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Transmission Expansion Planning Considering Wind Energy Conversion Systems Using PSO

K. Indira, B. Srinivasa Rao

Abstract*: *In power system studies the most important issue is Transmission Expansion Planning (TEP). The intend of TEP problem is to choose the placement as well as number of additional transmission lines, which are to be added to the existing system to suit growing demand in planning horizon. In this paper a new methodology for TEP is proposed, the presented Transmission planning is linked with generation cost, active power loss minimization by considering wind uncertainties. Firstly, the uncertainties involved in wind generation can be determined by using weigbull probability functions. Monte Carlo simulation study is able to be used to find the probability distribution functions of wind generation. Then, in TEP formulation the WTG uncertainties are considered. Particle swarm optimization (PSO) technique is used for solving the proposed single objective optimization problem. Simulation studies conducted on an IEEE 30 bus test system to certify effectiveness of the TEP problem with considering wind uncertainties.

Keywords*: *Transmission expansion planning (TEP); probability density function; Monte-Carlo simulation; Particle swarm optimization (PSO); Wind energy systems (WES).

I. INTRODUCTION

The main intend of Optimal Power flow (OPF) problem is to reduce the objective functions like generation cost, L-index and transmission line loss by tuning the independent variables (control) of power system. Belgin Emre, Rengin Idil [1] discussed about optimal power flow problem by using Newton Raphson based PSO. Nowadays conventional power plants are one of the causes for environmental pollution. In order to reduce the environmental pollution and CO2 levels, depletion of fossil fuels, renewable energy sources are the best alternative to conventional power units. Wind energy plays a major role in case of renewable energy sources. By incorporating WECS the generation cost function is not simple while in the case of cost function of normal conventional generators. The optimal power flow problem including wind energy conversion systems are proposed in [2]. The uncertainties involved in wind generation can be determined by using weigbull probability functions. The under and over estimated wind energy is associated with reserve and penalty costs respectively and these costs are also included in the Optimal power problem formulation in the case of WECS. In this paper, TEP is proposed considering OPF with WECS, TEP problem is extension of OPF problem. The intend of TEP is to provide the growing load demand in the future by expanding or constructing new transmission lines. In regulated environment TEP problem aims to reduce the line investment cost only which is different from deregulated environment.

Mathematical and meta-heuristic approaches are two different approaches which are used to study the TEP issue. The mathematical methods include linear and non linear programming [3] and Bender's decomposition [4]. Mathematical methods are dealing with problems like slow convergence and dimensionality issues. In order to avoid these complexities various artificial intelligence based methods have been successfully utilized to compute OPF problem. Likewise, some heuristic methods, for example Harmony Search [5], PSO [6], Genetic algorithms [7], ant colony [8] and differential evolution [9] are effectively utilized for taking care of the OPF along with TEP issue. In this paper, to work out OPF problem with consideration of WECS the PSO method is used. To test the effectiveness of the proposed method with different cases by considering TEP IEEE-30 bus test system is used.

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***** Correspondence Author (s)
K. Indira, PG scholar, Department of Electrical and Electronics Engineering, V R Siddhartha Engineering College, Vijayawada, A.P, India
Dr. B. Srinivasa Rao, Professor , Department of Electrical and Electronics Engineering, V R Siddhartha Engineering College, Vijayawada, A.P, India

II. PROBLEM FORMULATION OF OPF

The OPF main aim is to optimize the specific objective function such as generation cost, active power loss, emission and L-index by optimal tuning of the independent variables of power system [10], while fulfilling a all the equality as well as inequality constraints. OPF problem formulation is mathematically demoted as

Min $f(x,u)$ *(1)*

Subjected to: $y(X,U) = 0$ *(2)*

$z(X,U) \leq 0$ *(3)*

where y is equality constraint, z is the inequality constraint.
Equality constraints: The total generation must be equal towards the summation of total power demand and transmission losses of power system.

$$\sum_{i=1}^{n} P_{gi} = P_D + P_L \quad (4)$$

where P_{gi} - i^{th} generating units power output, the total demand of the load is P_d ; P_L - transmission line loss.
Inequality constraints: Inequality constraints include limits of system independent and dependent variables.

2.1. Control variables- (independent variables)

The generator real powers, and switchable VAR sources of reactive power, generator bus voltages, tap settings of transformer.

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$$U^T = [P_{G2} \dots . P_{GNG}, Q_{C1} \dots . Q_{CNC}, V_{G1} \dots . V_{GNG}, T_1 \dots . T_{NT}]$$
(5)

where u is control vector which consist of all independent variables

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, i = 1, \dots . . NG$$
(6)

P_{Gi} is the i^{th}generator real power output except at the slack bus varying from minimum to maximum values.

$$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max}, i = 1, \dots . . Nsh$$
(7)

where Q_{ci} is the shunt VAR compensations, where Nsh is the number of shunt VAR compensators.

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max}, i = 1, \dots . . NG$$
(8)

where V_{Gi} is the i^{th} generator voltage varying within the limits; NG - is the number of generators.

$$T_i^{min} \leq T_i \leq T_i^{max}, i = 1, \dots . . NT \qquad (9)$$

where T_i is the tap setting of transformer varying within the limits; NT - is the number of transformers.

*2.2. Dependent variables (State variables***)**

State variables of power system are also slack bus real power, voltages at load buses, reactive powers of generator and transmission line flows.

$$X^T = [P_{G1}, Q_{G1} \dots . Q_{GNG}, V_{L1} \dots V_{ld}, S_{L1} \dots S_{LNL}]$$
(10)

where dependent variables vector is represented by X

$$P_{G1}^{min} < P_{G1} < P_{G1}^{max} \qquad (11)$$

$P_{G1}^{max}, P_{G1}^{min}$, are the maximum and minimum limits of slack bus real powers.

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, i = 1, \dots . . NG$$
(12)

Q_{Gi} is the reactive power of i^{th} generating unit

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max}, i = 1, \dots . . N_{ld}$$
(13)

where V_{Li} is the i^{th}bus voltage varying from minimum to maximum limits, $N_{ld}$is the number of load buses.

$$S_{Li} \leq S_{Li}^{max}, i = 1, \dots NL \qquad (14)$$

S_{Li}^{max} - the i^{th}transmission line flow limit, NL - number of transmission lines.

Security constraints: Generator reactive power limits, load bus voltage limits and transmission line flow limits are considered as security constraints. In this paper to mitigate the security constraints violations the penalty function method [11] is used i.e. the violated values of security constraints are added to objective functions.

III. WIND ENERGY SYSTEMS (WES)

The optimum power flow problem incorporating wind uncertainties is discussed in this section. By incorporating non-conventional sources like wind energy, cost function of system is not simple we have to include wind generation cost function into the traditional OPF problem formulation. The mathematical formulation of cost functions including wind energy conversion systems are given below. Due to of the uncertainties of wind speed at any given time, cost function of wind generation consists of two components along with direct cost function. They are penalty cost function and reserve cost function. The over estimated cost of available wind power generation related to reserve cost. The under estimation of available wind power generation is related to penalty cost. The reserve cost function can be mathematically formulated as

$$C_{res,i} = k_{r,i} \int_0^{W_{gi}} (W_{gi} - W_{avb}) fW(W) dW \qquad (15)$$

where $k_{r,i}$ is the penalty coefficient of i^{th} wind generating unit.

The penalty cost function can be mathematically formulated as

$$C_{pen,i} = k_{p,i} \int_{W_{gi}}^{W_{r,i}} (W_{avb} - W_{gi}) fW(W) dW \qquad (16)$$

Where $k_{p,i}$ is the penalty coefficient of i^{th} wind generating unit; $fW(W)$ is the wind power PDF; w_{gi} is the power from i^{th} wind power generating unit; $W_{i,avb}$ is the wind power availability of i^{th} wind generator this is a random value varying from 0 to w_r, and probability of w_r is varying with probability Density function. The PDF of wind power output can be determined by using Monte Carlo simulation method, based on the Weibull distribution of wind where w_r is the rated wind power; C_i is the cost function for i^{th} thermal generating unit; $C_{w,gi}$ -the cost function for i^{th} wind unit; $C_{pen,i}$ is the penalty cost function; $C_{res,i}$ is the reserve cost function related with penalty due to over estimation of available wind power. For tracking the wind uncertainties a probabilistic wind model is a very suitable model. At a certain location the probability density function (PDF) of wind speed is generally obtained by Weibull distribution. In Weibull function the shape and scale parameters are present which are obtained by using the mean wind speed and standard deviation (SD) of the wind speed [12]. Wind speed consists of three parameters, they are cut in speeds *(V_{ci})*, cut out speeds (V_{co}) and rated speeds (V_{rate}) are involved in estimation of power output characteristics.

IV. TRANSMISSION PLANNING

TEP can be done by building new transmission lines with less cost, which change active and reactive power flow through the lines which already exist in power system network. Two network topologies are present to solve TEP problem.

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- Existing network (which consists of existing transmission lines)
- Modified network (consist of new transmission lines) to satisfy the growing load demand in future.

In this paper for solving TEP problem the load on the IEEE-30 bus system is increased by 80% and then the line flow violations are observed and corresponding lines are selected to mitigate the line flow violations.TEP problem is a non-linear mixed integer program. Garver [13] has proposed the use of linear programming technique for solving transmission expansion planning problem. Different models available for representing the transmission networks. There are four major types of network models have been used for representing the power system network in TEP studies [14]. They are DC power flow [15], transportation model, hybrid model and disjunctive model. The use of above model have the drawback that the transmission planning problem is different from reactive power planning problem so in this paper an AC TEP is considered where network reactive powers also included. Mj rider and R. Romero has been proposed [16] an accurate AC network modelling.

4.1 Mathematical modeling of AC TEP:

AC TEP can be mathematically formulated as by eqs (17) to (24).

$$\min v_t = c^t n \quad (17)$$

s.t

$$P(v,n) - P_G + P_d = 0 \quad (18)$$

$$Q(v,n) - Q_G + Q_d = 0$$

$$(N^{ex} + N^b)S^{from} \le (N^{ex} + N^b)S^0 \quad (19)$$

$$(N^{ex} + N^b)S^{to} \le (N^{ex} + N^b)S^0 \quad (20)$$

while c is the transmission lines cost vector, n is the added new lines. N^{ex} and N^b denotes diagonal matrices consist of transmission lines in case of expanded and base case respectively. v_t - line investment cost because of the building of new lines to the power system network. Where P_G, Q_G and P_d, Q_d are the active and reactive power vectors of generation and load. V represents the voltage vector. S^{from}, S^{to}, and S^0 - vectors of complex power flows and their maximum power flow limits.

4.2 Objective functions

(i) Minimization of total generation cost of a system is expressed as

$$\text{Min } f_1 = f_{1c} + f_{1w} \quad (21)$$

where $f_{1c} = \sum_{i=1}^{N} (a_i P_{gi}^2 + b_i P_{gi} + c_i)$ (22)

$$f_{1w} = \sum_{i}^{Nw} (C_{dir.i} + C_{res.i} + C_{pen.i}) \quad (23)$$

where f_{1c} the cost function for conventional generators is, f_{1w} is the cost function for wind generators. Nw is the number of wind units. a_i, b_i, c_i are the generator cost coefficients for i^{th}generating unit, n is the number of thermal units, and P_{gi} - power output of the i^{th}unit. If the WECS units in system are absent then cost function f_{1c} only exists.

(ii) Minimization of active power loss

$$f_2 = \sum_{k=1}^{NL} G_k [v_s^2 + v_r^2 - 2v_s v_r \cos(\theta_s - \theta_r)] \quad (24)$$

where G_k is the conductance of transmission line, θ_s and θ_r are the angles of buses, v_s, v_r are the voltages at bus s and r.

V. METHODOLOGY

PSO is the heuristic optimization technique which was developed in1995 by Eberhort and Kennedy. It is a well familiar method known to resolve comprehensive non linear problems effectively and it is one of the classifications of the Evolutionary computations [17], used to resolve the problems of optimization. For the every iteration, the velocity vector for each particle is in synch according to the chronological best position of that particle and the region particle best position. A solution which is optimal or near optimal is obtained to the natural moment of the particles and it can generate good quality solutions with a reduced amount of computational time and more constant convergence characteristics, where most analytical methods fail to converge. The velocities and positions are keeping up to date for all the particles using the following equations.

$$V_m^{K+1} = w_f * V_m^{k} + c_{p1} * r_{p1} * (p_b^{k} - X_m^{k}) + c_{g2} * r_{g2} * (G_b^{k} - X_m^{k}) \quad (25)$$

$$X_m^{k+1} = X_m^k + V_m^{k+1} \quad (26)$$

Where k is the iteration value, V_m^{k} velocity of a particle at k^{th} iteration, X_m^{k} is the location of particle at k^{th} iteration. Where stopping criteria is exceeding maximum iterations or good fitness value is obtained. Here generation cost & power loss of system can be solved by using PSO.

VI. SIMULATION RESULTS

The effectiveness of proposed method is verified by MATLAB programming. To resolve the optimal power flow problem by considering WECS with TEP a standard IEEE 30 bus test system is used. This test system consists of six generating units, 41 transmission lines, four tap changing transformers, nine shunt capacitors, the minimum and maximum limits of generator and generation cost coefficients are taken from [1]. Load demand of the system is defined as 2.8340p.u. Total population size is chosen as 50 and number of particles is 25 which include Pg's, Vg's, Taps and Q shunts. The test system results are compared for before and after TEP. The minimization of generation cost, active power loss is taken as two different objectives for the following cases.

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Case 1: Without WECS
Case 2: With WECS

In case of WECS the conventional generators at buses 4, 5 and 6 are replaced with wind generating units. The cut in speed, rated speed and cut out speed of given system are taken as 3m/s, 12m/s and 30m/s respectively.

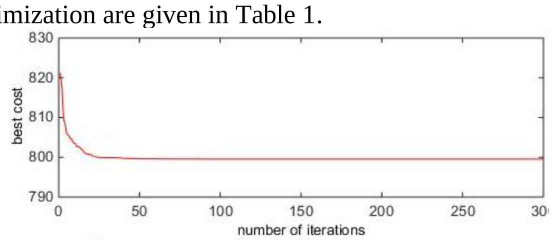
6.1 Before considering TEP

6.1.1 Case 1- Without WECS: The convergence plots of IEEE 30 bus test system for cost minimization and loss minimization are in Fig 1.(a) and Fig 1.(b) respectively. Before optimization the generation cost and power loss are 900.59($/hr), 5.32MW. By performing OPF using PSO, the total generation cost and active power loss of the system is reduced to 799.5408($/hr) and 3.05MW. Optimal values of the power generations corresponding to cost & power loss minimization are given in Table 1.

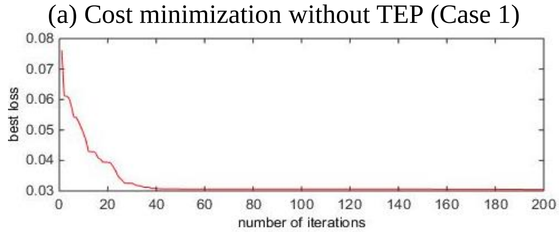
Table 1: Optimization results for generation cost minimization, active power loss without TEP

Case	*Case 1*			*Case 2*		
Independent variables	Base case	Cost objective	Loss objective	Base case	Cost objective	Loss objective
pg_1 (MW)	98.727	177.13	53.04	19.36	94.252	52.195
pg_2 (MW)	80	48.696	78.40	80	28.991	36.544
pg_3 (MW)	20	21.114	35.00	20	10	35
pg_4 (MW)	20	11.904	30.00	50	60	60
pg_5 (MW)	50	21.315	50.00	57	39.452	60
pg_6 (MW)	20	12	40.00	60	54.856	41.856
$\sum pg_i$ (MW)	288.72	292.16	286.45	286.3	292.16	286.45
Cost($/hr)	**900.59**	**799.5408**	964.07	**869.5615**	**785.83**	822.46
Power loss (MW)	**5.32**	8.76	**3.05**	**2.96**	4.1498	**2.194**

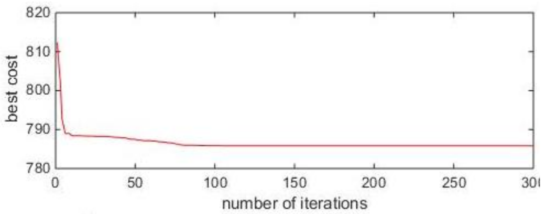
6.1.2 Case 2- With WECS: The Convergence plots of IEEE-30 bus test system for cost minimization and loss minimization by including WECS are shown in Fig 1.(c) and Fig 1.(d) respectively. Before optimization the total generation cost and power loss are 869.5615($/hr) and 2.96MW by performing OPF using PSO, the total generation cost and active power losses of test system is reduced to 785.83($/hr) and 2.194MW respectively. Optimal values of the power generations corresponding to cost and power loss minimization are given in Table 1.



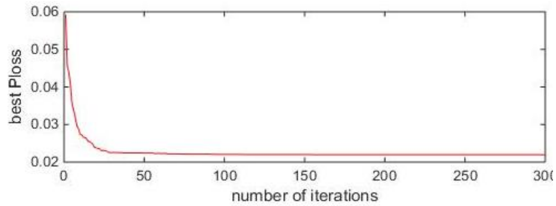
(a) Cost minimization without TEP (Case 1)



(b) Loss minimization without TEP (Case 1)



(c) Minimization of cost without TEP (Case 2)



(d) Loss minimization without TEP (Case 2)

Fig 1. Convergence characteristics for cost minimization and loss minimization without TEP

6.2 After considering TEP

The load at various buses of standard IEEE-30 bus test system is increased by 20%, 40%, 60% and 80% of the base case in order to identify line flow violations. The detailed results of each load demand are shown in Table 2. There is no line flow violation for 20% load enhancement; line 1-2 is violated for 40% load enhancement. For 60% load increment the lines 1-2, 2-13, 13-3, and for 80% load increment the lines 1-2, 2-13, 11-13, 13-3, 12-15 are violated their maximum power limits. It can be observed that with 80% load enhancement there are 5 lines violating their limits. In order to overcome this, TEP problem is solved by considering 9 candidate lines for the existing IEEE 30 bus system as shown in Table 3.

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Table 2: Effect of load change in IEEE - 30 bus test system

Independent variables	Base case	20% load added	40% load added	60% load added	80% load added
pg_1 (MW)	98.73	160.02	223.25	292.76	356.17
pg_2 (MW)	80	8	80	80	80
pg_3 (MW)	20	2	20	20	20
pg_4 (MW)	20	2	20	20	20
pg_5 (MW)	50	5	50	50	50
pg_6 (MW)	20	2	20	20	20
$\sum pg_i$ (MW)	288.73	350.02	413.25	478.57	546.17
Load (MW)	283.4	340.08	396.76	453.44	510.12
Overloaded lines	-	-	1	3	5

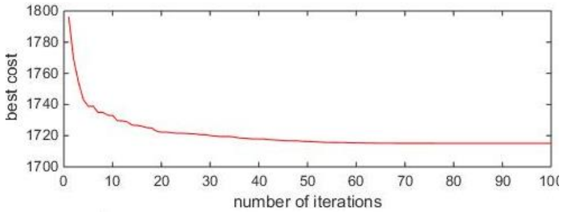
Table 3: Added transmission line details and cost for transmission expansion planning

Corridor	2-13	11-13	12-15	10-21	13-3	1-2
Number of lines added (9)	2	2	1	1	1	2
Total cost ($)	24206					

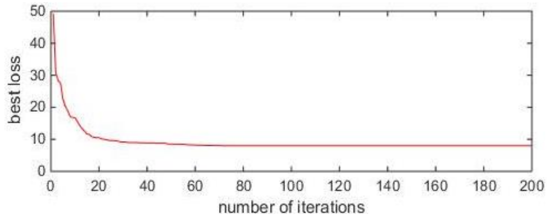
The total investment cost for given planning problem is 24206$. Now by considering this modified IEEE 30 bus test system with inclusion of new lines the following case studies conducted.

6.2.1 Case 1- Without WES:

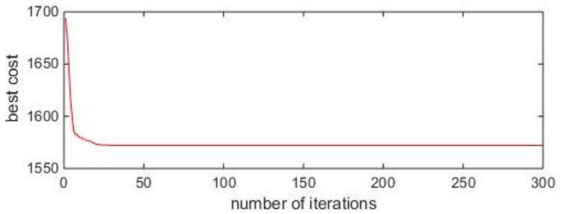
The Convergence characteristics for cost minimization and loss minimization without WECS by considering TEP problem are in Fig 2. (a) & Fig 2. (b) respectively. By considering TEP before optimization the fuel cost is 1794($/hr), active power loss is 22.89MW. By performing OPF with TEP problem using PSO, total generation cost and active power loss of test system is decreased to 1714($/hr) and 7.7MW respectively. The minimization of cost and power loss optimal values are shown in below Table 4.



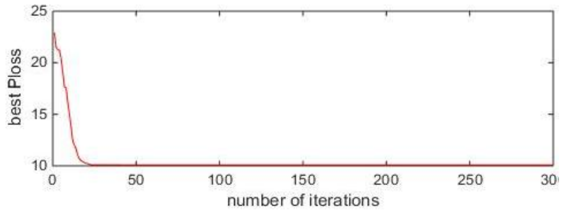
(a). Cost minimization with TEP (Case 1)



(b). Loss minimization with TEP (Case 1)



(c). Cost minimization with TEP (Case 2)



(d). Loss minimization with TEP (Case 2)

Fig 2. Convergence plots for TEP

6.2.2 Case 2 - With WES:

The convergence characteristics for generation cost minimization & loss minimization with WECS by taking into consideration TEP problem are shown fig Fig.2. (c) & 2. (d) respectively. Before optimization the cost and power loss are 1787.77($/hr), 21.79MW. By performing OPF considering TEP with WES using PSO, the generation cost & active power loss of test system is minimized to 1561($/hr) and 10.1MW respectively. The optimum values of power generations corresponding to cost and power loss are given in Table 4.

Table 4: Optimization results for TEP without and with WES

Independent variables	*Case 1*			*Case 2*		
	Base case	Cost objective	Loss objective	Base case	Cost objective	Loss objective
pg_1 (MW)	343.11	292.76	101.98	341	237.64	133.18
pg_2 (MW)	8	72.985	144	80	60.475	144

pg_3 (MW)	2	72.907	63	20	44.249	63
pg_4 (MW)	2	29.539	54	20	60	60
pg_5 (MW)	5	30.083	90	50	60	60
pg_6 (MW)	2	28.942	64.77	20	60	60
$\sum pg_i$ (MW)	533.01	527.2	517.82	531.9	522.3	520.2
Cost($/hr)	1794	**1714**	2225	1787.77	**1561**	1729.3
Power loss (MW)	22.89	17.1	**7.7**	21.79	12.25	**10.1**

VII. CONCLUSION

In this paper an attempt has been made to solve TEP problem using PSO with consideration of WES. Initially the OPF is solved using PSO generation cost minimization & power loss reduction. Later the effect of WECS is taken with consideration for implementing OPF problem. Here the generator cost function is not simple by incorporating WECS. Here penalty cost and reserve cost, which are associated with over and under evaluation of wind energy are included in the generator cost function. For IEEE 30 bus system the TEP analysis carried at by increasing 80% of the load on the system and total line cost is also determined for newly added lines. Then the OPF problem is implemented for TEP problem with and without WECS. The proposed methodology can be extended for implementing multi objective optimization problem using different methods with TEP by considering WECS.

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