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Resource aware wind farm and D-STATCOM optimal sizing and placement in a distribution power system

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ABSTRACT

Doubly fed induction generators (DFIG) based wind farms are capable of providing reactive power compensation. Compensation capability enhancement using reactors such as distributed static synchronous compensator (D-STATCOM) while connecting distribution generation (DG) systems to grid is imperative. This paper presents an optimal placement and sizing of offshore wind farms in a coastal distribution system that is emulated on an IEEE 33 bus system. A multi-objective formulation for optimal placement and sizing of the offshore wind farms with both the location and size constraints is developed. Teaching learning algorithm is used to optimize the multi-objective function constraining on the capacity and location of the offshore wind farms. The proposed formulation is a multi-objective problem for placement of the wind generator in the power system with dynamic wind supply to the power system. The random wind speed is generated as the input and the wind farm output generated to perform the optimal sizing and placement in the distributed system. MATLAB based simulation developed is found to be efficient and robust.

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1. INTRODUCTION

With 7200 kilometers of the coastal region, India has the capability of installing offshore wind farms ranging to around 70 GW and above. Optimal placement and sizing of DGs for minimized loss and higher reliability using discrete particle swarm optimization (DPSO) is developed on a semi-urban 37 bus distribution system [1]. Multi distributed generation (DG) placement and sizing adopting particle swarm optimization (PSO) based multi-objective optimization considering loading in the line, active and reactive power loss, voltage profile, and MVA intake by the grid as the parameters [2]. Distributed network operators (DNO) and the distributed generation owners (DGO) invest in the equipment in a different way. Optimal sizing and placement of DG that acts as the tradeoff between both their investments for a planning period are developed [3]. A two-stage heuristic method is applied to obtain the benefit-sharing between both DNO and DGO. Voltage stability margin improvement by introducing renewable energy to voltage sensitive buses is formulated using mixed-integer nonlinear programming [4]. Improved multi-objective harmonized system (IMOHS) and non-dominated sorting genetic algorithm II (NSGA-II) algorithms are compared for the optimal placement and sizing of DG. Power loss and voltage profile are considered as the multiobjective function for convergence [5]. Kalman filter-based algorithm that chooses the optimal size of the DG in steps of 10 KW is applied on a 60 mega volt ampere (MVA) scale distribution network. Optimal locator index is introduced to determine the power loss sensitivities and to adopt the best location of the DG [6]. A multiobjective formulation that includes minimizing the number of DGs and maximizing voltage stability is applied for DG placement and sizing problem. Nonlinear programming is applied to the multiobjective problem and shown better efficiency [7]. A multiobjective approach for DG sizing and placement is developed for an IEEE 33 bus system that benefits both the DG owners and distribution companies. It uses PSO algorithm to optimize both operational and generation-based parameters [8]. A non-iterative method for DG sizing and placing that gives the output directly is developed [9]. According to the sensitivity factors, a priority list is developed and executed to give a quick solution for the sizing and placement problem. An improved nondominated sorting genetic algorithm-II (INSGA-II) is developed for the sizing and placement of DGs [10]. Recently the popularity of the offshore wind farm is evident with the research findings on uniform wind speed and large sea area in the offshore environment. Both medium voltage alternating current (MVAC) and medium voltage direct current (MVDC) distribution system's performance is evaluated for the offshore wind farms [11]. Direct load flow solution with the kirchoff voltage law (KVL) and kirchoff current law (KCL) is implemented with offshore wind farms in the distribution system and the performance evaluation is carried out. Anticipating the inherent voltage instability due to the squirrel cage induction generator (SCIG) a DG configuration that combines both the SCIG and DFIG is used to solve the voltage instability issue. The IEEE 1547 standard that standardizes the connection of distributed energy resources (DERs) to the main grid describes that the unity power factor needs to be maintained. This literature has a setup that would allow the DFIG to absorb the reactive power that is fed by the SCIG to the grid thus paving the way to follow IEEE 1547 standards [12]. Optimal sizing and placement of flexible air conditioning transmission system (FACTS) devices and renewable distributed generators with varying and stable renewable energy input is discussed in literatures [13]-[18]. New contribution from the conventional approaches is proposed in [19], which is the scenario reduction algorithm unlike the cost reduction algorithm due to voltage unstability. Instead of the cost reduction algorithm that reduces the cost of power production due to voltage unstability, this implementation concentrates on voltage unstability reduction which is called the scenario reduction algorithm. The constraints of availability of the wind generation in the bus need to be constrained for an in situ scenario. Previous publications dealing with the placement of the wind generation system has allowed the constant wind generation system as the DG in the placement problem. Dynamics of the wind speed variation need to be adopted in the placement of the wind generator.

This paper provides the placement of the wind generation system by formulating the wind placement system by calculating the probabilistically variable wind generation in only a few selected buses. A multiobjective sizing and placement of DG and D-STATCOM are combined in the solution that is implemented on an IEEE 33 bus distributed system. This paper proposes the multiobjective objective function with benefit to cost ratio obtained from $ration$, $maintenance\ cost$, and $nvestment\ cost$. The multiobjective formulation also includes network security index and the voltage safety factor. The paper is organized in the following manner. Section 2 discusses the multiobjective formulation that includes the voltage stability as well as the cost-based constraint. Section 3 discusses the results and discussion of the optimization framework, followed by a conclusion and references.

2. PROBLEM FORMULATION

The primary contriution of this paper is obtaining the placement of the wind generation system with multiobjective function that include, cost security, and safety of the network. Dynamic wind veariation is considered as the DG in this formulation. The problem is formulated to minimize the total cost of wind power generation and maintenance. In the total cost, there are three parts. Investment cost (IC), operation, and maintenance cost (OMC) of DG including the interest rate and inflation rate are considered. The benefits of cost due to the placement of DG are considered along with the benefit to cost ratio (BCR). This has to be maximum so that the benefits are more while maintaining the voltage stability factor (VSF) and network security index within the limit. Formulation of the multiobjective problem is is being as, the size of the wind turbine generator is calculated by using (1) with wind velocity as the input. For determining the output power of the wind turbines, the annual average speed is considered as 6.02 m/s.

$$P_{rated} = 0.5\rho A v_w^3 C_p \tag{1}$$

$$P_{DG\ ren} = \begin{cases} 0\ V < V_{cin}\ or\ V_w > V_{out} \\ P_{rated}\ (V_w - V_{cin})/\ (V_N - V_{cin})\ V\_cin\ \leq V\_w \leq V\_N \\ P_{rated}\ V_N \leq V_w \leq V_{cout} \end{cases} \tag{2}$$

Here, $P_{rated} - is\ the\ total\ DG\ power\ required V_w - wind\ velocity\ in \frac{m}{s}$, $V_{cin} - cutin\ speed\ in \frac{m}{s}$, $V_{cout} - cutout\ speed\ in \frac{m}{s}$, $V_N - nominal\ speed\ in \frac{m}{s}$, c_p Performance coefficient of the turbine, ρ Air density (kg/m^3), A - Turbine swept area (m^2).

– The total cost of renewable DGs due to installation, operation and maintenance is given in (3) with the maintenance, interest, and BCR components.

$$Cost_{DG\ ren} = \sum_{i=2}^{N}\sum_{j\in type} IC_{ij} * n_i * l_i + \left(\sum_{i=2}^{N}\sum_{j\in type} OMC_{ij} * P_{DG\ ren\ ij} * n_i * l_i\right) * CPV \tag{3}$$

Where

$IC_{ij} - Ivestment\ cost\ type\ 'j'\ renewable\ DGat\ bus\ 'i'$

$OMC_{ij} - Operation\ and\ maintenance\ cost\ of\ type'j'renewable\ DGat\ bus\ 'i'$

$n_i - number\ of\ DG\ unit\ connected\ at\ the\ bus\ 'i'$

$l_i - location\ variable\ at\ bus\ \ 'i'(0\ or\ 1)$

$P_{DG\ ren\ ij} - Power\ generated\ by\ type\ \ 'j'DG\ at\ the\ bus\ 'i'$

$N - number\ of\ buses\ in\ the\ network$

$CPV - cumulative\ present\ value$

$$CPV = \frac{(1-PV^{N_y})}{(1-PV)} \tag{4}$$

Here, The present value of cost

$$PV = \frac{1+\frac{IF}{100}}{1+\frac{IR}{100}} \tag{5}$$

Where, $-Inflation\ rate, IR - interest\ rate$ and $N_y - Number\ of\ year\ in\ the\ planning\ horizon$

– In (6) defines the overall benefits that is obtained by introducing the renewable DGs in the distribution network.

$$〖Benefit〗\_(DG\_Statcom\ ren) = \{(∑\_(i = 2)^N▒ 〖∑\_(j ∈ type)▒ 〖(P\_(DG\ ren\ ij) + Q\_(Statcom\ ren\ ij)) * n\_i 〗 * l\_i) + 〗 Δ 〖Ploss〗\_(DG\ ren\ ) \} * C\_hr * 8760 * CPV \tag{6}$$

Where, $\Delta Ploss_{DG\ ren}$ –Power loss due to allocation of renewable DGs,

$C_{hr} - Cost\ of\ electricity$

Here C2 is statcom cost. Qst is the reactive power placed in at the bus in MVAR. The benefit to cost ratio BCR is given in (8).

$$C2(Q_{ST}) = \frac{1000XQ_{ST}}{8760X15}(0.0002466Q_{ST}^2 - 0.2243Q_{ST}+150.527) \tag{7}$$

$$BCR_{DG\ ren} = \frac{Benefit_{DG\_STATCOM\ ren}}{Cost_{DG\ ren}} \tag{8}$$

– Voltage stability factor

Voltage stability factor (VSF) in any bus due to the introduction of DG placement in any line of the distribution network is defined in equation (9), for i+1th bus.

$$VSF_{i+1} = (2V_{i+1} - V_i) \tag{9}$$

Where, V_i −voltage magnitude at bus i , V_{i+1} −voltage magnitude at bus i+1 and VSF for the entire network is given by.

$$VSF = \frac{\sum_{i=1}^{N-1} VSF_{i+1}}{(N-1)} \tag{10}$$

– Network security index

Security of the network also should be considered on the placement of DG.

$$LL_i = \frac{L_{MVA,i}}{L_{MVA_{max,i}}} \tag{11}$$

Network security index can be formulated as given in (12).

$$NSI = \frac{\sum_{i=1}^{N-1} LL_i}{(N-1)} \tag{12}$$

Certain buses can't use wind energy as it has the complexity in connecting the wind turbine in that location neglecting few buses using the following equation.

$$B_{feasibile,i} \leq \ Optimal\ location < B_{infeasible,i}$$

$$here\ i - index\ of\ the\ B_{feasible}\ \&\ B_{infeasible}$$

Similarly,

$$total\ demand\ in\ MVA = \ \sum_{i=1}^{n} \sqrt{(P_{Di}^2 + Q_{Di}^2)} \tag{13}$$

$$0 \leq \ Optimal\ size < total\ demand\ in\ MVA$$

A low value is better. So, the objective function is represented as.

$$minimize\ f\left(P_{DG\ ren\ ij}, n_i, l_i\right) = \left(1 + \left(\frac{1}{BCR}\right)\right) + \left(1 + \frac{1}{VSF}\right) + NSI + \frac{P_{loss_{without}}}{P_{loss_{with}}} \tag{14}$$

In the formulation, the wind generation cost is taken from [20]. The (14) defines the objective function that needs to be minimized using the metaheuristic methods. The convergence of both the PSO and teaching-learning-based optimization (TLBO) algorithm will follow this objective function which includes both the voltage stability and cost parameters in it. The IEEE 33 bus distributed system is used to validate the problem formulation and the results and discussion obtained are as explained in the next section.

3. TEACHER AND LEARNER ALGORITHM

This algorithm is made of the teacher-learning ability of the teacher and student in a classroom. The TLBO algorithm is divided into two parts. Teacher phase and Learner phase. The population (control variable/the parameters need to be identified) X is randomly initialized. The search space is of $N \times D$. The N is the number of learners and D is the course offered. This is the problem dimension. The iteration count ($IT_{\max}$) is the total number of iteration carried out and this is the stopping criteria. By defining the size of the DG (in Wattage), STATCOM location (line number) and number of DG as the independent variables and considering the equation (14) as the objective function TLBO algorithm is applied to obtain the best of the DG size, STATCOM location and number of DGs. Optimization algorithm that runs for few number of iterations is executed and results are obtained using the algorithm similar with modified objective function and condition of wind energy resources availability. The multiple objectives like the benefit to cost ratio (BCR), voltage stability factor (VSF), network security index, and loss minimization are considered. The BCR and VSF are maximized with minimization of losses and network service integration (NSI) is carried out.

4. RESULTS AND DISCUSSION

Wind DGs are placed in the IEEE 33-bus radial distribution system with 33 buses in the implementation using MATLAB. Total load size of 3.715 MW and 2.3 MVar with 12.66 kV. As the grid standards the lower and upper limit 0.95 p.u and 1.05 p.u respectively. Here the DG is considered as the wind turbine connected with the DFIG generatorThe multi-objective function is tested with PSO and TLBO algorithm. The wind data used in the solution is as given in Table 1. The wind data is selected with a random generation of wind as the nature of wind daily cannot be predicted exactly. According to [20], [21] average of 6.06 is assumed for calculations. The algorithm is run many times and tested for robustness.

Table 1. Wind data considered [21], [22]

Parameters	Values
Wind available buses	2 to 16
wind not available buses	17 to 33
Cut-in speed in m/s	6
Cutout speed in m/s	13
Wind velocity considered in m/s	6.06 [21], [22]
Air density in kg/m^2	1.225
C_F	0.59
Length of the wing (m)	52 m

The problem thus formulated in the previous section stipulates the placement of the wind buses in the buses mentioned as “wind available buses” in the above table. The constraint also extends to the amount of power generated in each bus in the wind buses. The formulation is optimized using both the PSO and TLBO algorithms [23]-[25]. The (14) is defined as the objective function and is minimized for better placement and sizing of the DG.

The curve of convergence for both the PSO and the TLBO based optimal sizing and placement is as shown in Figure 1. The convergence of the TLBO exhibits earlier convergence and with lesser cost than the PSO algorithm. Since the STATCOM placement also is combined for the DG placement in the implementation the voltage stability is assured in the buses. TLBO algorithm is giving better fitness by minimizing the cost objective function. Observing the convergence graph in Figure 2 indicates that the TLBO converged at the 13th iteration and PSO at the 50th iteration. A slightly better voltage profile is observed in the TLBO algorithm compared to the PSO algorithm as is shown in Figure 1.

Table 2 exhibits voltage stability in all the buses with DG and the STATCOM placement is optimized using both PSO and the TLBO algorithm. It is also evident from Table 2 that the voltage stability improvement is better with TLBO algorithm when compared to the PSO algorithm. The cost of the wind generation for calculation is obtained from [22]. Although the PSO and TLBO algorithms are applied for the placement and sizing in different peaces of literature literatures [23]-[25].

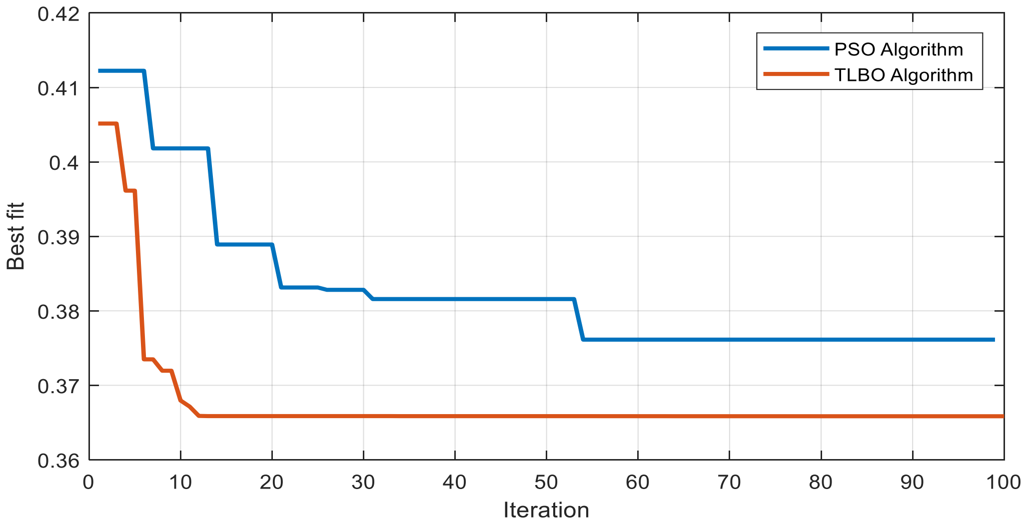

Figure 1. Convergence waveform of TLBO and PSO

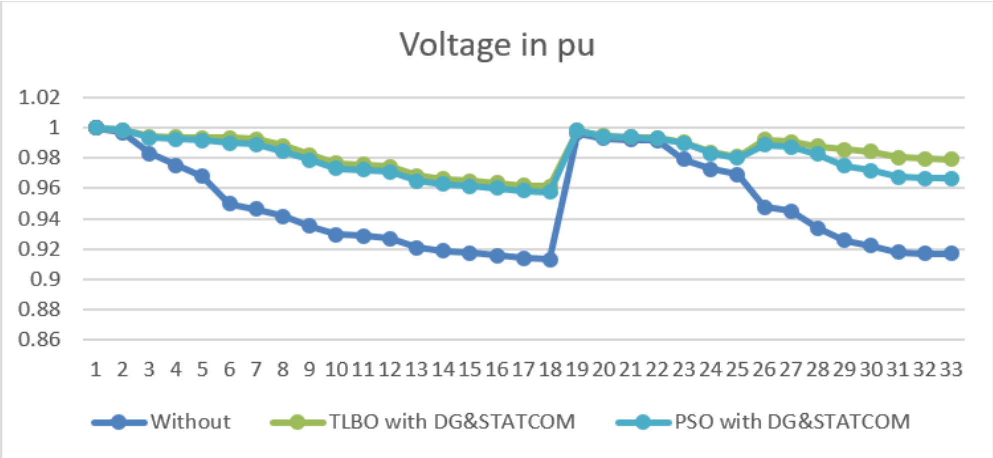

Figure 2. Voltage profile of the base case, PSO and TLBO

Table 2. Voltage values in per unit (pu)

	Voltage in pu		
Bus no.	Without DG and DSTATCOM	TLBO with DG & STATCOM	PSO with DG & STATCOM
1	1	1	1
2	0.9970	0.9988	0.9986
3	0.9829	0.9942	0.9934
4	0.9754	0.9937	0.9924
5	0.9680	0.9936	0.9918
6	0.9497	0.9933	0.9900
7	0.9462	0.9927	0.9892
8	0.9414	0.9881	0.9846
9	0.9351	0.9821	0.9786
10	0.9293	0.9766	0.9731
11	0.9284	0.9758	0.9722
12	0.9269	0.9743	0.9708
13	0.9208	0.9685	0.9650
14	0.9185	0.9664	0.9628
15	0.9171	0.9650	0.9615
16	0.9157	0.9637	0.9601
17	0.9137	0.9618	0.9582
18	0.9131	0.9612	0.9576
19	0.996	0.9982	0.9981
20	0.9929	0.9947	0.9945
21	0.9922	0.9940	0.9938
22	0.9915	0.9933	0.9932
23	0.9793	0.9906	0.9898
24	0.9726	0.9840	0.9832
25	0.9693	0.9807	0.9799
26	0.9477	0.9923	0.9889
27	0.9451	0.9911	0.9874
28	0.9337	0.9877	0.9828
29	0.9255	0.9855	0.9750
30	0.9219	0.98427	0.9716
31	0.9178	0.9803	0.9677
32	0.9169	0.9795	0.9668
33	0.9166	0.9792	0.9665

Table 3 depicts the location and sizing of the DG and also the indexes defined in the formulation, The TLBO exhibits better index values either it is the voltage-based index or the cost-based indexes. The placement and sizing of the DG and D-STATCOM placement are better with the TLBO algorithm in all the indexes and the loss and cost values. The size of DG placed using the TLBO algorithm is 2.2577MW and the D-STATCOM is of 1.2502 mega volt ampere reactive (MVAR). The size of DG placed using the PSO algorithm is 2.1421 MW and the D-STATCOM is of 1.058 MVAR. The fitness function that is proportional to the cost is 0.3664 units with the TLBO algorithm as compared to 0.3761 units with the PSO algorithm. Using TLBO the fitness minimizes 2.57%.

The cost objective is lesser with the TLBO algorithm compared to the PSO algorithm. This improves the VSF by 0.44%, NSI by 0.43%, and the total loss minimized by 13.35 %. These all happen when the BCR of the nearly the same value. So, without compromizing the cost of the STATCOM the improvements are done in the test system considered. The proposed multi-objective formulation with dynamic wind speed input clearly improves the fitness while the TLBO algorithm is implemented. From table it is evident that the TLBO algorithm dominates in every aspect of the multi-objective formulation proposed. Thus, the multi-objective formulation with dynamic wind generation input is found to be working effectively with good voltage stability and network security.

Table 3. Convergence results of TLBO and PSO

Parameters	TLBO	PSO
	with DG & STATCOM	with DG & STATCOM
Fit	0.3664	0.3761
BCR	2.7700	2.7846
VSF	0.9826	0.9783
NSI	0.4345	0.4330
Loss in KW	52.8162	60.9530
Location	7,30	7,28
Size in MW	2.2577,1.2502	2.1421,1.058

5. CONCLUSION

Multi-objective placement and sizing of DG and D-STATCOM problem formulated based on the availability of the wind resources is solved using both PSO and TLBO algorithm. The stable voltage stability and cost reduction are evident in the implementation of both the metaheuristics methods. Although voltage stability is evident in both the algorithms the TLBO algorithm exhibited better convergence both in terms of improved performance indexes and also the cost minimization. Thus, the proposed multi-objective formulation has shown good performance while introducing the dynamic wind generation input. Cost, network security and the voltage safety is found optimized to obtain the optimized placement of the wind generator.

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