantage of the calculation efficiency of the proposed approach is mainly due to the linear relaxation of transmission line loss constraints. After linear relaxation of secondary linear transmission loss constraints, the original problem is converted into a quadratic programming problem, which can be solved quickly by CPLEX.

C. CASE 2: POLISH 2746-NODE SYSTEMS

To validate the extensibility of the proposed approach, we use the Polish 2746-node systems. The system parameters are derived from the 2746-node system in Matpower 5.1, which corresponds to a load peak on a certain day in winter. Notes that this system is much larger than that of the aforementioned IEEE30-node system and IEEE118-node system, and the difficulty of solving the problem also increases.

The results obtained by QCQP, SCIP and the proposed method are shown in Table 3. From the Table 3, QCQP and SCIP are very close in terms of total generation cost and network loss, respectively. There is a little difference between the proposed method in this paper and the two methods mentioned above. This is mainly due to the small mismatch between the transmission line loss variable and the actual transmission line loss after the linear relaxation of transmission line loss constraints. As the scale of system is enlarged, the error accumulates step by step and which will reach a very larger value. At the same time, in the optimization process, the value of transmission line loss variable is generally close to the relaxed linear constraints, which makes the transmission line loss variable P_j^l less than or equal to the actual line loss $V_{l,N}^2 G_l \theta_l^2$, and it results in the total output of proposed method is slightly less than the QCQP and SCIP. When properly increasing the number of linear slack segments of the line loss curve that will help to reduce the mismatch between the proposed method and QCQP and SCIP in the total power generation cost and network loss, but the calculation time will increase.

VI. CONCLUSION

This paper proposed a generation scheduling algorithm based on linear relaxation and mixed integer programming. This method using linear relaxation and mixed integer programming model is used to deal with the transmission line loss constraints, transforms the original power optimization scheduling problem into a quadratic planning or mixed integer quadratic programming problem, and solved by a commercial optimization solver, CPLEX. IEEE 30-node system, IEEE 118-node system and Polish 2746-node system are used to test the proposed problem. The validity and expansibility of the proposed method are verified, and compared with the two algorithms, QCQP and SCIP. The final results shows that the method proposed in this paper can obtain an optimal scheduling solution efficiently.

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YUNKAI LEI (Member, IEEE) received the Ph.D. degree in electrical engineering from Tianjin University, Tianjin, China, in 2018.

He is currently working as the Grid Planner with the State Grid Sichuan Economic Research Institute. His research interests include reliability and risk assessments of power system and the integrated energy systems.

FANG LIU is an engineer. Her research interests include optimization and control methods and their applications in power systems.

AO LI is an engineer. His research interests include optimization and control methods, and the coordinated operation of integrated energy systems.

YUNCHE SU is an engineer. Her research interests include the areas of power system stability analysis and control, the control of wind power generation systems, and nonlinear control theory.

XINTING YANG is an engineer. His research interests include nonlinear adaptive control, power quality, and power system control and its operation.

JIEHUI ZHENG (Member, IEEE) received the B.E. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2012, and the Ph.D. degree in electrical engineering from the South China University of Technology (SCUT), Guangzhou, China, in 2017. He is currently a Lecturer with SCUT. He has authored or coauthored more than 40 peer-reviewed SCI journal articles. His research interests include the area of optimization algorithms, and decision making methods and their applications in integrated energy systems.