Spatial Power Network Expansion Planning Considering Generation Expansion

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***Abstract*—This paper introduces an efficient approach on static spatial power network expansion planning integrated with generation expansion, while considering complicated environments based on the raster map in geographic information systems (GIS). Candidate plants could be built on any cell in the map, which means that terminals of candidate lines connected to candidate plants are not fixed. This is a remarkable difference from the literature in which the terminals of candidate lines are fixed. The objective is to minimize the total system cost, subject to prevailing investment and operation constraints. The model is formulated as a mixed-integer linear programming (MILP) problem via integer algebra techniques. A two-step approach is proposed to address the computational complexity. The first step searches optimal electric line routes via dynamic programming, while the second step solves a simplified MILP problem for obtaining final optimal generation and transmission planning strategies based on optimal line routes derived from the first step. In most cases, the proposed two-step approach would derive the same global optimal solutions as those by solving the original formulation directly. Thus, the proposed two-step approach can significantly improve the computational efficiency while maintaining the solution optimality. Numerical examples demonstrate the effectiveness of the proposed approach.**

***Index Terms*—Dynamic programming, generation expansion, geographic information systems, mixed-integer linear programming, power network planning, routing.**

NOMENCLATURE

Indices:

b	Index for load blocks.
$d, \bar{d}$	Index for directions.
$i, \bar{\imath}$	Index for rows in a raster map.
$j, \bar{\jmath}$	Index for columns in a raster map.
k, m, n	Indices for lines/generation plants/buses
t	Index for years.
w	Index for alternative capacities.

Sets:

$\boldsymbol{B}$	Set of load blocks.
$\boldsymbol{D}$	Set of directions, $D = \{1, 2, \ldots, 8\}$.
$\boldsymbol{F}B$	Set of forbidden cells for candidate lines.
$\boldsymbol{F}G$	Set of forbidden cells for candidate plants.
$\boldsymbol{K}$	Set of candidate electric lines, $K = K^0 \cup K^1$.
$\boldsymbol{K}^0, \boldsymbol{K}^1$	Sets of candidate electric lines with both terminals fixed/one moveable terminal.
$\bar{\boldsymbol{K}}$	Set of existing electric lines.
$\boldsymbol{LT}$	Set of terminal cells for candidate electric lines.
$\boldsymbol{M}$	Set of candidate plants.
$\bar{\boldsymbol{M}}$	Set of existing plants.
$\boldsymbol{N}$	Set of buses.
$\boldsymbol{W}$	Set of alternative capacities for candidate plants.

Parameters:

BL	Bus-line incidence matrix.
BG	Bus-plant incidence matrix.
CT	Maximum number of units to be built in a candidate plant.
DL	Demand.
EG	Accumulated cost of plants.
EL	Per unit value for the accumulated cost of lines.
$\underset{\sim}{F}$	Lower capacity limit of lines.
$\tilde{F}$	Upper capacity limit of lines.
G	Big enough positive number.
LG	Line-plant incidence matrix.
P	Rated power of units/plants.
R	System reserve requirement.
T	Payback period.
V	Variable cost of units.
X	Reactance of existing lines.
X^0	Per unit length reactance of candidate lines.

Manuscript received January 18, 2014; revised June 25, 2014; accepted September 09, 2014. Date of publication September 29, 2014; date of current version June 16, 2015. This work was supported by the National Natural Science Foundation of China, under grant 51347003, and the Fundamental Research Funds for the Central Universities, under grant 12MS19. This work was also supported in part by the U.S. National Science Foundation grants ECCS-1102064 and ECCS-1254310. Paper no. TPWRS-01623-2013.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRS.2014.2358237

φ Annual interest rate.

γ Salvage factor.

τ Duration time.

Variables:

e Electric line investment cost.

f Line flow.

IC Total investment cost.

OC Total operation cost.

p Power generation.

$\tilde{p}$ Generation capacity.

SV Total salvage value.

x Candidate electric line installation state.

y Candidate plant installation state.

λ Capacity selection state.

δ Voltage angle.

η Number of units to be built in a candidate plant.

I. INTRODUCTION

THE expansion planning problem of power systems is highly important because of the growing needs on electricity. The discrete nature of the installation states of new power facilities makes the power system expansion planning problem a large-scale mixed integer programming model.

The power system expansion planning problem includes generation expansion planning [1]–[5] and transmission expansion planning [6]–[8] as two distinct problems. Recently, more and more studies have focused on the coordination of generation and transmission expansion planning [9]–[15].

Nowadays, increasing concerns on environmental protection have attracted interests of the public opinion. Environmental impacts need to be carefully considered in power system planning problems. However, it is a challenging issue due to complex and diverse environments. Existing literatures usually ignore or simplify the impacts of complicated environments by assuming that locations of candidate generators and routes of electric power lines are given. Although this assumption avoids the computational complexity brought by the complicated environments, it increases the gap between the planning and the erection because of ignoring the environmental information.

Geographic information systems (GIS) organize, analyze, manage, and present all types of geographical data efficiently, which have a significant potential in solving spatial power system expansion planning problems with the consideration of complicated environments. By using vector graphics for representing concrete objects, such as regions and infrastructures, [16]–[19] studied the optimal electric line routing problem in the vector map. However, there are two major drawbacks with the vector map: 1) non-concrete environmental elements, such as weather, sunlight, and pollution, may not be easily represented in vector graphics; 2) irregular vector graphics used in the vector map bring difficulties for developing comprehensive methodologies on power network expansion planning problems. Reference [20] presented a dynamic programming (DP) approach for automated power lines route selection in a raster map. In [21], by dividing the map into square cells, a siting methodology incorporating the GIS technology, the statistical evaluation methods, and the stakeholder collaboration was developed for producing quantifiable and consistent transmission line siting decisions. Similarly, adopting the raster map and the GIS data, [22] identified candidate areas for generating units. Reference [23] presented an effective methodology for the spatial power network planning, which considered variant environmental factors in the line routing formulation and integrated them in the traditional power network planning problem. Although the line routing, the generation siting, and the power network planning have been studied using the raster map and GIS data, integrating power network expansion with generation expansion while considering complicated environmental information in raster map is still an open challenge.

Generally, the objective of power system planning in regulated environment is to economically serve the future demand, while satisfying system reliability requirements [4], [5], [13], [14]. In restructured electricity markets, however, the misaligned interests of stockholders, participants, independent system operators, and customers make the power system planning an even tougher challenge. In [24], a constructive proposal was offered on the interaction of generation and transmission in transmission planning. The proposal initiated in [24] has been extended to illustrate the importance of the selection of the economic criteria for planning transmission investment [25]. By investigating a two-node network, [26] revealed how financial transmission rights affect generation firm's incentives to support transmission expansion, while [27] indicated that an optimal open-loop transmission investment policy has a multiperiod structure. Three-level equilibrium model for generation and transmission expansion planning was proposed to simulate behaviors of transmission planners, generator owners, and the market operation in [9] and [28]. Reference [29] discussed the effects of transmission nonlinearities on the performance of renewable portfolio standards.

In this paper, we proposes an MILP formulation on co-optimized generation and transmission expansion planning problem based on a rasterized map in regulated environment. Therefore, the strategic interaction between power generation expansion and power transmission expansion decisions is ignored. In order to relieve the huge computational burden brought by the electric line routing, a two-step approach is presented. DP is applied to solve the optimal line routing in the first step. The second step solves a MILP problem for obtaining the final optimal generation and transmission planning strategy based on the optimal electric line routes derived from the first step. The major contributions of the paper are as follows.

1) Candidate plants could be built on any cell in the map, which means that terminals of candidate lines connected to candidate plants are not fixed. This is a remarkable difference between this paper and the existing literatures in which terminals of candidate lines were fixed. The paper holds one assumption that for a candidate line connected to a candidate plant only one terminal is moveable and the other terminal is a fixed-location bus in the existing power grid. It can be justified by identifying that candidate lines with two moveable terminals directly connect two candidate plants, which is not common in real world.

2) In most cases, the proposed two-step approach would derive the same global optimal solutions as those by solving the original formulation directly. Thus, the two-step approach can significantly improve the computational efficiency while maintaining the solution optimality, and is more suitable for the raster map with high resolutions.

The rest of the paper is organized as follows. In Section II, cells in the rasterized map and the proposed co-optimized spatial power network and generation expansion planning model are discussed. The enhanced techniques for improving the computational efficiency are described in Section III, including the equivalent MILP problem reformulation. Case studies and conclusions are presented in Sections IV and V, respectively.

II. Problem Formulation

A. Accumulated Cost Matrix and the Altitude Matrix

As mentioned in [20]–[23], an image map including geographical and environmental information can be rasterized into $NR \times NC$ square cells, in which the region covered by each cell is assumed to have similar environmental and altitude characteristics. The accumulated cost matrix and the altitude matrix were discussed in [23] for considering variants environment for candidate lines. In this paper, the same method is adopted for constructing accumulated cost matrices of candidate lines and plants, as well as the altitude matrix of cells.

B. Objective Function

The objective of the proposed coordinated spatial power network and generation expansion planning problem is to minimize the total system cost (1), including investment costs, operations costs, and salvage values. Investment costs include costs for installing new plants and electric power lines (2). Operation costs include variable costs of existing and new plants (3). The salvage value is the value of new facility at the end of the payback period (4):

$$F = \text{Min} \quad \text{IC} + \text{OC} - \text{SV} \tag{1}$$

$$\text{IC} = \sum_{k \in K} e_k + \sum_{m \in M} \sum_i \sum_j EG_{i,j} \tilde{p}_{m,i,j} \tag{2}$$

$$\text{OC} = \sum_t \frac{1}{(1+\varphi)^{t-1}} \sum_{b \in B} \left(\sum_{m \in \bar{M}} p_{m,b} V_m + \sum_{m \in M} \sum_w p_{m,w,b} V_w \right) \tau_b \tag{3}$$

$$\text{SV} = \gamma \text{IC}/(1+\varphi)^{T-1}. \tag{4}$$

C. Plant Constraints

$$\sum_i \sum_j y_{m,i,j} \leq 1 \quad \forall m \in M \tag{5}$$

$$\sum_{w \in W} \lambda_{m,w} = \sum_i \sum_j y_{m,i,j} \quad \forall m \in M \tag{6}$$

$$\eta_{m,w} \leq CT_m \lambda_{m,w} \tag{7}$$

$$\sum_i \sum_j \tilde{p}_{m,i,j} = \sum_{w \in W} \eta_{m,w} P_w \quad \forall m \in M \tag{8}$$

$$\tilde{p}_{m,i,j} \leq G y_{m,i,j} \quad \forall m \in M, \forall i, \forall j \tag{9}$$

$$y_{m,i,j} = 0 \quad \forall m \in M, \forall (i,j) \in FG \tag{10}$$

where $y_{m,i,j}$ is the binary variable that is equal to 1 if plant m is built in cell $C_{i,j}$, and 0 otherwise; $\lambda_{m,w}$ is the binary variable that is equal to 1 if plant m choose the wth capacity block, and 0 otherwise; $\eta_{m,w}$ is the number of units of the wth capacity block built in plant m, $\tilde{p}_{m,i,j}$ expresses the capacity of plant m in $C_{i,j}$; and $p_{m,w,b}$ is power generation of plant m at the wth capacity block in the bth load block. The load duration curve is modeled via multiple discrete load blocks. A candidate plant can only be built in one cell (5). Constraint (6) expresses that only one capacity block can be chosen for an installed plant. The number of units that can be built in a plant is limited (7). If a candidate plant is to be built, capacities of candidate units within the plant are chosen from a set of discrete capacity blocks; otherwise, their capacities are zeroes (8). If plant m is installed in $C_{i,j}$ ($y_{m,i,j} = 1$), $\tilde{p}_{m,i,j}$ is nonzero for $C_{i,j}$ and zero for all other cells (9). In addition, the installation of plants is not allowed in certain cells (10). In (2), the investment cost of a new plant depends on the capacity $\tilde{p}_{m,i,j}$ and the location (cell) of construction. Here, $EG_{i,j}$ is the accumulated cost of plants in $C_{i,j}$. The investment cost of line e_k is determined by (37) and (39). In (3), the power generation efficiency V_w for new plants varies depending on the installed capacities of individual generating units in a plant. If $\lambda_{m,w} = 1$, $p_{m,w,b}$ can be nonzero for the wth capacity block and zero for other capacity blocks (30).

D. Constraints for Lines

Constraints (11)–(23) describe various limitations on candidate lines. More detailed explanation could be found in authors' previous work [23].

1) Constraints for Non-Terminal Cells: If line k does not cross a non-terminal cell $C_{i,j}$, all eight variables $x_{k,i,j,d}$ are equal to zeros. Otherwise, if line k crosses $C_{i,j}$, at least two of eight variables $x_{k,i,j,d}$ are ones. In addition, it is not reasonable that line k selects more than two directions on $C_{i,j}$, which leads to that the sum of all eight variables $x_{k,i,j,d}$ must be equal to 2 or 0, as shown in (11):

$$2x_{k,i,j,d} \leq \sum_{\bar{d}} x_{k,i,j,\bar{d}} \leq 2 \quad \forall k \in K, \forall d, \forall (i,j) \notin LT_k \tag{11}$$

where the binary variable $x_{k,i,j,d}$ is used to represent whether an electric line k selects the direction d in cell $C_{i,j}$ or not.

2) Constraints for Fixed-Location Terminal Cells: If $C_{i,j}$ is a terminal cell of an installed candidate line k, only one of eight variables $x_{k,i,j,d}$ can be one as (12):

$$\sum_d x_{k,i,j,d} = x_k \quad \forall k \in K, \forall (i,j) \in LT_k. \tag{12}$$

3) Constraints That Relate Adjacent Cells: If a decision $x_{k,i,j,d}$ is made in $C_{i,j}$, its adjacent cells need to make corresponding decisions for keeping the consistency (13). For instance, $x_{k,i,j,1}$ and $x_{k,i-1,j-1,5}$ need to be ones (zeros) simultaneously:

$$\begin{cases} x_{k,i-1,j-1,5} = x_{k,i,j,1} & x_{k,i-1,j,6} = x_{k,i,j,2} \\ x_{k,i-1,j+1,7} = x_{k,i,j,3} & x_{k,i,j+1,8} = x_{k,i,j,4} \\ x_{k,i+1,j+1,1} = x_{k,i,j,5} & x_{k,i+1,j,2} = x_{k,i,j,6} \\ x_{k,i+1,j-1,3} = x_{k,i,j,7} & x_{k,i,j-1,4} = x_{k,i,j,8} \end{cases} \quad \forall k \in K, \forall i, \forall j. \tag{13}$$

4) Constraints for Forbidden Cells: Some cells are prohibited to construct electric lines (14):

$$\sum_{d} x_{k,i,j,d} = 0 \quad \forall k \in K, \forall (i,j) \in FB. \tag{14}$$

5) Constraints for Tighter Formulations: Additional constraints (15)–(20) are added for deriving a tighter formulation and improving the computational efficiency. Detailed information on (15)–(20), including descriptions for $C_{d,1\sim 6}$, can be found in authors' previous work [23]:

$$\begin{cases} x_{k,i,j,d_1^+} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,1} < 0 \\ x_{k,i,j,d_1^-} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,2} < 0 \end{cases} \quad \forall k \in K, \forall i, \forall j \tag{15}$$

$$\begin{aligned} d_1^+ &= (d+1) \mod 8 \\ d_1^- &= (d-1) \mod 8 \end{aligned} \tag{16}$$

$$\begin{cases} x_{k,i,j,d_2^+} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,3} < 0 \\ x_{k,i,j,d_2^-} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,4} < 0 \end{cases} \quad \forall k \in K, \forall i, \forall j \tag{17}$$

$$\begin{aligned} d_2^+ &= (d+2) \mod 8 \\ d_2^- &= (d-2) \mod 8 \end{aligned} \tag{18}$$

$$\begin{cases} x_{k,i,j,d_3^+} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,5} < 0 \\ x_{k,i,j,d_3^+} \le 1 - x_{k,i,j,d} & \text{if} \quad C_{d,6} < 0 \end{cases} \quad \forall k \in K, \forall i, \forall j \tag{19}$$

$$\begin{aligned} d_3^+ &= (d+3) \mod 8 \\ d_3^- &= (d-3) \mod 8. \end{aligned} \tag{20}$$

6) Coupling Constraints Between Candidate Line Investment Decision Variables and Direction Variables: If a candidate line k is not built, its corresponding $x_{k,i,j,d}$ are all zeros (21):

$$x_k \le \sum_{i} \sum_{j} \sum_{d} x_{k,i,j,d} \le G x_k \quad \forall k \in K. \tag{21}$$

7) Line Length Equations: The length of candidate line k is given in (22), which is obtained via accumulating the line length in $C_{i,j}$ on direction d along the line route indicated by $x_{k,i,j,d}$:

$$s_k = 0.5 \sum_{i} \sum_{j} \sum_{d} S_{i,j,d} x_{k,i,j,d} \quad \forall k \in K \tag{22}$$

where $S_{i,j,d}$ is the line length in $C_{i,j}$ on direction d [23].

8) Line Investment Cost Equations: The investment cost of candidate line k is given in (23):

$$e_k = 0.5 \sum_{i} \sum_{j} \sum_{d} EL_{i,j} S_{i,j,d} x_{k,i,j,d} \quad \forall k \in K. \tag{23}$$

E. Coupling Constraints Between Candidate Lines and Plants

If a candidate plant is not built, all candidate lines connected to it should not be invested (24). Otherwise, at least one candidate line should be invested (25). For a candidate plant m, if line k is not connected to it (i.e., $LG_{k,m} = 0$), (26) is equivalent to (11). Otherwise, the following two situations are considered: if plant m is built in $C_{i,j}$ (i.e., $y_{m,i,j} = 1$), which means that $C_{i,j}$ is a terminal of line k, (26) is equivalent to (12) with the consideration of (13) and (21); if plant m is not built in $C_{i,j}$, (26) is equivalent to (11):

$$x_k \le \sum_{m \in M} \sum_{i} \sum_{j} LG_{k,m} y_{m,i,j} \quad \forall k \in K \tag{24}$$

$$\sum_{i} \sum_{j} y_{m,i,j} \le \sum_{k \in K} LG_{k,m} x_k \quad \forall m \in M \tag{25}$$

$$2 \left(x_{k,i,j,d} - \sum_{m \in M} LG_{k,m} y_{m,i,j} \right) \le \sum_{\bar{d}} x_{k,i,j,\bar{d}} \le \left(2 - \sum_{m \in M} LG_{k,m} y_{m,i,j} \right) \quad \forall k \in K. \tag{26}$$

F. System Operation Constraints

The system spinning reserve requirement (27) ensures enough spinning reserves provided by units. (28) represents the load balance at each bus. The power limits for existing plants are considered in (29), and the power limits for candidate plants are formulated as (30)–(31). Existing line flows are modeled by (32)–(33). For candidate lines, power flows depends on the installation status of the line (34)–(35):

$$\sum_{m \in \bar{M}} P_m + \sum_{m \in M} \sum_{w} \eta_{m,w} P_w - \sum_{n} DL_{n,b} \ge R_b \quad \forall b \tag{27}$$

$$\sum_{k} BL_{k,n} f_{k,b} = \sum_{m} BG_{m,n} p_{m,b} - DL_{n,b} \quad \forall n, \forall b \tag{28}$$

$$0 \le p_{m,b} \le P_m \quad \forall m \in \bar{M}, \forall b \tag{29}$$

$$0 \le p_{m,w,b} \le \eta_{m,w} P_w \quad \forall m \in M, \forall w, \forall b \tag{30}$$

$$p_{m,b} = \sum_{w} p_{m,w,b} \quad \forall m \in M, \forall b \tag{31}$$

$$\underset{\sim}{F}_k \le f_{k,b} \le \tilde{F}_k \quad \forall k \in \bar{K}, \forall b \tag{32}$$

$$f_{k,b} = \frac{1}{X_k} \sum_{n} BL_{k,n} \delta_{n,b} \quad \forall k \in \bar{K}, \forall b \tag{33}$$

$$x_k \underset{\sim}{F}_k \le f_{k,b} \le x_k \tilde{F}_k \quad \forall k \in K, \forall b \tag{34}$$

$$f_{k,b} = \frac{1}{s_k X_k^0} \sum_{n} BL_{k,n} \delta_{n,b} \quad \forall k \in K, \forall b. \tag{35}$$

The nonlinear formulation (35) can be linearized by integer algebra techniques and solved via MILP [23].

III. Improved Formulation

The formulation proposed in Section II integrates optimal investment and routing decisions of candidate lines, optimal investment and siting decisions of candidate plants, as well as the power network security evaluation. The complicated optimal electric line routing introduces considerable computational challenges in the proposed formulation, especially when considering relatively high resolutions in the raster map. To solve the co-optimized spatial power network expansion and generation expansion problem in a reasonable computation time, a two-step approach integrating MILP with DP is presented. That is, DP is first applied for solving the optimal electric line routing problem, and the second step solves the remaining MILP problem for the co-optimized power network expansion and generation expansion with optimal electric line routes from the first step.

A. Optimal Electric Line Routing Based on DP

DP is a suitable optimization technique for solving the optimal line routing problem using the GIS raster structures [20]. The sequence of cells along a line route represents the stages in the DP terminology, and the accumulated transition cost between the two neighboring cells is optimized in the objective. From any starting cell, if optimal routes of the eight neighbor cells of $C_{i,j}$ are known, the optimal route of $C_{i,j}$ can be determined via (36):

$$\Psi_{i,j} = \underset{(\bar{i},\bar{j})\in\Gamma_{i,j}}{\text{Min}} \left(\Psi_{\bar{i},\bar{j}} + \psi_{\bar{i},\bar{j}}\right) \tag{36}$$

where $\Psi_{i,j}$ is the optimal route from the starting cell to $C_{i,j}$, $\psi_{\bar{i},\bar{j}}$ is the investment cost of line from $C_{\bar{i},\bar{j}}$ to $C_{i,j}$, and $\Gamma_{i,j}$ is the set of the eight neighbor cells of $C_{i,j}$.

The DP optimization process selects the consecutive stages by choosing the cell links that would lead to the minimum accumulated transition cost over the entire map. That is, one single DP process can obtain all optimal routes between the origin cell and all other cells over the entire map. The details of the DP-based optimal electric line routing problem can also be found in [20].

In this paper, terminals of all candidate lines are given as input parameters except those connected to candidate plants. That is, locations of candidate plants are not fixed, which makes terminals of candidate lines connected to them moveable. If both terminals of a candidate line are moveable, we have to perform approximately $NR \times NC$ DP optimization processes to obtain optimal routes for that line. This would result in unbearable computational costs in the raster map with relatively high resolutions. Since additional candidate lines connected to candidate plants are to integrate plants into the existing power grid, without loss of generality, we assume that for a candidate line connected to a candidate plant, only one terminal is moveable and the other terminal is a fixed-location bus in the existing power grid. In the worst case, the number of DP optimization processes that need to be performed is equal to the number of fixed-location terminals. However, it can be reduced by a sophisticated tuning on the sequence of terminals to be explored via the DP optimization process. The idea is to divide the fixed-location terminals of candidate lines into two categories with different priorities for processing. The fixed-location terminals connected to moveable terminals via candidate lines belong to the first category and have the highest processing priorities. That is, terminals in the first category will be processed first. The remaining fixed-location terminals form category 2. Terminals in category 2 are sorted in the descending order by the number of fixed-location terminals (excluding terminals in category 1 and higher priority terminals in category 2) they are connected to via candidate lines. This order is used to determine the priority of terminals to be processed in category 2. The idea can be illustrated by the example shown in Fig. 1, which is to find optimal routes for all candidate lines as shown in dash lines. In the example illustrated in Fig. 1, there are five fixed-location terminals of candidate lines, including 1 and 3–6. Terminal 1 belongs to the first category because it is connected to the movable terminal 2, while terminals 3–6 belong to the second category. For all terminals in the second category, terminal 3 is connected to two other fixed-location terminals 4 and 5 (excluding the higher-priority terminal 1), and terminals 4–6 are connected to 2, 3, and 1 other fixed-location terminals, respectively. Thus, terminal 5 has the highest priority in category 2. Terminals 3 and 4 are the second highest priority terminals in category 2, which are connected to one other fixed-location terminal (excluding the higher-priority terminals 1 and 5), and terminal 6 has the lowest priority in category 2. Using the priority order of (1, 5, 3, 4, 6) or (1, 5, 4, 3, 6) for the DP procedure, the first DP process explores the optimal routes for candidate lines 1-2 and 1-3, the second DP process explores the optimal routes for candidate lines 5-6, 5-4, and 5-3, and the third DP process explores the optimal route for candidate line 3–4. Thus, only 3 DP processes is needed to obtain all possible optimal routes for all candidate lines. On the other hand, using other sequences may lead to higher numbers of DP processes. For instance, using the ascending order of terminal indices (1, 3, 4, 5, 6), 4 DP processes is needed to obtain optimal routes for all candidate lines, in which the first DP process explores the optimal routes for candidate lines 1–2 and 1–3, the second DP process explores the optimal routes for candidate lines 3–4 and 3–5, the third DP process explores the optimal routes for candidate line 4–5, and the fourth DP process explores the optimal routes for candidate line 5–6.

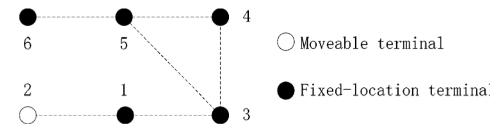


Fig. 1. Simple network example.

B. Second Step MILP Problem With Optimal Line Routes

With the optimal line routes obtained via DP, the co-optimized spatial power network expansion and generation expansion problem can be reformulated by eliminating the line routing related constraints (11)-(26). Furthermore, the line length equation (22) and the line investment cost equations (23) are reformulated as (37)–(38) for candidate lines with two fixed-location terminals. Similarly, for candidate lines with one moveable terminal, (22)–(23) can be reformulated as (39)–(41). Equations (37)–(38) indicate that the investment cost and the length of a line with two fixed-location terminals depend on the line installation state, while (39)–(41) indicate that the investment cost and the length of a line with one moveable terminal depend on the line installation state and the location of the candidate plant to which it is connected:

$$e_k = x_k \hat{E}_k \quad \forall k \in K^0 \tag{37}$$

$$s_k = \hat{S}_k / x_k \quad \forall k \in K^0 \tag{38}$$

$$e_k = x_k \sum_i \sum_j \hat{x}_{k,i,j} \hat{E}_{k,i,j} \quad \forall k \in K^1 \tag{39}$$

$$s_k = \sum_i \sum_j \hat{x}_{k,i,j} \hat{S}_{k,i,j} \Bigg/ x_k \quad \forall k \in K^1 \tag{40}$$

$$\hat{x}_{k,i,j} = \sum_{m\in M} LG_{k,m} y_{m,i,j} \quad \forall k \in K^1 \tag{41}$$

where $\hat{E}$ and $\hat{S}$ are the investment cost and the length for lines, respectively, which can be calculated along with the optimal line routes. $\hat{x}$ are binary variables indicating the locations of moveable terminals of lines, which are related to the location of candidate plants to which the lines are connected.

Thus, with the optimal line routes obtained via DP, the co-optimized spatial power network expansion and generation expansion problem is to optimize the objective function (1)–(4) subject to constraints (5)–(10) and (27)–(41). The advantage of this two-step approach is that the computational burden can be significantly reduced by separating optimal line routing $x_{k,i,j,d}$ in the first step from the optimal network and generation expansion in the second step.

In the proposed two-step approach, the optimal line routes between any two cells obtained via DP in the first step are inputs to the second step MILP formulation. Authors' previous work [23] indicated that the minimum investment cost of lines may not always derive the optimal solution in terms of the minimum total system cost. On certain occasions, line routes deviating from the minimum investment cost line routes may relieve power network congestions by tuning line parameters and reallocating power flows, which may avoid new line installations and reduce the total system cost. Fortunately, such a situation is rare. Thus, the proposed two-step approach would derive the same global optimal solutions as those by solving the original formulation directly in most cases.

Note that nonlinear constraints (35), (38), and (40) can be linearized by integer algebra techniques [30] and incorporated into the second step MILP formulation. Given a binary variable l and a continuous variable $q \in \{q_{\min}, q_{\max}\}$, the linearized equivalent representation for the bilinear term lq is given as (42)–(43), where the new continuous variable h represents the bilinear term lq:

$$q - q_{\max}(1-l) \le h \le q - q_{\min}(1-l) \quad (42)$$

$$q_{\min} l \le h \le q_{\max} l. \quad (43)$$

Thus, for candidate lines with two fixed-location terminals, (35) and (38) can be rewritten as (44), which can be linearized as (45) by the mixed-integer linear disjunctive formulation [7]. For candidate lines with one moveable terminal, (35) and (40) can be rewritten as (46). By applying (42)–(43), the left hand side of (46) is equivalently substituted by linear constraints, and the right hand side of (46) is linearized by the mixed-integer linear disjunctive formulation [7] as shown in (47)–(49):

$$f_{k,b} x_k \hat{S}_k = x_k \sum_n BL_{k,n}\delta_{n,b} \qquad \forall k \in K^0, \forall b \quad (44)$$

$$\left| f_{k,b}\hat{S}_k - \sum_n BL_{k,n}\delta_{n,b} \right| \le M(1-x_k) \qquad \forall k \in K^0, \forall b \quad (45)$$

$$f_{k,b} \sum_i \sum_j \hat{x}_{k,i,j} X_k^0 \hat{S}_{k,i,j} = x_k \sum_n BL_{k,n}\delta_{n,b} \qquad \forall k \in K^1, \forall b \quad (46)$$

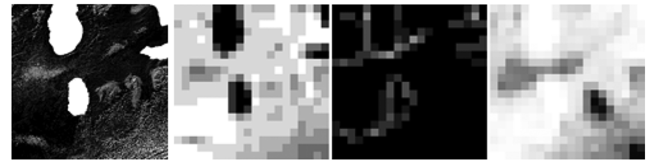
$$\left| \sum_i \sum_j r_{k,b,i,j} X_k^0 \hat{S}_{k,i,j} - \sum_n BL_{k,n}\delta_{n,b} \right| \le M(1-x_k) \qquad \forall k \in K^1, \forall b \quad (47)$$

$$f_{k,b} - f_{k,\max}(1-\hat{x}_{k,i,j}) \le r_{k,b,i,j} \le f_{k,b} - f_{k,\min}(1-\hat{x}_{k,i,j}) \qquad \forall k \in K^1, \forall b \quad (48)$$

$$f_{k,\min}\hat{x}_{k,i,j} \le r_{k,b,i,j} \le f_{k,\max}\hat{x}_{k,i,j} \qquad \forall k \in K^1, \forall b \quad (49)$$

where $r_{k,b,i,j} = f_{k,b}\hat{x}_{k,i,j}$.

In summary, the final MILP formulation of the co-optimized spatial power network and generation expansion problem in the second step is to optimize the objective function (1)–(4) subject to constraints (5)–(10), (27)–(32), (34), (37), (39), (45), and (47)–(49). This MILP problem can be effectively solved by commercial MILP solvers such as CPLEX.



(a) (b) (c) (d)

Fig. 2. Image and raster maps of the planning region.

TABLE I
ACCUMULATED COSTS AND ALTITUDES

No	Color	Cost for plants (10^3\$/MW)	Cost for lines (10^3\$/p.u.)	Altitude (p.u.)
1		300.00	10.00	0.00
2		637.50	21.25	0.50
3		975.00	32.50	1.00
4		1312.50	43.75	1.50
5		1650.00	55.00	2.00
6		1987.50	66.25	2.50
7		2325.00	77.50	3.00
8		2662.50	88.75	3.50
9		--	--	4.00

IV. Case Studies

In this section, a 4-bus system, 7-bus system, the modified IEEE 30-bus system, and the modified IEEE 118-bus system are used to analyze the effectiveness of the proposed approach. The DP optimization process is developed in MATLAB. The MILP formulation is implemented in GAMS 23 and solved using CPLEX 11. The numerical results are carried out on an Intel Core I5 2.50-GHz personal computer with 3 GB of RAM. $X_k = 0.001$, $\varphi = 8\%$, $T = 20$, $CT_m = 1$, and $\gamma = 5\%$ are used for all studies. The MIP relative optimality gap is set to 0.1%.

A. Case Studies of the 4-Bus System

Image map of the planning region in Fig. 2(a) is rasterized by 20×20 cells. Accumulated costs of lines and plants are shown in Fig. 2(b) and (c), respectively. Altitude information of cells is shown in Fig. 2(d). Table I lists the colors as well as their corresponding accumulated costs and altitudes. In Table I, "--" indicates forbidden cells.

The 4-bus system shown in Fig. 3 is applied for comparing optimal solutions derived from the original formulation (OM) in Section II and the improved formulation (IM) in Section III. The existing system is shown with solid lines, and candidate facilities are shown via dashed lines. Capacities of all lines are 100 MW. Capacity of existing plant 1 is 300 MW, with the variable cost of 45 \$/MWh. Capacity of candidate plant 2 is 100 MW, with the variable cost of 30 \$/MWh. For simplicity, one load block is considered, with the magnitude of 2.9 times of the base load and the time duration of 8760 h. The base load of D1 is 40 MW. The base load of D2 increases from 0 MW to 66 MW.

Optimal line routes derived from OM and IM are compared in Fig. 4, when the base load of D2 is 54 MW. In Fig. 4, all fixed buses are shown with red squares, and locations of moveable buses for new plant installations are represented as red circular frames. Curves with different colors indicate optimal routes of constructed lines.

In Fig. 4, final planning decisions of OM and IM are different when the base load of D2 is 54 MW. A new line L04 is built to relieve the congestion of L03 in IM, while in OM the final line route of L03 can deviate from the minimum investment cost line

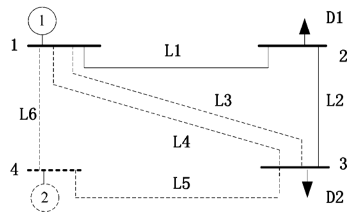


Fig. 3. The 4-bus system.

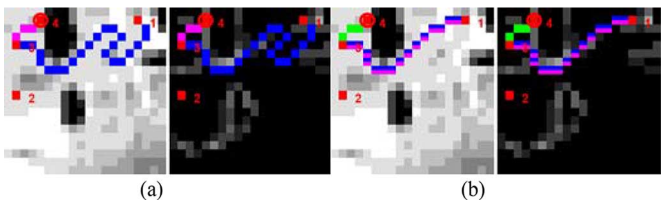


Fig. 4. Optimal result of OM and IM. (a) OM. (b) IM.

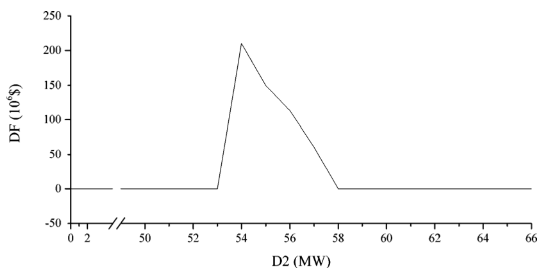


Fig. 5. *DF* with respect to the base load of D2.

route in order to increase its reactance and decrease the power flow.

Fig. 5 provides differences in the total costs of optimal solutions derived from OM and IM $(DF = F_{IM} - F_{OM})$ with respect to the base load of D2. It can be observed from Fig. 5 that *DF* is none zero only if 53 MW $<$ D2 $<$ 58 MW; otherwise, *DF* is zero.

From Figs. 4 and 5, the following conclusions can be drawn: 1) OM may obtain better solutions than IM in certain cases; 2) IM and OM would derive the same global optimal solutions in most cases.

B. Case Studies of the 7-Bus System

The proposed method is applied to the 7-bus test system as shown in Fig. 6, which is modified based on the Garver test system in [31]. The supply-side of this system is composed of three existing plants 1, 2, and 3 located at buses 1, 2, and 3, and two candidate plants 4 and 5 located at moveable buses 6 and 7, respectively, which can be constructed in any cell. Capacities of plants 1, 2, and 3 are 200, 200, and 150 MW, respectively. Variable costs of the three existing plants are all equal to 45 \$/MWh. Alternative capacities of units in candidate plants are 30, 60, and 100 MW, with variable costs of 40, 35, and 30 \$/MWh, respectively. The information of candidate lines is shown in Table II. Three load blocks are considered as 1.0, 1.5, and 2.9 times of the base load in [31], with time durations of 5000, 3000, and 760 h. Image map of the planning region in Fig. 2(a) is rasterized by 40×40 cells. Accumulated costs of lines listed in Table I are decreased by a factor of 2.

Four cases are discussed to show the effect of the proposed model. In Case 1, locations of candidate plants 4 and 5 are fixed in cells (8, 12) and (27, 14), respectively. Case 2 considers moveable candidate plant locations. Cases 3 and 4 are the same as Case 2, except that the load level of the third load block is increased to 2.975 and 3.0 times of the base load.

Optimal results of the four cases, including optimal costs, installed plants, and constructed lines, are compared in Tables III–V and Fig. 7(a)–(d), respectively.

The generation investment costs in cells (8, 12) and (27, 14) are 300×10^3 \$/MW, which is the lowest in the entire planning region. However, the lowest generation investment cost may not lead to the lowest total cost. The optimal result of Case 1 shows that the strategy of simply pursuing the lowest generation investment cost would result in a relatively higher total cost as compared to Case 2. In Case 1, plant 4 located on bus 6 is connected to buses 2 and 4 via lines 11 and 12, while plant 5 located on bus 7 is connected to bus 5 via line 14. In addition, lines 8 and 9 are constructed for relieving power network congestions.

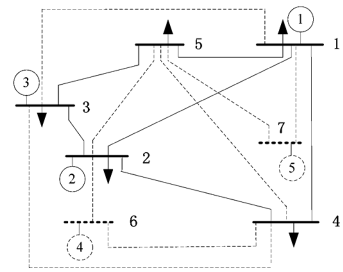


Fig. 6. The 7-bus system.

TABLE II
CANDIDATE LINES DATA OF THE 7-BUS SYSTEM

Line	From	To	Capacity (MW)	Line	From	To	Capacity (MW)
7	1	3	50	11	2	6	50
8	2	5	50	12	4	6	50
9	3	4	50	13	1	7	50
10	4	5	50	14	5	7	50

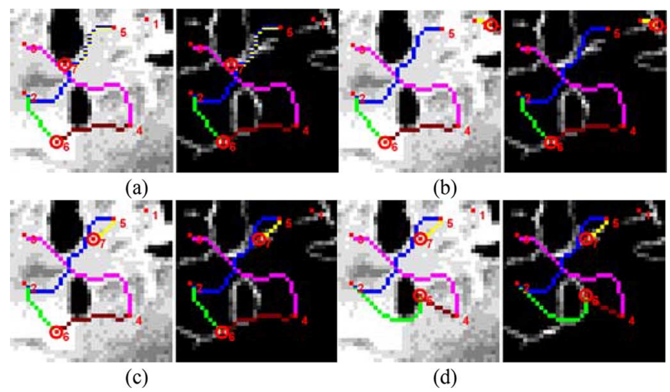


Fig. 7. Optimal results of cases 1–4. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

TABLE III
COSTS OF ALL THREE CASES (10^6 \$)

	Case 1	Case 2	Case 3	Case 4
Unit investment cost	60.00	68.25	68.25	135.75
Linc investment cost	1060.52	956.61	994.41	1016.79
Operation cost	1140.47	1165.75	1175.64	1177.40
Salvage cost	12.98	11.87	12.31	13.35
Total Cost	2248.01	2178.74	2225.99	2316.59

TABLE IV
CONSTRUCTED LINES OF THE FOUR CASES

Line	Case 1		Case 2		Case 3		Case 4	
	Cost (10^6\$)	Length (p.u.)	Cost (10^6\$)	Length (p.u.)	Cost (10^6\$)	Length (p.u.)	Cost (10^6\$)	Length (p.u.)
7	0	--	0	--	0	--	0	--
8	293.05	18.04	293.05	18.04	293.05	18.04	293.05	18.04
9	318.18	20.30	318.18	20.30	318.18	20.30	318.18	20.30
10	0	--	0	--	0	--	0	--
11	113.04	7.82	113.04	7.82	113.04	7.82	211.25	13.01
12	198.96	11.01	198.96	11.01	198.96	11.01	123.13	6.31
13	0	--	33.40	2.21	0	--	0	--
14	137.30	9.48	0	--	71.19	3.86	71.19	3.86

TABLE V
INSTALLED PLANTS OF THE FOUR CASES

Plant	Items	Case 1	Case 2	Case 3	Case 4
4	Cost(10^6\$)	30.00	30.00	30.00	97.50
	Capacity(MW)	100.00	100	100	100
	Location	(8, 12)	(8, 12)	(8, 12)	(17, 21)
5	Cost(10^6\$)	30.00	38.25	38.25	38.25
	Capacity(MW)	100.00	60.00	60.00	60.00
	Location	(27, 14)	(37,38)	(31,21)	(31,21)

There is a tradeoff between the generation expansion and the power network expansion. In comparison with Case 1, in Case 2 plant 5 is moved to cell (37, 38) and connected to bus 1 via line 13 with relatively higher generation investment costs and lower line investment costs. The lower total cost of Case 2 indicates that the coordination of generation and transmission expansion planning can derive more economical solutions.

In Case 3, when the third load block is increased to 2.975 times of the base load level, no feasible solution can be obtained if candidate plant 5 is connected to bus 1 via line 13, due to the violation of the power network security constraints. Alternatively, connecting plant 5 to bus 5 via line 14 would mitigate the violation of power network security constraints. However, the investment cost of line 14 turns out to be quite high with plant 5 staying in cell (37, 38). Therefore, plant 5 moves to cell (31, 21) for decreasing the investment cost of line 14 in Case 3.

In Case 4, the third load block is increased to 3.0 times of the base load level. In such a situation, no matter where plants 4 and 5 are located at, no feasible solution can be achieved if plants 4 and 5 stay in cells (8, 12) and (31, 21), respectively. However, changing locations of plants is an alternative way to obtain a feasible solution. Thus, the optimal solution of Case 4 moves plant 4 to cell (31, 21) with a relatively higher generation investment cost.

C. Case Studies of the Modified IEEE 30-Bus System

The original IEEE 30-bus system which can be found in http://shodhganga.inflibnet.ac.in/bitstream/10603/1221/18/18_appendix.pdf has 30 existing buses, 41 existing lines, and 6 existing generating plants. We consider 16 candidate lines and 7 candidate plants, where candidate plants are connected to moveable buses. Data for candidate plants and lines are shown in Tables VI and VII, respectively. Variable costs of existing plants are all 45 \$/MWh. Alternative capacities of candidate units are 10, 30, and 60 MW, with variable costs of 40, 35, and 30 \$/MWh, respectively. Three load blocks are considered as 1.0, 1.5, and 2.1 times of the base load level, with corresponding time durations of 5000, 3000, and 760 h, respectively. The image map of the planning region in Fig. 2(a) is rasterized by 100×100 cells. Accumulated costs of lines listed in Table I are decreased by a factor of 5. The optimal result is shown in Fig. 8. Installed plants and constructed lines are listed in Tables VIII and IX, respectively.

In order to investigate the performance of the proposed algorithm, IM, OM, and a hybrid genetic algorithm (GA) and linear programming (LP) approach (HA) are applied for solving the

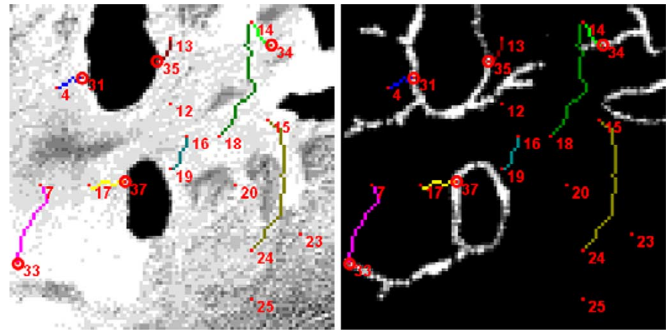


Fig. 8. Optimal results of the modified IEEE 30-bus system.

TABLE VI
CANDIDATE LINE DATA OF THE MODIFIED 30-BUS SYSTEM

Line	From	To	Capacity (MW)	Line	From	To	Capacity (MW)
42	4	31	60	50	14	16	32
43	23	32	60	51	14	18	32
44	7	33	60	52	15	19	32
45	14	34	60	53	15	23	32
46	13	35	60	54	15	24	32
47	16	36	60	55	16	19	32
48	17	37	60	56	16	20	32
49	12	17	32	57	16	23	32

TABLE VII
CANDIDATE PLANT DATA OF THE MODIFIED 30-BUS SYSTEM

Plant	Bus	Plant	Bus	Plant	Bus
7	31	10	34	13	37
8	32	11	35		
9	33	12	36		

TABLE VIII
CONSTRUCTED LINES OF THE MODIFIED 30-BUS SYSTEM

Line	Cost(10^6\$)	Length(p.u.)	Line	Cost(10^6\$)	Length(p.u.)
42	21.73	2.50	49	0	--
43	0	--	50	0	--
44	74.39	5.90	51	89.19	8.75
45	23.66	2.04	52	0	--
46	28.30	1.87	53	0	--
47	0	--	54	145.85	10.49
48	37.28	2.76	55	33.26	2.93

TABLE IX
INSTALLED PLANTS OF THE MODIFIED 30-BUS SYSTEM

Plant	Cost(10^6\$)	Capacity(MW)	Location
7	18.00	60.00	(78,23)
8	0	0	(--,--)
9	18.00	60.00	(21,3)
10	18.00	60.00	(88, 81)
11	18.00	60.00	(83, 46)
12	0	0	(--,--)
13	18.00	60.00	(46, 36)

TABLE X
CPU Time of IM, OM, and HA (s)

Items	Resolutions				
	20×20	30×30	40×40	50×50	100×100
IM	5	14	20	55	134
OM	468	3235	17952	--	--
HA	429	429	429	430	431

TABLE XI
Total Costs of IM, OM, and HA (10^6 $)

Items	Resolutions				
	20×20	30×30	40×40	50×50	100×100
IM	2350.92	2046.20	1974.23	1931.87	1777.97
OM	2350.92	2046.20	1974.23	--	--
HA	2350.92	2046.20	2035.71	2022.56	1890.01

same problem. The HA is implemented in MATLAB based on optimal line routes derived from the first step, in which the GA is devoted to handle the combinatorial nature of coordinated spatial power network and generation expansion (the location and the capacity of plants, as well as the structure of the network), while the LP is used for solving economic dispatch of individuals generated by GA. For the sake of comparison, we assume that the network formulation is linearized (i.e., bus voltages and losses are ignored) for the HA. The population size and the maximum iteration of the HA are set as 60 and 200, respectively. CPU times and results of IM, OM, and HA in different resolutions of raster maps are presented in Tables X and XI, respectively. It is noted that: 1) For the raster map with low resolutions, IM, OM, and HA can obtain the same optimal solutions. However, the CPU time of the proposed MILP formulation is lower than that of OM and HA. 2) The CPU time of the OM increases much faster than that of the IM with increased resolution of the raster map, while the CPU time of the HA almost remains unchanged because the CPU time of the HA is mainly affected by the population size and the maximum iteration. 3) The OM cannot obtain a feasible solution for the raster map with the resolution of 50×50 and above before running out of the memory. 4) Comparing results of IM, the solution of HA deteriorates significantly with the increase in the resolution of the raster map, because the premature convergence is the main obstacle to the application of heuristic algorithms like GA.

D. Case Studies of the Modified IEEE 118-Bus System

The IEEE 118-bus system is used to demonstrate the effectiveness of the proposed approach to large power systems. The system includes 186 existing lines and 54 existing generating plants. The detailed data can be found in motor.ece.iit.edu/data/SCUC_118test.xls. Line capacities are modified to observe more congestion. Data for 12 candidate plants and 24 lines are shown in Tables XII and XIII, respectively. Capacities of candidate lines are all 60 MW. Other parameters are the same as those of Section IV-C. The optimal result is depicted in Fig. 9.

The final optimal solution is obtained in about 1248 s. Seven generation sources with the total generation capacity of 390 MW are invested, with the total investment costs of $\$117.00 \times 10^6$. Accordingly, the installation of 9 transmission lines with the total capacity of 540 MW costs about $\$333.11 \times 10^6$. Other objective values include the total operation cost of $\$5998.73 \times 10^6$ and the salvage cost of $\$5.22 \times 10^6$.

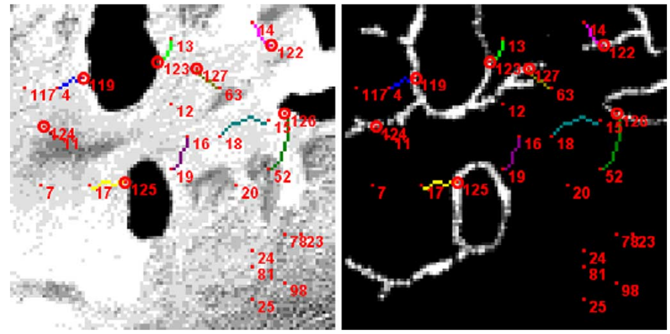


Fig. 9. Optimal results of the modified IEEE 118-bus system.

TABLE XII
Candidate Line Data of the Modified 118-Bus System

Line	From	To	Line	From	To	Line	From	To
187	4	119	195	63	127	203	16	20
188	23	120	196	12	17	204	16	23
189	7	121	197	14	16	205	81	128
190	14	122	198	14	18	206	78	129
191	13	123	199	15	11	207	98	130
192	11	124	200	15	117	208	78	81
193	17	125	201	15	18	209	24	25
194	52	126	202	16	19	210	14	117

TABLE XIII
Candidate Plant Data of the Modified 118-Bus System

Plant	Bus	Plant	Bus	Plant	Bus	Plant	Bus
56	119	59	122	62	125	65	128
57	120	60	123	63	126	66	129
58	121	61	124	64	127	67	130

V. Conclusion

This paper provides an innovative MILP formulation for the spatial power network expansion planning considering generation expansion, which explores optimal generating plant sizing and siting as well as the optimal electric line investment and routing, and integrates them into the power network evaluation in the raster map. Furthermore, the two-step approach integrating MILP with DP is proposed to improve the computational efficiency. Following conclusions are observed through numerical case studies:

1) In this paper, the locations of candidate plants are movable. The moveable locations of candidate plants would derive more economical planning solutions than the fixed locations of candidate plants.
2) The moveable locations of candidate plants bring about variable line parameters of candidate lines connected to them and, in turn, variable power flows distributed in power network. This would derive more economical and flexible solutions than the traditional power system planning which assumes fixed terminals of candidate line, at the cost of increased computational complexity.
3) The two-step approach can significantly improve the computational efficiency, and is more suitable for the raster map with high resolutions.

Although the proposed model is a static one which considers the single snapshot of power system planning, it can be expanded to multi-objective planning, multi-period dynamic planning, and uncertainty planning with minor modifications, which would be investigated in the future work.

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