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A dynamic optimal expansion planning model integrating renewable energy sources

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ABSTRACT

As the development of Renewable Energy Sources (RES) technologies increases, the problem of intermittency and variability from the RES integration into the grid arises for system planners. Therefore, this paper presents a dynamic multi-objective optimization model for the generation and transmission expansion planning (GTEP) problem with consideration to renewable energy sources. The proposed mathematical model minimizes the investment costs for transmission network and renewable energy expansion planning, operation costs and emissions for fossil fuel generating units as well as maximizes the economic incentives for utilizing renewable energy generating units. The dynamic planning strategy for the optimization problem is to consider the annual investment decisions associated with renewable energy sources integration and its effects on the GTEP procedure. The developed model is solved using CPLEX 12.8.3 and applied to a Garver's six bus test system and the numerical results show that the dynamic model permits system planners to adjust the system to future changes with time and ensures more utilization of renewable energy sources annually.

Keywords: Dynamic planning, Renewable energy source, Expansion, Generation and transmission system.

NONMENCLATURE

Sets	
t	set of periods
i	set of fossil fuel generators
k	set of demand
RES	set of renewable energy generating units
l	set of transmission lines
Parameters	
r	discount factor
IC_l	investment cost for prospective transmission line
IC_{RES}	investment cost of prospective renewable energy generating unit
OC_i	operation cost for fossil fuel generators
$x_{i,} y_i$ and z_i	operation cost coefficients for fossil fuel generators i
$p_{i,} q_i$ and r_i	emission coefficients for fossil fuel generators i
B_l	susceptance of transmission line l
M	disjunctive factor
α	duration of operation (hr)
$P_l^{\max}$	maximum power flow in transmission line l
$P_{RES}^{\max}$	maximum capacity of renewable energy generating units
$P_i^{\max}$	maximum capacity of fossil fuel generators i
$P_{k,t}$	load demand at period t
$P_{RES,c,t}$	capacity for investment choice c of prospective RE generator at period t
C^{IbI}	economic incentives for utilizing renewable energy power
w_1 and w_2	weighting factor
Variables	
$\beta_{l,t}$	decision variable for prospective line l at period t
$\beta_{RES,t}$	decision variable for prospective renewable generating unit at period t
$P_{i,t}$	optimal power generated from fossil fuel generators i at period

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$P_{RES,t}$ optimal power generated from renewable energy generating unit at period t
$P_{l,t}$ optimal power flow on transmission line l at period t
$\theta_{n,t}$ phase angle in node at period t

1. INTRODUCTION

1.1 Motivation

Globally, there is desire to reduce electricity generation through fossil fuel energy resources owing to its environmental impacts and instability of oil prices. To address these issues, the development of renewable energy sources technologies has been encouraged so as to find a lasting solution to the problem of global warming across the world. Among the RES available, wind and solar energy serve as the best alternative owing to their maturity and ability to mature the growing energy demand in the world [1]. Government policies have been introduced in order to foster the utilization of RES in the energy sector through some economic incentive schemes such as feed-n tariffs, investment-based incentive and VAT [2]. Generation and transmission expansion planning is highly essential in order to effectively determine ways of reinforcing the existing power network with integration of new renewable energy sources so as to optimally serve the system loads while reducing the CO2 emissions as well as improving world energy sustainability [3].

1.2 Literature review

Generation and transmission expansion planning is by nature a long-term planning horizon scheme owing to its capital intensiveness and long-lasting impacts on power system, therefore, it is key factor when considering energy security for long term system operation. There are two expansion planning approaches namely [4]:

(a) Static approach: This involves making expansion planning from the beginning of the planning period with consideration to annualized investment costs. In this case, most of the decisions are not going to be revisited.
(b) Dynamic approach: This approach involves establishing expansion planning decisions at different time stages of the planning horizon using yearly representation of investment decisions.

The dynamic model delivers more precise solutions and corrective actions are ensured in the system throughout the target period; however, it expands the complexity and computational intractability of planning problem. These expansion planning approaches has been considered in the literatures. [4] presents a dynamic transmission expansion planning problem considering uncertainties and investment decisions on energy resources with emphasis on reducing the computational burden of the system. In [5], a multi-stage optimization model was developed for minimizing the investment and generation costs. [6] and [7] studied static generation and transmission expansion planning problem with more consideration to the system investment and operational costs.

Expansion planning for generation and transmission has been studied extensively for decades. Recently, researchers have analyzed and categorized the GTEP problem into different perspectives such as: modelling approach, solution method, expansion strategies, reliability, environmental effect and planning horizon [8][9]. Reference [10] presents an integrated generation expansion planning problem considering the effects of renewable energy generation on the efficiency of conventional power plants. In [11], a robust transmission expansion planning with consideration to the worst-case scenario and the stochastic nature of load and renewable energy sources was presented. Reference [1] proposed a multi-objective GTEP model for minimizing investment and operation costs with emphasis on wind farm location and economic incentives whilst [12] developed a new stochastic model for GTEP problem with consideration to uncertainty from renewable energy and operational constraints.

1.3 Research contributions

This study is an extension of [1], where a static composite generation and transmission expansion planning model was developed for minimizing generation and transmission investment costs, operation cost and emissions of fossil fuel generating units as well as maximizing the feed-in tariffs for using renewable energy generating units. The main contributions in this work are:

(a) The dynamic multi-objective GTEP problem is proposed in this work to evaluate the yearly representation of investment decisions at different periods of the planning horizon.
(b) To determine how the multi-stage model enhances optimal usage of renewable energy sources with minimum financial resources and at

the same time assisting system planners to adjust to meet the future changes with time.

(c) To determine the influence of investment-based incentives on the generation and transmission expansion planning procedure.

2. PROBLEM FORMULATION

The central planner is saddled with the responsibility for determining the optimal generation and transmission expansion plans to meet the load demand as well as set investment-based incentives to renewable energy investors serving as a financial relief and quick recovery of investment to investors. Therefore, this paper presents a dynamic generation and transmission expansion planning problem with the aim of minimizing renewable energy generation and transmission line investment costs, operation and emissions from fossil fuel generation as well as maximizing the investment-based incentive for renewable energy utilization in the power system.

2.1 Objective function

The objective functions are expressed as follows:

To simplify the model, the cost and emission functions in Equations (2) and (3) are expressed as a quadratic function and a weighting factor in Equation (4) is employed to makes the objective functions comparable:

$$OC_i\left(P_{i,t}\right) = x_i + y_i P_{i,t} + z_i P_{i,t}^2 \tag{2}$$

$$\mathrm{E}_i\left(P_{i,t}\right) = p_i + q_i P_{i,t} + r_i P_{i,t}^2 \tag{3}$$

$$\omega_1 + \omega_2 = 1 \tag{4}$$

2.2 Model constraints

$$\sum_i P_{i,t} + \sum_{RES} P_{RES,t} - \sum_l P_{l,t}^{+} + \sum_l P_{l,t}^{-} = \sum_k P_{k,t} \tag{5}$$

$$0 \le P_{RES,t}^{\max} \le \overline{P_{RES}} \tag{6}$$

$$P_{RES,t} \le P_{RES,t+1} \tag{7}$$

$$P_{RES,t}^{\max} = \sum_c \beta_{RES,c.t} P_{RES,c.t} \tag{8}$$

$$\sum_c \beta_{RES,c.t} = 1 \tag{9}$$

$$\beta_{RES,c.t} \in \left[0.1\right] \tag{10}$$

$$\beta_{l.t} \in \left[0,1\right] \tag{11}$$

$$P_{l,t} = B_l\left(\theta_{sl,t} - \theta_{rl,t}\right) \tag{12}$$

$$-\left(1-\beta_{l,t}\right)M \le P_{l,t} - B_l\left(\theta_{sl,t} - \theta_{rl,t}\right) \le \left(1-\beta_{l,t}\right)M \tag{13}$$

$$-P_l^{\max} \le P_{l,t} \le P_l^{\max} \tag{14}$$

$$-\beta_{l,t} P_l^{\max} \le P_{l,t} \le \beta_{l,t} P_l^{\max} \tag{15}$$

$$0 \le P_{i,t} \le P_i^{\max} \tag{16}$$

$$0 \le P_{RES,t} \le P_{RES}^{\max} \tag{17}$$

$$-\pi \le \theta_{n,t} \le \pi \tag{18}$$

The operational constraints are briefly detailed as follows:

- Equation (5) is a power balance constraint which enforce that at each node n, the sum total of power from the fossil fuel, renewable energy and the power flowing in and out of the transmission lines equals the demand.
- Equations (6) – (9) are the renewable energy constraints. Constraint (6) imposes that the capacity of renewable energy sources to be constructed must not exceed its upper limit at any time t. Constraint (7) impose that renewable energy power at the present planning period must be less or equal to the next planning period. Constraints (8)-(9) define that the renewable energy plant can only be built at once, at any planning period t.
- Constraints (10) and (11) define the binary decision variables for candidate renewable energy generators and the transmission lines to be built and they are equal to 1 if built and 0 otherwise.
- Constraints (12) and (13) express the flow on the existing and candidate transmission lines respectively.
- Constraints (14) and (15) are the transmission line capacity for the existing and candidate lines respectively and it enforces that the transmission line capacity must not exceed it maximum capacity.
- Equations (16) and (17) are the generation limit for fossil fuel and renewable energy units respectively and impose that the generation limit must not exceed its lower and upper limits.
- Constraint (18) imposes that the phase angle must be kept within safe limit.

3. RESULTS AND DISCUSSION

The developed model is illustrated using the Garver’s six bus test system as depicted in Figure 1, to assess the model performance. The test bus system contains six nodes with three generators, five demands

$$Min\left[\frac{1}{(1+r)^{t}}\left\{\omega_1\left(\sum_{t}\sum_{RES}IC_{RES}P_{RES,t}^{\max}+\sum_{t}\sum_{l}IC_{l}\alpha_{l,t}+\alpha\sum_{t}\sum_{i}OC_{i}P_{i,t}-C^{IbI}\sum_{t}\sum_{RES}IC_{RES}P_{RES,t}^{\max}\right)+\omega_2\left(\alpha\sum_{t}\sum_{i}\mathrm{E}_{i}P_{i,t}\right)\right\}\right] \quad (1)$$

Table 1. Optimal power generated from fossil fuel on Garver’s 6-bus system.

	Period (year)									
Generators	1	2	3	4	5	6	7	8	9	10
$P_{k,t}$ (MW)										
1	150	150	149	150	150	145	146.28	143.54	142.72	140.47
2	160	176	188	118	169	200	224.72	245.5	248.28	304.54
3	-	-	-	-	-	-	-	8	32	80

Table 2. Optimal power generated from RES on Garver’s 6-bus system.

	Period (year)									
RES	1	2	3	4	5	6	7	8	9	10
$P_{\Re,t}$ (MW)										
1	125	125	125	125	150	175	175	175	175	200
2	240	240	280	400	400	400	400	400	400	400
3	60	120	120	120	120	120	120	120	120	120
4	25	25	50	75	75	100	150	200	250	275

Table 3. Optimal power flow on the transmission lines on Garver’s 6-bus system.

Lines	Period (year)									
	1	2	3	4	5	6	7	8	9	10
$P_{j,t}$ (MW)										
1-2	20.07	25.17	43.05	68.16	51.89	63.78	48.92	47.76	44.81	53.17
1-4	31.55	37.05	47.93	61.84	53.11	56.22	48.08	45.71	42.57	47.56
1-5	43.38	74.78	88.02	66	83	85	100	95.53	93.62	89.27
2-3	78.45	88.95	94.07	96.16	95.89	83.78	82.92	76.29	70.43	72.44
2-4	98.38	87.78	99.02	100	100	100	98	100	98	99.27
3-5	100	100	99.98	64.84	89.61	78.72	99.08	100	100	90.73
2-6	-	-	-	-	-	-	-	-	23.47	40.38
3-5	96.62	89.22	100	100	100	100	98.92	92	100	100
4-6	-	-	-	81.16	63.39	96.28	86	97	98	100
4-6	-	-	-	-	-	-	-	-	-	100

Table 4 System Performance for static and dynamic GTEP of a Garver’s 6-bus System

Characteristics	Static GTEP	Dynamic GTEP
Objective function ($M)	92.72	35.75
Emissions (Ib-M)	22.54	21.07
Total Power generated by RES (MW)	920	995
Total Power generated by Fossil fuel (MW)	600	525
Total transmittable power on the lines	810.97	792.82

and six transmission lines. The data for the six-bus test system can be found in [1]. The planning horizon is targeted to be 10 years with annual load growth of 1.1% at the planning period and discount rate is 10%. The MIQP mathematical model have been validated and solved using CPLEX 12.8.3 solver embedded in AIMMS platform. AIMMS is a numerical solvers and modelling language designed for large scale optimization problems and advanced planning systems [13].

3.1 Results

Sensitivity analysis is performed in this section to evaluate the performance of the model proposed. The simulated results obtained was compared with the static approach with the same level of load demand at the final year of the planning period.

Table 1 presents the simulated optimal generated power from fossil fuel generating units over the target planning period. Similarly, Table 2 depicts the year-to-year optimal power sizing required by the renewable energy generating units. Table 3 gives the optimum power flow on the existing and candidate transmission lines. Table 4 gives the system performance for the test bus system when considering the static and dynamic planning approaches.

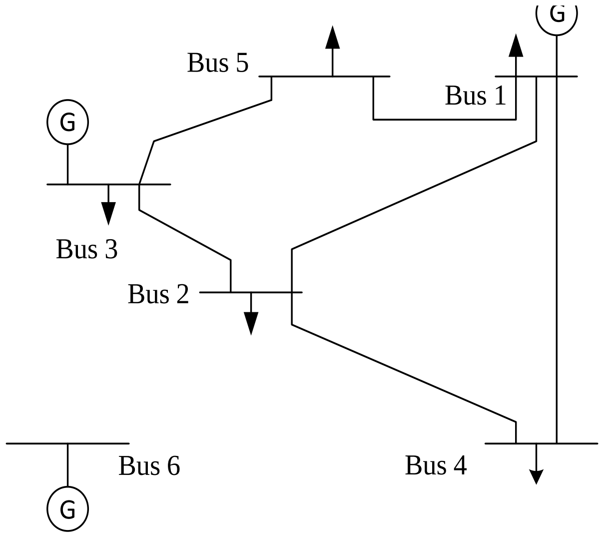

Fig. 1. IEEE Garver's 6 bus system.

3.2 Discussion

The optimization results will be analyzed based on the two planning strategies and their influence on the system performance.
From Figure 2, it can be seen that the total transmittable power on the existing and candidate transmission lines for dynamic planning approach are less when compared to the static approach. This is achievable owing to the year-to-year representation of investment decisions of the transmission lines and also improves the voltage profile of the system as depicted in Figure 3.
Figures 4 and 5, it can be observed that dynamic planning approach gives improved utilization of RES of about 65% against 60.5% in static planning system approach. The improve utilization of RES help to significantly reduce the CO2 emissions in the system. The year-to-year representation of investment decisions of RES generation and transmission network system aid the reduction of the overall system costs because only the required renewable energy generating unit for the year is installed and once a unit can only be installed once in the system at any planning period.

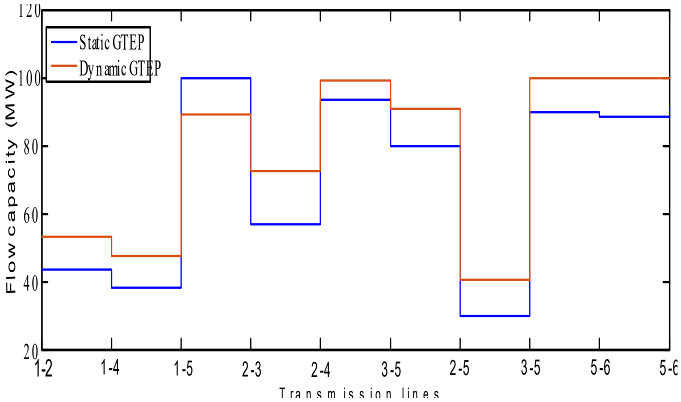

Fig. 2. Optimal transmittable power on transmission lines.

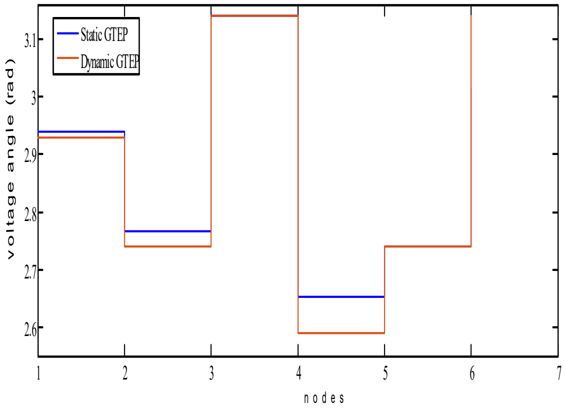

Fig. 3. Optimal voltage angles.

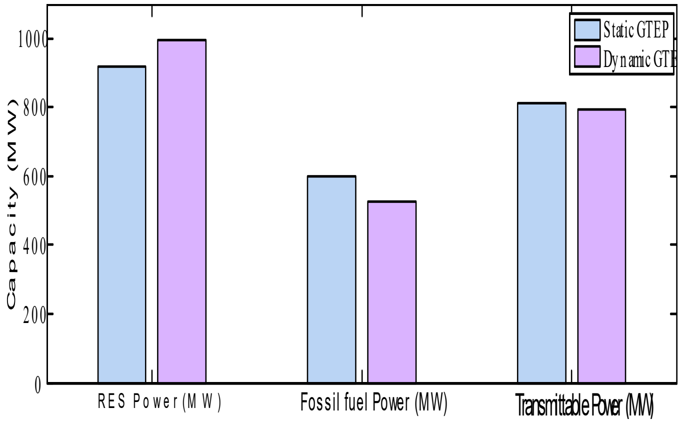

Fig. 4 System performance for generated and transmittable power.

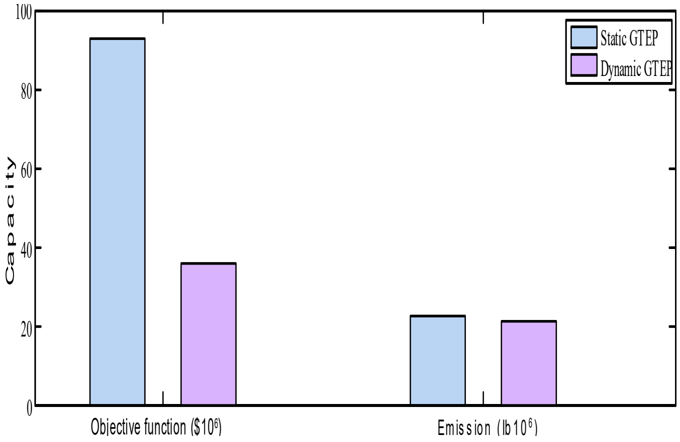

Fig. 5 System performance for costs and emissions.

4. CONCLUSION

This paper presents a long-term planning system for combined generation and transmission expansion planning system with incorporation of RES in the system. The MIQP problem helps to minimize the investment costs for RES generation and new transmission lines, operation and emissions for fossil fuel generating units as well as maximizing the investment-based incentive for utilizing RES. The influence of the single stage and multi-stage planning system was carried out and analyzed through the system performance of the test bus. The proposed model was validated on the Garver six bus test system and the simulation results obtained demonstrate that the long-term investment decisions performs better than a single stage planning system owing to its ability to give a precise optimization solution and encourages more utilization of RES with reduced CO2 emissions. The developed model gives an efficient solution for long-term system planning with yearly cost reduction.

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