Transmission network planning considering line maintenance plan with new energy resources integration

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Abstract. In this paper, a stochastic optimization model of transmission network planning considering annual planned maintenance of lines under new energy integration is proposed. This model combines the planning model and maintenance model together, and can determine the optimal transmission capacity of lines and the annual maintenance plan simultaneously. In addition, in order to take into account the uncertainty of wind power output, the multi-scenario probabilistic method is used, and the nonlinear constraints in the model is equivalently linearized, therefore the model can be converted into a mixed integer linear model and can be directly solved by the commercial solver. To validate its effectiveness and superiority, the proposed stochastic optimization model is tested on the IEEE RTS-24 system.

1. Introduction

With the rapid development of the renewable energy generation and the continuous expansion of the power grid, the operation and planning of the power system is facing more severe security and reliability problems [2], and the transmission network planning should be more flexible with respect to the variation conditions.

Reasonable maintenance plan of transmission line is an important measure to ensure the safety and reliability of the line. Usually the line maintenance plan is based on the known transmission network, and the basic goal is to ensure the optimal maintenance economy and the least impact on the users under the premise of safe and reliable transmission of electric energy [3]. During maintenance, the transmission line under maintenance is generally shutdown, which will change the network structure, reduce the transmission capacity of the system, and cause power redistribution. There is a coupling relationship between planning module and maintenance module [4].

Traditional transmission network planning determines the optimal transmission capacity for each line considering a relative long optimization period, such as several years [5]. Planning module and maintenance module possess different time span and they usually be implemented separately. After the
planning module is finished and the maintenance procedure is implemented based on the results of planning [6]. When the uncertainty introduced by renewable generation increases, the coupling relationship between planning and maintenance becomes stronger, and it becomes meaningful to considering the planning model together with the maintenance model. Although N-1 security can be considered during the planning procedure [7], and the safety and reliability of the power system are not well respected when the maintenance planning is implemented, especially a significant proportion of renewable energy is integrated [8]. If the N-2 security criterion is considered in planning module, would be too conservative [9], which would result in excessive investment.

In this paper, we propose a stochastic optimization model which combines the planning module and maintenance module together. By doing so the interaction between the two models is well respected, which can yield a better results compared considering the planning module and maintenance module separately.

2. Mathematical model

The objective function of the proposed model is to minimize the total annual cost.

\[
\min \sum_{l \in N_L} c_L T_l + \sum_{t \in N_T} \sum_{l \in NL} c_l q_{lt} + \sum_{s \in \Omega} \rho_s \left( \sum_{t \in N_T} \sum_{g \in NG} c_g P_{s,t} + \sum_{t \in N_T} \tau_t \chi P_{s,w,t}^* \right)
\]

where \(N_L\) is the set of transmission lines to be optimized. \(c_l\) is the investment cost of line \(l\) per unit length and per unit capacity. \(L_l\) is the length of line \(l\). \(T_l\) is the transmission capacity of line \(l\). \(N_T\) is the number of optimization period. \(M_L\) is the set of lines to be maintained. \(c_{lt}\) is the maintenance cost of line \(l\) when maintenance is started from period \(t\). \(q_{lt}\) is the binary variable to represent whether line \(l\) starts maintenance at time period \(t\). If line \(l\) starts maintenance from period \(t\), \(q_{lt}\) takes 1. Otherwise, \(q_{lt}\) takes 0. \(\Omega\) is the set of scenario considered. \(\rho_s\) is the occurrence probability of scenario \(s\). \(\tau_t\) is the duration of the time \(t\). \(NG\) is the set of generators. \(c_g\) is the operating cost of unit \(g\). \(P_{s,t}\) represents the output power of unit \(g\) during period \(t\) under scenario \(s\). \(NW\) is the set of wind turbine generation. \(\chi\) is the wind spillage cost. \(P_{s,w,t}^*\) represents the spilled power of wind turbine \(w\) during period \(t\) under scenario \(s\).

The model is subject to the following constraints:

1) Transmission line capacity constraints:

\[
f_{s,i,j} = B_i \left( \theta_{s,j(i),t} - \theta_{s,i(j),t} \right) z_{i,t}, \forall s \in \Omega, \forall l \in N_L, \forall t \in N_T
\]

\[-z_{i,t} T_i \leq f_{s,i,j} \leq z_{i,t} T_i, \forall s \in \Omega, \forall l \in N_L, \forall t \in N_T
\]

\[z_{i,t} = 1 - y_{i,t}, \forall l \in N_L, \forall t \in N_T
\]

\[T_{i}^{\text{min}} \leq T_i \leq T_{i}^{\text{max}}, \forall l \in N_L
\]

where \(f_{s,i,j}\) represents the power flow in line \(l\) under scenario \(s\) during period \(t\). \(B_i\) is the susceptance of the transmission line \(l\); \(\theta_{s,i(j),t}\), \(\theta_{s,j(i),t}\) represent the phase angles of the two endpoints \(i,j\) of line \(l\) respectively. \(y_{i,t}\) represents whether line \(l\) is in maintenance state during period \(t\). When line \(l\) is in maintenance state during period \(t\), \(y_{i,t}\) takes 1, otherwise, \(y_{i,t}\) takes 0. \(z_{i,t}\) is also a binary variable. \(T_{i}^{\text{min}}\) and \(T_{i}^{\text{max}}\) are the minimum and maximum transmission capacity of line \(l\) respectively.
and $T^\text{max}_l$ represent the upper and lower limits of transmission construction capacity, respectively. In the paper, $T^\text{min}_l$ is set to 0, $T^\text{max}_l$ is set to $+\infty$.

2) Nodal power balance constraint:

\[
\sum_{g \in N_G} P_{s,g,t} + \sum_{w \in N_W} \sum_{i \in N} P_{s,w,t} - \sum_{i \in N} P_{l,t} = \sum_{i \in \{Fr(i)\}} f_{s,j,t} - \sum_{i \in \{To(i)\}} f_{s,j,t}, \quad \forall s \in \Omega, \forall g \in N_G, \forall w \in N_W
\]

where $P_{s,w,t}$ represents the output power of wind turbine $w$ during period $t$ under scenario $s$. $N_l$ is the set of node. $P_{l,t}$ is the load demand at node $i$ during period $t$. $i \in \{n(i)\}$ represents the line whose starting point is node $i$. $i \in \{o(i)\}$ represents the line whose ending point is node $i$.

3) Unit operating constraints:

\[
P^\text{min}_g \leq P_{s,g,t} \leq P^\text{max}_g, \quad \forall s \in \Omega, \forall g \in N_G
\]

\[
0 \leq P_{s,w,t} \leq P^\text{fct}_{s,w,t}, \quad \forall s \in \Omega, \forall t \in N_T, \forall w \in N_W
\]

\[
P^*_{s,w,t} = P^\text{fct}_{s,w,t} - P_{s,w,t}, \quad \forall s \in \Omega, \forall t \in N_T, \forall w \in N_W
\]

where $P^\text{min}_g$ and $P^\text{max}_g$ represent the upper and lower limits of unit $g$ respectively.; $P^\text{fct}_{s,w,t}$ represents the predicted output of wind turbine $w$ during period $t$ under scenario $s$.

4) Unit operating constraints:

In the paper the wind speed uncertainty is modelled by Weibull distribution [11, 12]. The relationship between the wind speed $v$ and wind power output $P_w$ is modelled using the follow expression.

\[
P_w = \begin{cases} P_r & v < v_{ci} \\ \frac{P_r (v - v_{ci})}{v_r - v_{ci}} & v_{ci} \leq v \leq v_r \\ 0 & v < v_{ci} \text{ or } v > v_{co} \end{cases}
\]

where $P_r$ is the rated power of wind turbine. $v_r$ is the rated wind speed. $v_{co}$ is the cut-out speed. $v_{ci}$ is the cut-in speed. After the wind power distribution is obtained by convolution, it is discretized into several scenarios.

5) Transmission line maintenance constraints:

\[
\begin{cases} y_{l,t} \in \{0,1\}, \forall l \in M_L, T^\text{start}_l \leq t \leq T^\text{end}_l \\ 0 & \text{otherwise} \end{cases}
\]

\[
\begin{cases} q_{l,t} \in \{0,1\} \\ \sum_{t=T^\text{start}_l}^{T^\text{end}_l} q_{l,t} = 1, \forall l \in M_L, T^\text{start}_l \leq t \leq T^\text{end}_l 
\end{cases}
\]
\[ q_{l,t} \geq y_{l,t} - y_{l,t-1}, \forall l \in M, T_{l,\text{start}} \leq t \leq T_{l,\text{end}} \]  
(13) 
\[ y_{l,t} - y_{l,t-1} \leq y_{l,t}, D_{l,t-1}, \forall l \in M, T_{l,\text{start}} \leq t \leq T_{l,\text{end}} \]  
(14) 
\[ \sum_{t=T_{l,\text{start}}}^{T_{l,\text{end}}} y_{l,t} = D_{l}, \forall l \in M, T_{l,\text{start}} \leq t \leq T_{l,\text{end}} \]  
(15) 
\[ \sum_{l \in M} h_{l} y_{l,t} \leq H, \forall l \in M, T_{l,\text{start}} \leq t \leq T_{l,\text{end}} \]  
(16) 
\[ \sum_{l \in M} y_{l,t} \leq y_{l,\text{max}}, \forall l \in M, T_{l,\text{start}} \leq t \leq T_{l,\text{end}} \]  
(17)

where expression (11) represents the constraint of line maintenance time window. \( T_{l,\text{start}} \) and \( T_{l,\text{end}} \) are the start and end time periods for maintenance of line \( l \), respectively. Expression (12) represents that during the maintenance time window the maintenance must be implemented. \( q_{l,t} \) represents that the maintenance of line \( l \) is started from period \( t \). Expression (13) represents the relationship between \( q_{l,t} \) and maintenance status \( y_{l,t} \). Expression (14) represents the continuity of line maintenance. \( D_{l} \) is the duration of maintenance of line \( l \). Expression (15) represents the maintenance duration constraint. Expressions (16) represents the constraint of line maintenance resources. Here \( h_{l} \) is the amount of resources required by overhaul line \( l \) in unit period. \( H \) is the total maintenance resources. And expression (17) represents the constraint of the maximum number of lines that can be repaired at the same time in each period. Here \( y_{l,\text{max}} \) is the upper limit of the number of lines allowed for maintenance.

6) N-1 security constraint:

\[
\begin{align*}
 f_{s,j,t}^{(k)} &= B_{j} \left( \theta_{s,j,t}^{(k)} - \theta_{s,j,t}^{(k)} \right) z_{l,t} \\
 -z_{l,t} T_{l} &\leq f_{s,j,t}^{(k)} \leq z_{l,t} T_{l} \\
 T_{l,\text{min}} &\leq T_{l} \leq T_{l,\text{max}} \\
 \sum_{g \in \mathcal{N}_{g}} P_{g,s,t}^{(k)} + \sum_{w \in \mathcal{N}_{w}} P_{w,s,t}^{(k)} - \sum_{l \in \mathcal{L}} P_{l,t} = &\sum_{l \in \mathcal{F}(r(i))} f_{s,j,t}^{(k)} - \sum_{l \in \mathcal{T}(r(i))} f_{s,j,t}^{(k)} \\
 P_{g}^{\text{min}} &\leq P_{g,s,t}^{(k)} \leq P_{g}^{\text{max}} \\
 0 &\leq P_{s,w,t}^{(k)} \leq P_{s,w,t}^{\text{max}}
\end{align*}
\]  
(18)

where the superscript \( k \) represents the single outage event of line \( k \). In the proposed model, for simplicity, only the single outage of transmission line is considered in the N-1 security constraints.

3. Model solution

Nonlinear characteristics exist in the proposed model. For example, in expression (2) and its corresponding constraint in (18), the product of binary variable and continuous variable can be converted into the following linear form with the big M method [13]:

\[
\begin{align*}
 f_{s,j,t} - B_{j} \left( \theta_{s,j,t} - \theta_{s,j,t} \right) + (1-z_{l,t}) M &\geq 0 \\
 f_{s,j,t} - B_{j} \left( \theta_{s,j,t} - \theta_{s,j,t} \right) - (1-z_{l,t}) M &\leq 0
\end{align*}
\]  
(19)
\[
\begin{align*}
\left\{ f^{(k)}_{i,j,t} - B_i \left( \theta^{(k)}_{s,i,t} - \theta^{(k)}_{s,i,t} \right) + (1 - z_{i,t})M \right\} & \geq 0 \\
\left\{ f^{(k)}_{i,j,t} - B_i \left( \theta^{(k)}_{s,i,t} - \theta^{(k)}_{s,i,t} \right) - (1 - z_{i,t})M \right\} & \leq 0
\end{align*}
\]  
(20)

where M is a very large number.

Constraints (4) – (6) and their corresponding constraint in (18) can be reduced to the following linear form by introducing two continuous auxiliary variables \( R_{l,t} \) and \( Q_{l,t} \):

\[
\begin{align*}
-Q_{l,t} & \leq f_{s,l,t} \leq Q_{l,t} \\
z_{l,t}T_{\text{min}} & \leq Q_{l,t} \leq z_{l,t}T_{\text{max}} \\
(1 - z_{l,t})T_{\text{min}} & \leq R_{l,t} \leq (1 - z_{l,t})T_{\text{max}} \\
Q_{l,t} & = T_{l} - R_{l,t}
\end{align*}
\]  
(21)

In the expression above, when \( z_{l,t} \) is equal to 1, \( R_{l,t} \) is equal to 0, \( Q_{l,t} \) is equal to \( T_{l} \), and \(-T_{l} \leq f_{s,l,t} \leq T_{l} \) is satisfied. When \( z_{l,t} \) is equal to 0, \( Q_{l,t} \) is equal to 0, thus \( f_{s,l,t} \) is 0. Similar corresponding constraint in (18) can be converted into the following linear form:

\[
\begin{align*}
-Q^{(k)}_{l,t} & \leq f^{(k)}_{s,l,t} \leq Q^{(k)}_{l,t} \\
z_{l,t}T_{l}^{\text{min}} & \leq Q^{(k)}_{l,t} \leq z_{l,t}T_{l}^{\text{max}} \\
(1 - z_{l,t})T_{l}^{\text{min}} & \leq R^{(k)}_{l,t} \leq (1 - z_{l,t})T_{l}^{\text{max}} \\
Q^{(k)}_{l,t} & = T_{l} - R^{(k)}_{l,t}
\end{align*}
\]  
(22)

Therefore, all nonlinear constraints are transformed into linear constraints, the model belongs to a mixed integer linear programming problem and the model can be solved by the existing commercial solver such as CPLEX.

4. Case analysis

The IEEE-RTS 24 system [14, 15] is used as the example. Three 300MW wind turbines are considered and each wind turbine is connected to node 2, 14 and 16, respectively. For simplicity, only three scenario of wind power output are considered, i.e., s1, s2 and s3 with probability of 0.46, 0.16 and 0.38, respectively. This example takes 1 year as the entire optimization period of planning model, which includes 52 periods. The investment cost per unit length per unit per capacity of the line is set as 2000 yuan/(km·MW). The required load forecast value and detailed data of wind power output in multiple scenarios can be found in [5]. For comparison, two cases are proposed.

Case 1: Run the planning module first, then run the maintenance module.

Case 2: Optimizing the planning and maintenance modules together by the proposed method.

(1) Comparison of two cases

After optimization, the results of the two cases are shown in Table 1. In the table, load curtailment cost of case 1 is calculated after the maintenance procedure by minimizing the load curtailment cost with the given maintenance schedule, and the price for losing 1 MW load is set as 10000 yuan/MW.
Table 1. Optimization results

| scheme | The cost of load curtailment (10^6 yuan) | investment cost (10^6 yuan) | Operating cost (10^6 yuan) | Maintenance cost (10^6 yuan) | The total cost (10^6 yuan) |
|--------|------------------------------------------|-----------------------------|---------------------------|-----------------------------|--------------------------|
| case1  | 2567.5450                                | 737.1621                    | 9236.6214                 | 7.0555                      | 12548.3840               |
| case2  | 0.00                                     | 871.6474                    | 9146.9880                 | 7.0155                      | 10025.6509               |

From Table 1, it can be found that in case1, planning is implemented first, then run the maintenance module. Although the investment cost is relatively lower, the N-1 security is not always satisfied during maintenance, significant load curtailment cost will occur. Case2 possesses a higher investment cost, the transmission capacity is larger, the dispatching room is larger, which results in a lower operating cost and the load curtailment cost is 0. Therefore, decoupling the planning and maintenance modules would result in a significant load curtailment cost, which will significantly increase the total cost.

(2) Influence of the number of lines that can be repaired at the same time on the planned maintenance.

In order to analyze the influence of the number of repairable lines in the proposed model, four cases are considered. Here for simplicity the uncertainty of wind turbine output is not considered.

Case 1: the $y_{\text{max}}$ used in (17) is 1;
Case 2: the $y_{\text{max}}$ used in (17) is 2;
Case 3: the $y_{\text{max}}$ used in (17) is 3;
Case 4: the $y_{\text{max}}$ used in (17) is 4.

The corresponding results for the four cases are as follows:

Table 2. Optimization results with respect to different $y_{\text{max}}$

| Case   | investment cost (10^6 yuan) | Operating cost (10^6 yuan) | Maintenance cost (10^6 yuan) | The total cost (10^6 yuan) |
|--------|-----------------------------|-----------------------------|-------------------------------|---------------------------|
| case1  | 846.4422                    | 9053.8925                   | 7.0720                        | 9907.4067                 |
| case2  | 830.1001                    | 9033.2474                   | 7.0210                        | 9870.3685                 |
| case3  | 802.7069                    | 8941.2556                   | 6.9795                        | 9750.9420                 |
| case4  | 806.2024                    | 8928.1040                   | 6.9758                        | 9741.2822                 |

From table 2, it can be seen that with the increase of the number of permitted maintenance $y_{\text{max}}$, the total cost will gradually decrease. The meaning of the proposed model is enhanced.

5. Conclusions

In this paper, a stochastic transmission network planning model considering line maintenance and renewable energy integration is established. After linearization, the model becomes to a mixed integer linear programming problem. From the proposed model, it can be concluded that it is meaningful to combining the planning module and maintenance module together.

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