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Integrated Optimization of Combined Generation and Transmission Expansion Planning Considering Bus Voltage Limits

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Abstract – A novel integrated optimization method is proposed to combine both generation and transmission line expansion problem considering bus voltage limit. Most of the existing researches on the combined generation and transmission expansion planning cannot consider bus voltages and reactive power flow limits because they are mostly based on the DC power flow model. In this paper the AC power flow model and nonlinear constraints related to reactive power are simplified and modified to improve the computation time and convergence. The proposed method has been successfully applied to Garver's six-bus system which is one of the most frequently used small scale sample systems to verify the transmission expansion method.

Keywords: Generation expansion planning, Transmission expansion planning, Integrated optimization, AC power flow model

1. Introduction

The purpose of a generation and transmission expansion planning is to decide the type and number of generators and transmission lines that should be added to the power system, and the appropriate time to add them, so that future electricity demand and the reliability conditions can be met at the least cost [1]. Finding the optimal solution of the problem in a practical power system has always been a challenging issue during the last several decades due to its large dimension, non-convexity and various uncertainties.

To name a few, several artificial intelligence techniques have been applied to solve the problem, such as fuzzy theory [2, 3], artificial neural network [4], genetic algorithm [5, 6], simulated annealing [7], particle swarm optimization [8], etc. Also, in order to tackle the various uncertainties, stochastic programming [9], stochastic mixed-integer programming [10] and fuzzy-based mixed-integer programming [11], etc. have been extensively studied. Furthermore, generation expansion planning based on market environment has been extensively studied due to recent development of electricity wholesale markets in several countries [12-14].

One of the most important issues arisen recently in generation and transmission expansion planning is that the investment and construction of high voltage transmission lines are continuously hampered by the increasing Nimby phenomena due to harmful effects of extra high-voltage transmission lines. Traditionally, generation expansion planning is optimized based on the assumption that all the generators are located at a single nodal point and, hence, the transmission congestion or network loss is not considered during the generation expansion optimization process. And the optimization of transmission expansion planning is performed separately after the locations of the new generators are all fixed. The main reason why the optimizations of generation expansion and transmission expansion are performed separately is mainly due to its curse of dimensionality and computation.

However a separate optimization of generation and transmission expansion planning may lead to the following problems:

1) The optimization result of generation expansion planning may result in an infeasible solution from the viewpoint of transmission expansion planning. Improper locations of generators may lead to build transmission lines that require intractably high cost or long time to build. Because of the infeasibility of transmission constructions, the generator included in the generation expansion planning may be cancelled or delayed, which causes the instability of the demand and supply condition.
2) The result of the separate optimization of the generation expansion and the transmission expansion may be a sub-optimal solution compared to the result that can be obtained from the combined optimization of generation and transmission expansion problem.
3) In some countries, such as South Korea, the generation expansion planning and transmission expansion planning are performed by the different governmental agencies, which makes the overall process unnecessarily long and inflexible [15].

Several research results have been published to study the integrated approach for optimization of the combined generation and transmission expansion planning problems

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[16-27]. One of the most typical methods for the integrated optimization is to use the Generalized Benders' decomposition (GBD) method as in [16]. However, the biggest problem of the GBD method is that the convergence of method is guaranteed only when the sub-problem is convex and linear and hence most of the results have been based on the linearized DC power flow model. Some results based on the AC power flow model can be found in the literature without guarantee of convergence due to nonlinearity and non-convexity of the sub-problem [18].

Meanwhile, there have been limited research results on the integrated optimization based on the formulation of the nonlinear mixed-integer programming for the combined generation and transmission expansion planning problem [19, 27]. These results are also based on the linearized DC power flow to reduce the overall calculation time and convergence, and hence the constraints related to reactive power flows and bus voltage limits are not considered.

This paper proposes an early stage research result on integrated optimization of the combined generation and transmission expansion planning based on AC power flow model including various constraints related to reactive power flow limits through transmission lines and bus voltage limits.

In the following sections the mathematical formulation of the proposed method and solution method are described. The proposed method is applied to the Garver's six-bus power system which is one of the most frequently used small scale sample power system for the transmission expansion planning researches. The simulation results are shown in Section 4. Conclusions are given in the last section.

2. Mathematical Formulation

2.1 Nomenclature

I, j	Index of bus
g	Index of generator
Ω_g	Set of all generators including existing generators and new generators
$\Omega_{g,new}$	Set of all new generators
Ω_b	Set of all buses including existing buses and new buses
PG_g	Real power output of generator (MW)
QG_g	Reactive power output of generator (MVar)
P_{ij}	Real power flow between i and j (MW)
Q_{ij}	Reactive power flow between i and j (MVar)
Ql_{ij}	Reactive power losses between i and j (MVar)
$V_{i,t}$	Bus voltage magnitude in pu at bus i at time t
$V_{\max}$	Upper bound on the voltage magnitude (p.u)
$V_{\min}$	Lower bound on the voltage magnitude (p.u)
$\theta_{ij,t}$	Phase angle difference between i and j at t (rad)
g_{ij}	Conductance of existing T/L between i and j (p.u)
b_{ij}	Susceptance of existing T/L between i and j (p.u)
$g_{ij,new}$	Conductance of new T/L between i and j (p.u)
$b_{ij,new}$	Susceptance of new T/L between i and j (p.u)
$PD_{i,t}$	Real power demand at bus i at time t (MW)
$QD_{i,t}$	Reactive power demand at bus i at t (MVar)
OC_g	Operation cost of each generator ($/MWh)
CP_g	Investment cost of generators (M$)
TC_{ij}	Investment cost of T/L between i and j (M$)
d	Discount rate
$S_{g,\max}$	Maximum apparent power output of each generator for existing generators (MVA)
$S_{g,\max,new}$	Maximum apparent power output of each generator for new generators (MVA)
S_{ij}	Maximum apparent flow limit on T/L between bus i and j (MVA)
$u_{ij,t}$	Integer variable decision variable for a prospective line between buses i and j at time t.
$u_{ij,\max}$	Maximum number of prospective lines between i and j
$z_{g,t}$	Binary decision variable for a prospective generator at time t.
$L_{g,i}$	Binary variable if generator g is connected to bus i
t, T	Index of time and planning period

2.2 Assumptions

In order to combine generation and transmission expansion planning problems, it is indispensable to incorporate the power flow calculation in the mathematical formulation. If the linearized DC power flow model is used, the overall calculation time and the convergence of the optimization can be significantly improved, but the reactive power flow through transmission lines and the bus voltages cannot be considered. Therefore, the feasibility of the results obtained from the expansion planning based on the DC power flow model should be analyzed by a separate AC power flow analysis to check that there exist any excessive reactive power flows and bus voltages [19]. The main idea of this paper is that if AC power flow model is used during the combined generation and transmission expansion planning, it is possible to eliminate the need of separate feasibility analysis using the detailed AC power flow model or at least to minimize the possibility of repeating the overall optimization procedure due to infeasible reactive power flows and bus voltages.

It is obvious that the computation time for the overall optimization will be so increased if the full nonlinear AC power flow model is used that it is necessary to simplify some of the mathematical formulations to reduce the complexity of the optimization.

In this paper the simplifications are performed based on the following assumptions to improve the computation time and the convergence of the optimization:

1. Technical characteristic of generators are ignored.
2. When the investment costs of generator and transmission

lines are calculated, the real power loss is ignored because resistance of the transmission lines is usually significantly smaller than line reactance. However, the real power loss is considered when the operating cost is calculated.

3. The operation cost of transmission lines and the salvage values of the generators and transmission lines at the end of the planning period are ignored.
4. Characteristics of newly built transmission lines between bus *i* and *j* are identical with existing transmission lines between bus *i* and *j*.
5. All impracticable candidates of transmission lines based on topology analysis are excluded from the planning model.

2.3 Mathematical formulation of the proposed method

2.3.1 Objective function:

The objective function of the proposed method is defined as the combined costs of operation cost, generation investment cost and transmission investment cost as follows:

$$J=\sum_{t=1}^{T}\frac{1}{(1+d)^{t}}\{(\sum_{g}^{\Omega_g}PG_{g,t}OC_g+\sum_{i}^{\Omega_b}\sum_{j}^{\Omega_b}(u_{ij,t}-u_{ij,t-1})TC_{ij}$$
$$+\sum_{g}^{\Omega_{g,new}}(z_{g,t}-z_{g,t-1})CP_g)\} \tag{1}$$

where the first term is the operation cost of generators, and the second and third terms are the investment cost of the newly built transmission lines and generators, respectively. And the following constraints are considered:

2.3.2 Limits on the apparent power of the generators:

In general the apparent power output of a generator is characterized by loading capability curve as shown in Fig. 1 and it is approximated by the following inequalities:

$$PG_g{}^2+QG_g{}^2\le S_{g,\max}{}^2\,,\quad \forall g\in\Omega_g \tag{2a}$$
$$PG_{g,new}{}^2+QG_{g,new}{}^2\le z_g S_{g,\max,new}{}^2\,,\quad \forall g\in\Omega_g \tag{2b}$$

However if the above nonlinear inequality constraints are directly used, the nonlinearities of the overall optimization problem become too complex. It is possible to reduce the nonlinearities of the problem by linearizing the power capability curve into the following four linear inequality constraints:

$$QG_{g,t}\le a_1PG_{g,t}+a_2S_{g,\max}\,,\quad \forall t\,,\quad \forall g\in\Omega_g \tag{3a}$$
$$QG_{g,t}\le b_1PG_{g,t}+b_2S_{g,\max}\,,\quad \forall t\,,\quad \forall g\in\Omega_g \tag{3b}$$
$$QG_{g,t}\ge c_1PG_{g,t}+c_2S_{g,\max}\,,\quad \forall t\,,\quad \forall g\in\Omega_g \tag{3c}$$

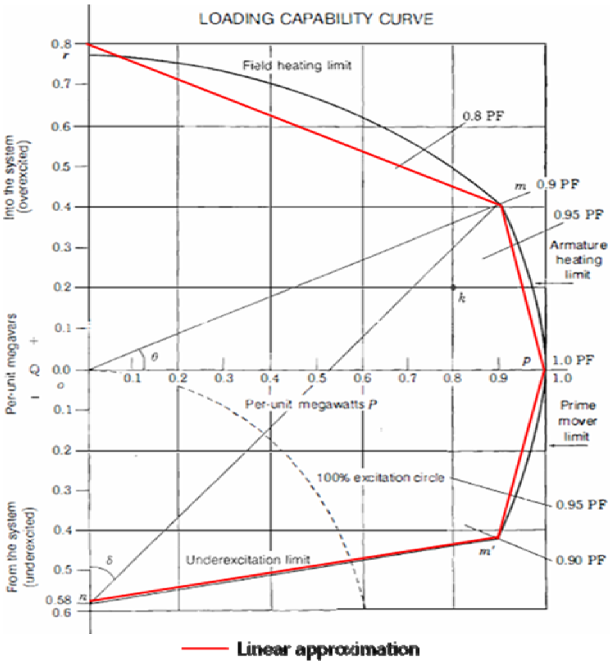

Fig. 1. Linearization of loading capability curve [28]

$$QG_{g,t}\ge d_1PG_{g,t}+d_2S_{g,\max}\,,\quad \forall t\,,\quad \forall g\in\Omega_g \tag{3d}$$

where a_i and b_i are all constants, which are selected as shown in Fig. 1.

2.3.3 Node Balance (Kirchhoff's 1st Law):

$$\sum_{g}^{\Omega_g}PG_{g,t}L_{g,j}+\sum_{i}^{\Omega_b}P_{ij,t}=PD_{j,t}\,,\quad \forall t,\, j\in\Omega_b \tag{4a}$$
$$\sum_{g}^{\Omega_g}QG_{g,t}L_{g,j}+\sum_{i}^{\Omega_b}Q_{ij,t}-\sum_{i}^{\Omega_b}Ql_{ij,t}=QD_{j,t}\,,\forall t,\, j\in\Omega_b \tag{4b}$$

where Eq. (4) represents the Kirchhoff's first law (KCL) for real and reactive power at each node. As mentioned above, only the reactive power losses are considered as in Eq. (4b) as they are not negligible because of the relatively large reactance of the transmission lines.

2.3.4 AC Power Flow:

The general nonlinear AC power flow is calculated as the following equations:

$$P_{ij}=V_i^2g_{ij}-V_iV_j(g_{ij}\cos\theta_{ij}+b_{ij}\sin\theta_{ij}) \tag{5a}$$
$$Q_{ij}=-V_i^2b_{ij}-V_iV_j(g_{ij}\sin\theta_{ij}-b_{ij}\cos\theta_{ij}) \tag{5b}$$
$$Ql_{ij}=-b_{ij}(V_i^2+V_j^2-2V_iV_j\cos\theta_{ij}) \tag{5c}$$

Most of the commercial solvers for the mixed integer nonlinear programming do not allow to use trigonometric functions, therefore, sin sin and $\cos\theta$ in the above equation can be approximated to $\sin\theta \approx \theta$ and $\cos\theta \approx 1-\theta^2/2$ as θ has generally small values. Therefore, the Eqs. (5a) through (5c) can be approximated as follows:

$$P_{ij,t} = -V_{i,t}V_{j,t}(b_{ij} + u_{ij,t}b_{ij,new})\theta_{ij,t} \qquad (6a)$$

$$Q_{ij,t} = -(b_{ij} + u_{ij,t}b_{ij,new})(V_{i,t}{}^2 - V_{i,t}V_{j,t}(1-\frac{\theta_{ij,t}{}^2}{2})) \qquad (6b)$$

$$Ql_{ij,t} = -(b_{ij} + u_{ij,t}b_{ij,new})(V_{i,t}{}^2 + V_{j,t}{}^2 - 2V_{i,t}V_{j,t}(1-\frac{\theta_{ij,t}{}^2}{2})) \quad (6c)$$

for $\forall t, \forall i, j \in \Omega_b$. The following inequality constraint is added to the above inequality constraints to avoid of the reactive power loss becoming greater than the reactive power flow through the transmission lines:

$$\left|Ql_{ij,t}\right| \le \left|Q_{ij,t}\right|, \quad \forall t, \forall i, j \in \Omega_b \qquad (6d)$$

2.3.5 Real and reactive power transmission flow limit:

The constraints on the real and reactive power transmission flow can be modeled by the following nonlinear inequality:

$$P_{ij,t}{}^2 + Q_{ij,t}{}^2 \le (S_{ij,\max} + u_{ij,t}S_{ij,\max,new})^2, \quad \forall t, \forall i, j \in \Omega_b \qquad (7)$$

These nonlinear inequalities are also linearized as follows:

$$Q_{ij,t} \le \alpha P_{ij,t} + (S_{ij,\max} + u_{ij,t}S_{ij,\max,new})(\sin\theta_k - \alpha\cos\theta_k)$$
$$\alpha = \frac{\sin\theta_k - \sin_{k+1}}{\cos\theta_k - \cos\theta_{k+1}}, k = 1, 2, \cdots, n-1, \quad \forall t, \forall i, j \in \Omega_b \qquad (8)$$

The above inequality is obtained by linearizing the Eq. (7) as shown in Fig. 2. It is obvious that the result become more exact if n is set to the larger number, we found that the result is acceptable even if n is set to 2, which is the roughest approximation as shown in the simulation result.

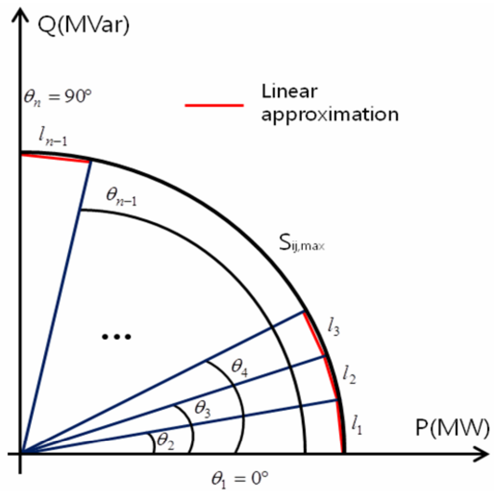

Fig. 2. Linear approximation for transmission flow limit

Demand and supply conditions for real and reactive power:

$$\sum_{g}^{\Omega_g} PG_{g,t} = \sum_{i}^{\Omega_b} PD_{i,t}, \quad \forall t \qquad (9a)$$

$$\sum_{g}^{\Omega_g} QG_{g,t} = \sum_{i}^{\Omega_i} QD_{i,t} + \sum_{i}^{\Omega_b}\sum_{j}^{\Omega_b} 0.5Ql_{ij,t}, \quad \forall t \qquad (9b)$$

Eqs. (9a) and (9b) explain the demand and supply conditions for the real and reactive power, respectively. The reason why the reactive power loss Ql_{ij} is multiplied by 0.5 in Eq. (9b) is to avoid the double calculation of reactive power losses.

2.3.6 Other constraints:

$$V_{\min} \le V_{i,t} \le V_{\max}, \quad \forall t, \forall i \in \Omega_b \qquad (10)$$

$$\theta_{ij,\min} \le \theta_{ij,t} \le \theta_{ij,\max}, \quad \forall t, \forall i, j \in \Omega_b \qquad (11)$$

$$u_{ij,T} \le u_{ij,\max}, \quad \forall i, j \in \Omega_b \qquad (12)$$

$$u_{ij,t-1} \le u_{ij,t}, \quad \forall t, \forall i, j \in \Omega_b \qquad (13)$$

$$z_{g,t-1} \le z_{g,t}, \quad \forall t, \forall g \in \Omega_g \qquad (14)$$

Eq. (10) is an inequality constraint for voltage magnitude at each node. Eq. (11) is an inequality constraint to limit the voltage angles in between $\pm 35°$ or ± 0.61 rad, which is typical values for the practical transmission line loadability [29]. Eq.(12) is a constraint to limit the number of new transmission lines between bus *i* and *j*. Eq.(13) and (14) explain numerical values of construction variables which are greater than or equal to a previous time at a specific time.

3. Solution Methods

The mathematical formulation described in the previous section is similar to that of the AC optimal power flow with transmission line security. However, there exist the following differences:

1. The proposed method is a long-term multi-year planning problem, whereas the general optimal power flow is usually analyzed only for a specific moment.
2. The optimal power flow usually assumes that the result of unit commitment or the generator start-up and shutdown schedule is already given. Therefore, it is mathematically modeled as a nonlinear programming, not mixed-integer nonlinear programming. However, the proposed method is modeled as a mixed-integer

nonlinear programming because of the decision variables whether to build the new generators and transmission lines.

Therefore, the proposed problem has been solved using MINLP solvers such as AlphaECP, Baron or Bonmin available with GAMS (General Algebraic Modeling System) (http://www.gams.com) [30].

4. Simulation Results

4.1 Simulation of Algorithm

The proposed method has been applied to one of the most frequently used sample power systems so called Garver's 6-bus system as shown in the Fig. 3 [31, 32]. As shown in Fig. 3, it is assumed that two generators on bus 1 and 3, and six transmission lines are already existed in the system. Bus 6 is assumed to be a pre-planned bus. Planning period is set to 5 years.

As mentioned in the assumption 5 in the Section 2.1, we eliminate the impractical candidates for new transmission lines based on topological analysis. Transmission lines between the adjacent buses such as 1-2 and 1-4 are eligible candidates for new construction, however, transmission lines 1-3 and 1-6, etc. are excluded from the eligible candidates. The load data are given in Table 1. The real and reactive demands of each bus are assumed to increase by 10% every year during the planning period. The data for the generators (both existing ones and new candidates) and the transmission lines are given in Tables 2 and 3, respectively. All the voltage limits are set to ±5% of the nominal values.

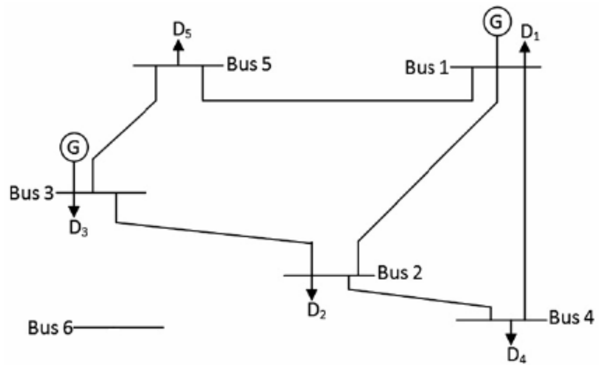

Fig. 3. Garver's 6-bus System

Table 1. Data for electricity demand [32]

Bus No.	PD (MW)	QD (MVAr)
1	55	11
2	164	32.8
3	27	5.4
4	109	21.8
5	164	32.8
6	0	0

Table 2. Data for the existing and candidate generators

Gen No.	S_{max} (MVA)	Location at Bus	Operation cost(M$/MW)	Construction cost(M$)
1	173	1	5	-
2	390	3	7	-
3	642	6	8.5	1000
4	400	5	10	2000

4.2 Simulation Results

The optimization result of the proposed method with the AC power flow model is shown in Table 4, Table 5 and Fig. 4, where the result of the expansion planning based on the DC power flow is also shown for comparison.

Table 3. Data for the candidate transmission lines

Corridor	r_{ij}(p.u)	x_{ij}(p.u)	Capacity(MVA)	Cost(M$)
1-2	0.04	0.4	100	40
1-4	0.06	0.6	80	60
1-5	0.02	0.2	100	20
2-3	0.02	0.2	100	20
2-4	0.04	0.4	100	40
3-5	0.02	0.2	100	20
3-6	0.048	0.48	100	48
4-6	0.03	0.3	100	30

Table 4. Generation expansion planning results

Expansion method	Generator expansion result	
	DC Analysis	Proposed Method
Year 2	G3	G3, G4

Table 5. Transmission line expansion planning results

Expansion method	Transmission line expansion result	
	DC analysis	Proposed method
Year 1	(2-3), (3-5) × 1	{(1-5), (3-5), (4-6)} × 1, (2-3) × 2
Year 2	(4-6) × 1	(2-6) × 1

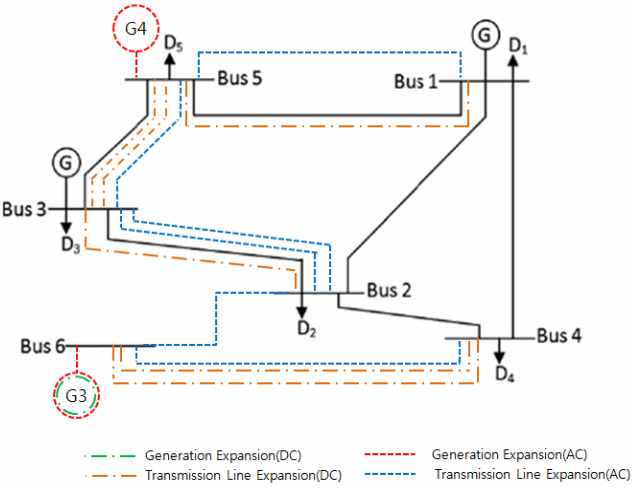

Fig. 4. Expansion results of the proposed method

Table 6. Calculation of voltage magnitude and phase angle (the final year)

Bus No.	Proposed method		Full AC power flow analysis model	
	V_i	θ_i	V_i	θ_i
1	1	0	1	0
2	1	-0.02	1	-0.022
3	1.015	0.051	1.02	0.046
4	1	-0.04	1	-0.043
5	1.046	-0.04	1.042	-0.047
6	1.034	0.075	1.042	0.07

As shown in the Table 4 and 5, both methods result in the construction of the generator G3 on bus #6 in Year 2 because the supply capacity becomes insufficient in that year due to the demand increase. However, the result of the proposed method requires another generator G4 on bus #5 in Year 2 to satisfy the constraints related to bus voltage limits and reactive power. This generator can be replaced with synchronous condenser because it is nothing to do with real power constraints.

The result of proposed method also requires more transmission lines compared to that of the expansion planning with DC power flow model due to the reactive power flow constraints through transmission lines.

However, it should be noted that the result from expansion planning based on DC power flow model should be further analyzed using AC power flow for voltage stability check and it is very probable that the feasibility cannot be met. In that case, whole expansion process should be repeated until the feasibility is met.

Table 6 shows the voltage magnitudes and phase angles which are by-product of the proposed method and they are compared with the simulation results from PSS/e, one of the most frequently used AC power flow model. As can be seen in the table, voltage magnitudes and phase angles from the proposed method are not very different from the result of the commercial AC power flow model. Therefore, even if the expansion planning result of the proposed method is further analyzed using very detailed AC power flow model, the possibility of failure of satisfying voltage stability is very limited.

5. Conclusions

The integrated optimization of the combined generation and transmission expansion planning problem has been widely studied during the last decades. However, most of the existing research results on the combined generation and transmission expansion planning problem are based on DC power flow model.

This paper proposed a novel integrated optimization method to combine generation and transmission expansion planning problem based on AC power flow model. The method is implemented as a mixed integer nonlinear programming model and successfully applied to the Garver’s 6-bus system which is one of the most frequently used for transmission expansion planning problem.

Though the calculation burden of the optimization is minimized significantly in the proposed method, further researches on the improvement of the proposed method should be performed for the proposed method to be applied to the real scale power system. For example, the proposed method is implemented using the commercial optimization solver such as GAMS. Therefore it is probable to improve the overall calculation time if the customized optimization algorithm is developed. Furthermore, the network reduction algorithm can be implemented to reduce the overall search space.

Even though the authors admit that further research is necessary for the proposed method to be applied to the practical scale of power systems, the result so far is very promising and has very high possibility for the successful application to the practical power system.

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