Cite as: N. V. Vigil, S. Majumder, V. Pradhan, V. Padmini and S. A. Khaparde, "Transmission Expansion Planning With Variable Wind Source," 2014 Eighteenth National Power Systems Conference (NPSC), 2014.

Transmission Expansion Planning With Variable Wind Source

N. V. Vigil, Subir Majumder, Vedanta Pradhan, Padmini V., and S. A. Khaparde *Senior Member, IEEE*

***Abstract*—Though a lot of research is reported on the transmission expansion planning (TEP), few have considered the impact of wind sources with varying penetration. Inadequate transmission capacities can result in spillage of the wind power. This has implications on loss of load and higher cost of generation. The proposed methodology formulates an integrated approach to TEP, which optimizes cost of new lines, spillage of wind power, loss of load and cost of generation. The resultant TEP problem is of the Mixed Integer Non Linear Programming (MINLP) type. Different scenarios are considered by varying the penetration levels resulting in different cases. The effect of growth in load demand is also considered. The formulation is tested using Garvers 6-Bus system and results are obtained using the Standard Branch and Bound (SBB) solver. As expected, optimum selection of new lines are able to reduce the spillage and cost of generation. The DCOPF results indicate the optimal schedule for the given load and wind generation data. The loss of load levels in different cases and corresponding cost of generation are reported for all cases. This approach can provide some insight to the decision maker to plan transmission expansion in presence of variable wind source and varying penetration level.**

***Keywords*—DCOPF Model, Loss of Load, Mixed Integer Non Linear programming (MINLP), Spilled Wind power, Transmission Expansion planning (TEP).**

I. INTRODUCTION

Transmission Expansion Planning (TEP) is done to identify where and when new lines are required to be built to meet the growing energy demands of energy industry. In developing countries most of the generating units are located far away from load centres. Therefore, investments in transmission takes a major part of the power industry investment requirements. Thus reducing the cost of transmission expansion will reduce the overall capital requirement. The integration of renewable energy (RE) such as wind energy into grid has made the TEP problem difficult. Wind power is the most widely applied renewable energy world wide. Increased uncertainties and the necessity to optimally utilize the generation, requires system reinforcements such as laying out new transmission lines.

TEP can be both static or dynamic planning [1]. In dynamic planning multiple years are considered, the calculations are very complex and optimal expansion in whole planning period is analysed. In static problem lines to be added in the current transmission system is studied. Literature available on the mathematical model for solving the static TEP problem is reported. Romero et al. [2] have done a comparative study of transportation models, hybrid models, DC power flow (DC-PF) models and disjunctive models, which are standard mathematical methods for solving the TEP problem. Urganly et al. [3] have studied the optimal location and the number of new lines, with an objective to minimize the investment cost using genetic algorithm. In their formulation the objective function constitutes the total line cost for building new lines, total wasted wind energy and total loss of load. Alguacil et al. [4] have modelled the TEP problem as a MINLP, considering the transmission loss reduction also as one of the objectives. However, the TEP problem can be formulated as a Non Linear Programming (NLP) [5] also considering corona power loss as an objective. Methodology to solve TEP model with security constraints using genetic algorithm is presented in [6]. Multi-stage, multi-objective TEP method is formulated for transmission grid reinforcement studies in a power system using wind generation and an optimal plan is obtained in [7]. A Branch and Bound (B&B) algorithm [8, 9] has been used to solve the basic TEP problem.

This paper aims at formulating a comprehensive TEP problem, considering line investment cost, cost of spilled wind, loss of load cost as well as the cost of conventional generators in supplying the required power to meet system load in a static planning framework. The problem is formulated in GAMS environment and the Standard Branch and Bound (SBB) solver [10] is used. The initial focus of the paper is on presenting a mathematical model of proposed TEP problem. A case study using Garvers 6-Bus system, with varying levels of wind penetration and load levels is done. The aim is to determine the optimal transmission reinforcement plan for the given system in all the studied cases and provide valuable insights for cost efficient TEP.

II. WIND MODEL AND SPILLAGE CALCULATION

Although, the wind power is uncertain, marginal cost of wind power is negligible compared to other conventional generators. Therefore, spillage of wind power is not desirable and optimum planning at transmission level is required. The mathematical model of wind power generation and spillage has been presented in this section.

A. Wind Model

The total power output of the wind farm is the sum of individual powers of all the wind turbines in that farm. The maximum power that can be extracted from the turbine is a

N. V. Vigil (e-mail: vigilnair@gmail.com), Vedanta Pradhan (e-mail: vedanta.pradhan@gmail.com), Padmini V. (e-mail: pjakkannavar.07@gmail.com) and S. A. Khaparde (e-mail: sak@ee.iitb.ac.in) are with Department of Electrical Engineering, IIT Bombay, Maharashtra, India. Subir Majumder (e-mail: subirmajumder@iitb.ac.in) is with Department of Energy Science and Engineering, IIT Bombay, Maharashtra, India.

function of the wind speed. The non-linear relationship [11] between the power output of the wind turbine and wind speed is given by the following equation:

$$P_w(\mathrm{V}) = \begin{cases} 0 & 0 \le \mathrm{V} \le \mathrm{V}_{\text{cut-in}} \\ (\mathrm{a}+\mathrm{bV}+\mathrm{cV}^2) & \mathrm{V}_{\text{cut-in}} \le \mathrm{V} \le \mathrm{V}_{\text{rated}} \\ \mathrm{P}_{\text{rated}} & \mathrm{V}_{\text{rated}} \le \mathrm{V} \le \mathrm{V}_{\text{cut-out}} \\ 0 & \mathrm{V} \ge \mathrm{V}_{\text{cut-out}} \end{cases} \tag{1}$$

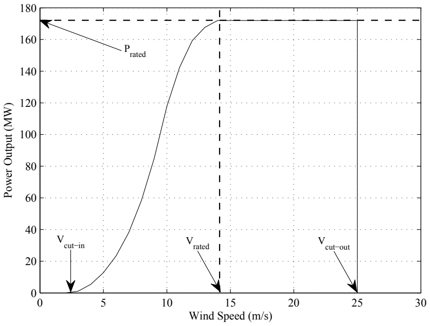

Fig. 1: Power Output vs. Wind speed for a typical wind turbine

Where, V is the wind speed, $\mathrm{V}_{\text{cut-in}}$, $\mathrm{V}_{\text{cut-out}}$, $\mathrm{V}_{\text{rated}}$ are the cut-in, cut-out and rated wind speeds respectively. $\mathrm{P}_{\text{rated}}$ is the rated output power of the wind turbine. Fig. 1 shows, the power output of a typical wind turbine with the specifications as: $\mathrm{P}_{\text{rated}}$ = 76 MW, $\mathrm{V}_{\text{cut-in}}$ = 3 m/s, $\mathrm{V}_{\text{rated}}$ = 14 m/s, $\mathrm{V}_{\text{cut-out}}$ = 25 m/s. The parameters a, b, c are specific for a given wind turbine and has been chosen from [12].

B. Spilled Wind Energy Calculation

The wind power that can be produced given the wind speed, but cannot be transmitted, because of line loading limits is called spilled wind (*SW*) power. *SW* is calculated by using the following formula:

$$SW = \sum_t max(0, P_{w,t} - f_{max}) \tag{2}$$

$$f_{max} = \sum_j n_{wdj} \times P_{wdj} \tag{3}$$

Where, f_{max} is the maximum transmission capacity from the wind farm, $P_{w,t}$ is the average wind power available during the t^{th} time block, n_{wdj} is the number of lines from wind farm to j^{th} bus, P_{wdj} is the power carrying capacity of line between wd^{th} and j^{th} bus and wd^{th} bus refers to the bus at which the wind turbine is connected.

III. TEP PROBLEM FORMULATION

The TEP problems in presence of a resource like wind power becomes more involved than that of a conventional TEP problem. It is desirable that the wind generation is used to the maximum as its variable cost is negligible. This assures an overall reduction in generation costs. However, transmission constraints limit the amount of wind power that can be continuously evacuated from the wind site. This leads to spillage of cheaper wind power at times of higher wind power output, thus leading to higher wind generation costs to meet system loads. Further, in a system with a significant level of wind penetration, spillage of wind may cause overall deficit of generation, leading to undesirable loss of loads. Although, addition of new lines to the system can potentially reduce spillage, it is eventually limited due to the line investment costs.

In order to take into account all these aspects, the TEP problem can be formulated as a multi-objective optimization problem with the following components:

1) Cost of new lines.
2) Cost of SW throughout the year ($CSWY$).
3) Cost of Loss of Load (CLL).
4) Cost of Generation (COG).

The following assumptions make the problem more tractable and are used in the mathematical formulation of the TEP problem that follows:

1) The network is approximated by a DC model.
2) Loss of Load is modelled as artificial generators with high marginal cost as high *CLL* is not acceptable.
3) The additional lines have the same cost as the earlier lines in the same Right of Way (ROW) (same sending and receiving end of the line).

The TEP model formulation is as shown below:

minimize v :

$$v = \sum_{i,j} n_{ij} c_{ij} + CSWY + CLL + COG \tag{4}$$

$$CSWY = C_{SW} \times SW \tag{5}$$

$$CLL = C_{LL} \times \sum_t \sum_i r_{i,t} \tag{6}$$

$$COG = \sum_t \sum_i C_{Gi} \times g_{i,t} \tag{7}$$

subject to :

$$\sum_j S_{ij} f_{ij,t} + g_{i,t} + P_{i,t} = d_{i,t} - r_{i,t} \tag{8}$$

$$f_{ij,t} - \gamma_{ij}(n_{ij}^0 + n_{ij})(\Theta_{i,t} - \Theta_{j,t}) = 0 \tag{9}$$

$$|f_{ij,t}| \le (n_{ij}^0 + n_{ij})\overline{f_{ij}} \tag{10}$$

$$0 \le g_{i,t} \le \overline{g_i} \tag{11}$$

$$0 \le r_{i,t} \le d_i \tag{12}$$

where,

v = Total cost to be minimized.

c_{ij} = Cost of line between i^{th} and j^{th} bus.

n_{ij} = Number of proposed lines between bus i and j.

C_{SW} = Marginal cost of spilled wind (constant during all the instants).

C_{LL} = Marginal cost of Loss of Load (constant for all the loads, during all the instants).

C_{Gi} = Marginal cost of power produced by the generator (constant during all the instants) connected at i^{th} bus.

S = Branch node incidence matrix of the given system.

$g_{i,t}$ = Generation at i^{th} bus and t^{th} instant.

$r_{i,t}$ = Artificial generator at i^{th} bus and t^{th} instant, with high incremental cost of generation.

$P_{i,t}$ = Wind power generation at i^{th} bus and t^{th} instant; non-zero if wind farm is connected at that bus.

$d_{i,t}$ = Net demand at i^{th} bus and t^{th} instant.

$f_{ij,t}$ = Power flow through the line connected between node i and j at t^{th} instant.

γ_{ij} = Susceptance of circuit between node i and j.

n^0_{ij} = Existing number of lines between node i^{th} and j^{th} bus.

$\overline{f_{ij}}$ = Maximum power flow between the line connected between node i and j.

$\theta_{i,t}$ = Bus angle at i^{th} bus and t^{th} instant.

Equation (8) and (9) represent, the power balance equation for the i^{th} bus and DC-PF equation respectively. Equation $(10), (11)$ and (12) represents line loading limit, generation limit and the loss of load limit respectively.

The TEP problem formulated above is an MINLP problem which is solved using (SBB) solver. The SBB solver is a combination of Branch and Bound methods [10] for MINLP and other NLP solvers from GAMS [13] software.

IV. CASE STUDY

A 138 kV Garver's 6-Bus reliability test system [14] (see fig. 3) shows the typical load-generation (capacity) scenario and the existing (thick) lines in the system. The system is deficit to begin with and bus 6 with a generation capacity of 600 MW is initially isolated from the system. For the studies carried out in this paper, the wind farm is sited at bus 6 along with a conventional generator, G6. With changing penetration levels of wind power, capacity of G6 is accordingly adjusted to maintain the maximum generation (injection) at bus 6 to 600 MW. The aim is to meet the entire load of the system with effective systems planning and hence the load pattern, as shown in figure 3, is maintained throughout, except in cases when load increment is affected. It is to be noted that the distribution of net load increment at load buses, as studied in this paper, are done in proportion to the base case load values.

Table IV in [14] can be referred for the network data, line cost (guide number × 10.8 × 10^3 \$) of existing as well as new lines to be added. For the case studies to follow, G1 and G3 are assigned low marginal cost of generation (10\$/MWh and 12\$/MWh respectively) while G6 (40\$/MWh) is an expensive generator. High marginal cost is also assigned to SW and loss of load (40\$/MWh and 41\$/MWh respectively) as both are undesirable. The steps taken in formulating the cases that follow are described below:

TABLE I: Generated test cases

Wind Penetration	Lines connected between 1^{st} and 6^{th} bus	Optimal No. of lines for given load	Optimal No. of lines for increased load
10% (wind farm capacity, 75 MW)	Case $1a$	Case $1b$	Case $1c$
20% (wind farm capacity, 150 MW)	Case $2a$	Case $2b$	Case $2c$
40% (wind farm capacity, 300 MW)	Case $3a$	Case $3b$	Case $3c$
60% (wind farm capacity, 450 MW)	Case $4a$	Case $4b$	Case $4c$

1) The entire year is divided into 24 time blocks of 15 days (or half monthly time blocks) each. The historical wind speed data [15] of the given wind site is available with ten minute periodicity. An average of such data for 15 days gives a representative generation data for a time block. 24 such data points for the study year from the reference wind power data (see fig. 2) for all the cases are to be studied. It is important to note that the data in figure 2 is normalised to the capacity of the wind farm.
2) The test cases generated are shown in table I. There are four case groups (Case $1-4$) across which the wind penetration levels[1] are changed. Further, in each case groups there are three sub-groups as seen from the Table I. Cases $1a$, $2a$, $3a$, and $4a$ form the base case in the corresponding case group. In these cases, bus 6 is connected to the rest of the network by an additional line of 70 MW capacity to bus 1 (which is an arbitrary choice) as shown in figure 3. Cases $1b-4b$ and $1c-4c$ are the cases where optimal number of lines to be added to the system are determined by the solution of the TEP problem (equations $4-12$). For cases $1c-4c$, total load has been increased from the initial base case value of 760 MW to 1100 MW (45% load increment). The schedules which are obtained as a result of optimization, are used to calculate table II, by using equations $(2), (3), (4), (5), (6)$ and (7). Cost of generation for generators G1, G3 and G6 are $COG1$, $COG3$ and $COG6$ respectively and are obtained from their schedules.

A. *Case 1: (10% wind penetration)*

1) Case $1a$: For 10% wind power penetration, maximum of the average power generation throughout the year is 47.9 MW (see fig. 2), which is less than the capacity of line $(1-6)$. Therefore, spillage of wind power is zero (see table II). However, because of lack of adequate generation capacity, the loss of load is high. Since the proportion of cheap wind power in the generation mix is less, the cost of generation is also very high.

2) Case $1b$: The optimal plan for 10% wind penetration is shown in figure 4. Addition of two new lines across bus 4 to

---

[1] % Wind penetration = $\frac{\text{Capacity of wind farm}}{\text{Total load of the system}} \times 100$

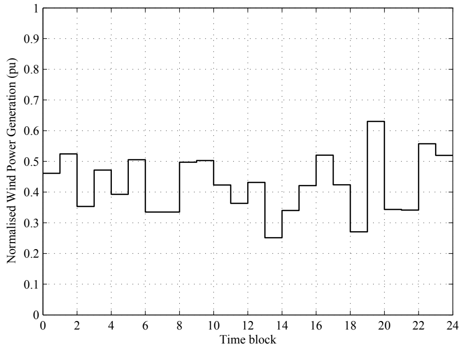

Fig. 2: Wind Power generation normalised to capacity of the Wind Farm

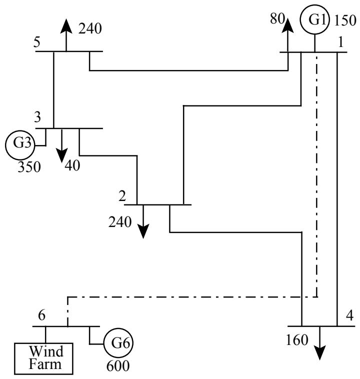

Fig. 3: Base case: Showing only one line is connected

bus 6 (each of 100 MW) increases the maximum generation that can be evacuated from bus 6 to 200 MW. This results in significant reduction in loss of load and hence the value of objective function, v.

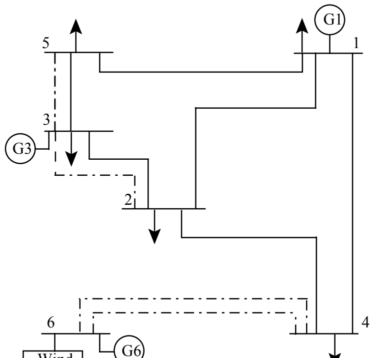

Fig. 4: Transmission lines to be planned for 10% wind power penetration (Case $1b$)

3) Case $1c$*:* The optimal plan for this case is shown in figure 5. New lines are added in between bus 6 and bus 4 to evacuate the generation available at bus 6. Additional lines which do not originate from bus number 6 are also added because of increased power flow. A large share of the costly generator G6 results in high cost of generation. G6 is capable of generating 525 MW, but optimality condition gives only 500 MW to be evacuated from bus 6. Since, some lines are hitting limit and increasing generation from G6, will require more lines which will reduce objective function.

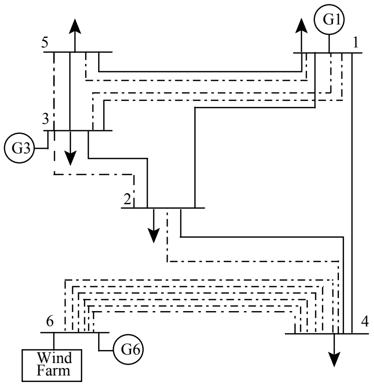

Fig. 5: Transmission lines to be planned for increased Load Demand (Case $1c$, $2c$, $3c$ and $4c$)

B. *Case* 2 *(20% wind penetration)*

1) Case $2a$*:* For 20% wind power penetration, maximum power generation from the wind turbine is 95.8 MW. Therefore, the capacity constraint (70 MW) of line $(6-1)$ may limit the evacuation of the excess wind power generation. This leads to spillage of wind. Inadequate transmission capacity leads to loss of load, which is comparable to that of case $1a$. However, an increased proportion of cheaper wind power in the generation mix results in reduced cost of generation and therefore, the objective function as compared to case $1a$.

2) Case $2b$*:* The optimal plan for this case is shown in figure 6. Two lines, one from 4 to 6 and another from 2 to 6 are required to supply all the wind power (having zero marginal cost) resulting in zero spillage and two lines from 3 to 5 are required to improve the network connectivity to reduce the loss of load as compared to case $2a$. Inclusion of higher percentage of cheaper wind power and lesser participation of costly G6, reduces the overall generation cost as compared to $1b$.

3) Case $2c$*:* The optimal plan remains the same as in case $1c$. However, for comparable loss of loads, the generation cost is reduced as the share of cheaper wind power in the supply mix is higher as compared to case $1c$.

C. *Case* 3 *(40% wind penetration)*

1) Case $3a$*:* With a maximum wind power production of approximately 190 MW, spillage is very high. Similar to cases $1a$ and $2a$, inadequate transmission results in high loss of load. Importantly, the participation of the costly generator G6 is reduced to zero as the entire transmission capacity of line $(6-1)$ is utilized by the wind farm.

2) Case $3b$*:* The optimal plan remains the same as in case $2b$. Just sufficient transmission capacity, reduces the spillage to zero. Loss of load is significantly reduced as compared to case $3a$. G6 also participates at times (when capacity

TABLE II: Comparison of Different Components of the Objective Function

Cases	Cost of lines (million \$)	$CSWY$ (million \$)	CLL (million \$)	$COG1$ (million \$)	$COG3$ (million \$)	$COG6$ (million \$)	Obj. fn. (million \$)
Case $1a$	0.204	0.00	109.900	12.96	28.77	13.02	164.80
Case $1b$	0.300	0.00	17.254	12.96	46.66	57.95	135.12
Case $1c$	0.918	0.00	39.050	12.96	46.66	153.65	253.24
Case $2a$	0.204	1.28	109.900	12.96	28.77	3.11	156.22
Case $2b$	0.300	0.00	25.370	12.96	46.66	38.67	123.96
Case $2c$	0.918	0.00	39.050	12.96	46.66	142.46	242.05
Case $3a$	0.204	20.53	109.900	12.96	28.77	0.00	172.36
Case $3b$	0.300	0.00	25.200	12.96	46.64	16.53	101.56
Case $3c$	0.918	0.00	39.050	12.96	46.66	120.1	219.69
Case $4a$	0.204	42.88	109.900	12.96	28.77	0.00	194.71
Case $4b$	0.480	0.00	0.070	12.96	46.41	19.92	79.84
Case $4c$	0.918	0.00	39.050	12.96	46.66	97.74	197.33

of transmission from bus 6 is available) to meet the load. However, dependence on the same for similar loss of loads is lesser as compared to case $2b$.

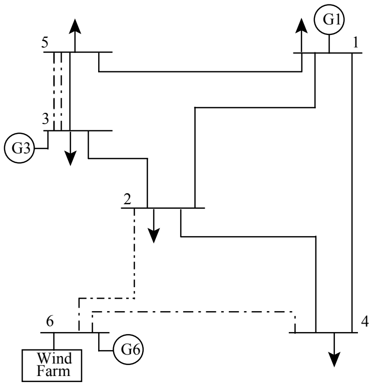

Fig. 6: Transmission lines to be planned for 20% and 40% wind power penetration (Case $2b$, $3b$)

3) Case $3c$*:* Costly generator G6 is used in lesser amount compared to case $2c$, which is substituted by wind power. The optimal plan remains the same as cases $1c$ and $2c$.

D. Case 4 *(60% wind penetration)*

1) Case $4a$*:* Results similar to earlier cases are observed here with maximum wind generation of around 287 MW and inadequate transmission capacity to evacuate the generation. For cases $1a-4a$, the load being met, participation of generators G1 and G3 are same and hence, total generation coming from bus 6 is same. Therefore, with increase in penetration, wind generator with zero marginal cost is utilised more compared to G6.

2) Case $4b$*:* The optimal plan is shown in figure 7. Spillage is zero, loss of load is almost negligible and the share of costly generator G6 in the generation mix is significantly reduced which results in the minimum objective function value in all the cases studied. Comparing cases $1b-4b$, it is seen that CLL as well as $COG6$ has increasing and decreasing trend, but $CLL+COG6$ with increase in wind penetration gets reduced. Since marginal cost of G6 and CLL are comparable, increasing and decreasing trend is a result of DC-PF constraint.

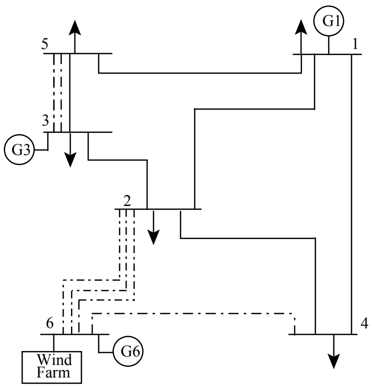

Fig. 7: Transmission lines to be planned for 60% wind power penetration (Case $4b$)

3) Case $4c$*:* The optimal topology still remains the same as in cases $1c-3c$, which is valid for the given network configuration. Cost of loss of load for increased load cases remains same. This may be a result of all the five lines from bus 6 to 4 are utilised equally for all the cases. When the wind penetration increases, G6 is used less. And hence v gets reduced for increased penetration. The number of lines to be added may not be same for varying wind penetration if network configuration is changed.

The marginal cost of G6 and C_{LL} are comparable, hence optimal participation of G6 and C_{LL} will be dependant upon DC-PF constraint. It is interesting to note that, for all the cases where optimal number of lines are calculated, spillage is reduced to zero because of low cost of wind power and high cost of spillage compared to marginal cost for addition of new lines. Table III summarizes the reinforcements in all the studied cases.

E. Observations

The following key observations are found from the studied cases:

1) Loss of load may result even with sufficient generation capacity if transmission capacity is adequate.
2) Co-existence of cheaper generation resources like wind power in the system makes the optimal transmission planning more important.

TABLE III: Solution of Garver's 6-Bus System For Different cases

ROW	New Lines to be Added								
	Case 1*a*, 2*a*, 3*a* and 4*a*	Case 1*b*	Case 1*c*	Case 2*b*	Case 2*c*	Case 3*b*	Case 3*c*	Case 4*b*	Case 4*c*
1 – 2	0	0	0	0	0	0	0	0	0
1 – 3	0	0	2	0	2	0	2	0	2
1 – 4	0	0	0	0	0	0	0	0	0
1 – 5	0	0	1	0	1	0	1	0	1
1 – 6	1	0	0	0	0	0	0	0	0
2 – 3	0	1	0	0	0	0	0	0	0
2 – 4	0	0	1	0	1	0	1	0	1
2 – 5	0	0	0	0	0	0	0	0	0
2 – 6	0	0	0	1	0	1	0	3	0
3 – 4	0	0	0	0	0	0	0	0	0
3 – 5	0	1	1	2	1	2	1	2	1
3 – 6	0	0	0	0	0	0	0	0	0
4 – 5	0	0	0	0	0	0	0	0	0
4 – 6	0	2	5	1	5	1	5	1	5
5 – 6	0	0	0	0	0	0	0	0	0
TOTAL	1	4	10	4	10	4	10	6	10

3) While reduced spillage with effective transmission can eventually reduce loss of load and overall cost of generation suboptimal planning (with lower line investment costs) can lead to higher system costs in the long run.
4) With increased system loads, a higher percentage of wind penetration is supported. Optimal transmission plan can reduce the dependence on costly conventional generators.
5) For minimum investment cost, with increased wind penetration, number of additional line reinforcements between two non-wind buses are determined by cost of ROWs.
6) Based upon transfer capacity of connected lines to a bus generator having low marginal cost will be exhausted first.
7) Limited transmission capacity forces the participation of costly generators into the network.

V. CONCLUSION

A mathematical model has been proposed and studied to solve the transmission network expansion planning with variable wind power. With different cases of wind penetration levels, the effect of sub-optimal transmission reinforcement, optimal reinforcement, and effect of load increment are studied and compared. The results obtained gave us an insight into the interactions among various components of the multi-objective TEP problem. With the comparison of different cases, suitable decisions can be taken for transmission reinforcement in a static planning framework. The proposed TEP formulation can be extended for wind farms connected at multiple number of buses, and also for dynamic planning over many years, which can provide the system planner with valuable information for a cost-effective transmission reinforcement.

REFERENCES

[1] E. Da Silva, H. Gil, and J. Areiza, "Transmission network expansion planning under an improved genetic algorithm," *IEEE Trans. Power Syst.*, vol. 15, no. 3, pp. 1168–1174, Aug 2000.

[2] R. Romero, A. Monticelli, A. Garcia, and S. Haffner, "Test systems and mathematical models for transmission network expansion planning," *IEE Proc. Gen. Trans. Distrib.*, vol. 149, no. 1, pp. 27–36, Jan 2002.

[3] F. Ugranli and E. Karatepe, "Transmission expansion planning considering maximizing penetration level of renewable sources," in *Innovations in Intelligent Syst. and App. (INISTA), 2013 IEEE Int. Symp.*, June 2013, pp. 1–5.

[4] N. Alguacil, A. Motto, and A. Conejo, "Transmission expansion planning: a mixed-integer lp approach," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1070–1077, Aug 2003.

[5] Z. Al-Hamouz and A. Al-Faraj, "Transmission expansion planning using nonlinear programming," in *Trans. and Distrib. Conf. and Exhib. 2002: Asia Pacific. IEEE/PES*, vol. 1, Oct 2002, pp. 50–55 vol.1.

[6] I. de J Silva, M. Rider, R. Romero, A. Garcia, and C. Murari, "Transmission network expansion planning with security constraints," *IEE Proc. Gen. Trans. Distrib.*, vol. 152, no. 6, pp. 828–836, Nov 2005.

[7] A. Arabali, M. Ghofrani, M. Etezadi-Amoli, M. Fadali, and M. Moeini-Aghtaie, "A multi-objective transmission expansion planning framework in deregulated power systems with wind generation," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 3003–3011, Nov 2014.

[8] M. Delgado, M. Pourakbari-Kasmaei, and M. Rider, "A modified branch and bound algorithm to solve the transmission expansion planning problem," in *Env. and Elect. Engg. 13th Int. Conf.*, Nov 2013, pp. 234–238.

[9] S. Haffner, A. Monticelli, A. Garcia, and R. Romero, "Specialised branch-and-bound algorithm for transmission network expansion planning," *IEE Proc. Gen. Trans. Distrib.*, vol. 148, no. 5, pp. 482–488, Sep 2001.

[10] GAMS SBB Solver. [Online]. Available: http://www.gams.com/dd/docs/solvers/sbb.pdf

[11] R. Billinton and W. Wangdee, "Reliability-based transmission reinforcement planning associated with large-scale wind farms," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 34–41, Feb 2007.

[12] P. Giorsetto and K. F. Utsurogi, "Development of a new procedure for reliability modeling of wind turbine generators," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no. 1, pp. 134–143, Jan 1983.

[13] A. Brook, D. Kendrick, and A. Meeraus, "GAMS, a User's Guide," *SIGNUM Newsl.*, vol. 23, no. 3-4, pp. 10–11, Dec 1988.

[14] L. Garver, "Transmission network estimation using linear programming," *IEEE Trans. Power App. Syst.*, vol. PAS-89, no. 7, pp. 1688–1697, Sept 1970.

[15] National Renewable Energy Laboratory. [Online]. Available: http://www.nrel.gov