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Optimal allocation of ESS in Wind Power Distribution

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***Abstract*— Due to rapid increase in demand and environmental pollution necessitates the wind penetration with energy storage systems play an vital role in both distributed and utility power systems. The benefit of an Energy Storage System is reduction of operating cost and improvement of voltage profile. So far literature review shows that improper size and placement of energy storage units leads to undesired power system cost as well as the risk of voltage stability, particularly in the case of high renewable energy penetration. This paper provides a solution to solve the above problem, a Hybrid Multi-Objective Particle Swarm Optimization (HMOPSO) method is proposed to minimize the power system cost and improve the system voltage profile by probing optimal sizing and sitting of storage units under consideration of uncertainties in wind power production. The proposed method is tested on both IEEE-30bus and IEEE 118-bus system to perform case studies.**

***Index Terms*— ESS, MOPSO, HMOPSO, Wind penetration**

I. INTRODUCTION

A high penetration of wind power raises a problem of system instability, caused by the nature of wind uncertainty. The integration of a Energy Storage System (ESS) is one of the best solutions to ensure the stability and power quality of a power system.

However, the utilization of wind power does not come without challenges. The higher penetration of renewable energy systems such as wind and solar PV has introduced many technical issues, including power quality, reliability, safety and protection, load management, grid interconnections and controls, A primary goal of a micro-grid is to operate a cluster of ESS that are placed in an area power system to provide power and energy with high reliability, and quality power supply to the local loads [3]. Most micro-grids are designed to be connected to the utility grid. In case of grid power outage, they isolate themselves from the grid and manage the local loads, voltage, and frequency.

The operating cost of power system is reduced by selling stored energy at high prices and sharing peak loads of the larger system, the best locations and sizes of a ESS in power system can achieve significant benefits as follows

1. Enhance power system reliability and power quality.
2. Reduce the power system cost and control high-cost energy imbalance charges.
3. Minimize the power loss and improve theVoltage profiles.

Serve the demand for peak load and correct the power factor**.** With the rapid development of technology in an ESS, large scale energy storage systems have attracted more attention. Due to the wide application of ESS, it is significant to optimally determine the location and capacity of ESS. An economic dispatch and optimal capacity of ESS has been discussed in [2]. This algorithm combining multiphase dynamic programming was proposed to maximize fuel-cost savings and benefits due to energy pricing differences between peak-load and light-load periods. The research in [3] presented a methodology to optimize the allocation and economic operation of energy storage devices in a low-voltage micro-grid system. A genetic algorithm (GA) optimization technique based on a multiple objective function was utilized in [4] to evaluate the economic impact of the energy-storage-specific costs on the net present value of energy storage installations in distribution substations. The work in [5] proposed a two-stage stochastic optimal algorithm for sizing the ESS in an isolated wind-diesel power system. The author considered the wind penetration, ESS efficiency, and diesel operating strategy to minimize the cost of supplied energy. The research in [7] made the use of particle swarm optimization to achieve optimal dispatch of controllable loads and generators as well as effectively utilizing the battery storage of each micro grid. The cost of the micro grid is reduced by selling stored energy at high prices and peak loads from the larger system. The authors in [6] focused on the optimal ESS for maximizing the support to the network voltage control in a distributed system.

MOPSO has become an efficient tool for solving the nonlinear, non-differentiable, multi-model as well as discrete variables optimization problems due to its flexible applications and better robustness in controlling parameters [9]. It has already been widely utilized to solve the multi-objective optimization problems on power system by searching for an acceptable non-linear-optimal set. In [8], Xu and Singh proposed a modified particle swarm optimization based on multi-objective optimization algorithm to solve the energy storage design problem which not only includes energy storage capacity and power rate, but also the operation strategy. The author in [11] proposed a MOPSO method to determine an optimal SVC installation scheme for the required loading margin with the SVC installation locations and capacities derived from the union of the SVC installations for all considered contingencies. The authors in [7] proposed an developed PSO algorithm to dispatch 140 thermal generation units for an very large-scale power system of South Korea. The algorithm functioning with the conventional linearly decreasing inertia weights and adopting a crossover operation scheme to reduce the network losses and fuel costs. In [14], a novel PSO based on a multi-objective optimization algorithm to improve the performance of reactive power dispatch was proposed.

This paper provides a solution by using Hybrid Multi-Objective Particle Swarm Optimization (HMOPSO) to

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allocate the ESS for minimizing wind-penetrated power system operation cost is proposed. The uncertainty of wind power is considered as an essential part of the cost probability optimization problem to determine the ESS sizing and placements.

II. DISCRETIZING WIND PROFILE

Different from the conventional placement analysis, which is typically conducted under a worse case (e.g., heavy load without wind power), this paper aims to analyze the optimal allocation for ESS by considering the distribution of wind power The basic concept of this discretizing method is to calculate the first few moments of wind power distribution and then find the corresponding finite points.

Wind Distribution

Weibull distribution is considered to be a more accurate method to provide the probabilistic description of wind speed[16]. Due to the great flexibility, Weibull distribution has been broadly applied to present probability distribution of wind speed, which is defined as follows:

$$f\left({}^{x}/_{\lambda,k}\right)=\frac{k}{\lambda}\left(\frac{\lambda}{x}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}} \qquad (1)$$

Where k is called the shape parameter, and λ is the scale parameter.To obtain the wind power distribution, a linear approximation equation is utilized as shown in

$$P=\begin{cases} 0 & if\ X \le V_i\ or X > V_o \\ A+BX & if\ V_{ci} \le X \le V_n \\ M & if\ V_n \le X \le V_o \end{cases} \qquad (2)$$

Where P is the injected power. X is genuine wind speed, M is the maximum power of wind turbine,$A\ and\ B$ are the linear coefficients, and V_i, V_o, V_n denote the cut-in wind speed, cut-out wind speed, and normal wind speed, respectively.

III. PROBLEM FORMULATION

The optimal storage placement and sizing problem is formulated as a constrained nonlinear integer optimization problem with both locations and sizes of storage devices being discrete. The objective function encompasses the wind probability and power system operation cost. The objective function is restricted by equality and inequality.

A. *Objective Function*

The goal of this project is optimally allocating the ESSs and generator outputs in order to minimize the total expected system operation cost and improve the voltage profile, while considering the uncertainties of wind power generation. The multi-objective functions are given by

$$\left.\begin{aligned} min\, f_1 &= \Sigma_{i=1}^{5} Prob_i.Cost_i \\ \min f_2 &= \Sigma_{k=1}^{n} \left(\frac{v_k - V_k^{spec}}{\Delta V_k^{max}}\right)^2 \end{aligned}\right\} \qquad (3)$$

Where

n total number of bus node;

V_k^{spec} expected voltage

ΔV_k^{max} maximum of voltage deviation

$Prob_i$ probability of operation cost at the I scenario;

$Cost_i$ total operation cost at the I scenario;

$$Cost_i = \sum_{j}^{NG} C\left(P_{G_j}\right) + C_w + C_s$$

$$cost_i = \Sigma_{j=1}^{NG}\left(a_j + b_j.P_{Gj} + C_j.P_{Gj}^2\right) + C^{opw}.P_{Wind} + C^{OPS}.P_{Storage}$$

(4)

Where

NG Number of generators

$C\left(P_{G_j}\right)$ fuel cost of generator I (\$/h);

C_w cost of wind power generator(\$/h);

C_s cost of energy storage system(\$/h);

a_i, b_i, c_i fuel cost coefficients of generator i;

C^{OPS} operation cost of ESS (\$/MWh);

C^{opw} operating cost of wind power generator(\$/MWh);

P_{Wind} power of wind power generator (MW);

$P_{Storage}$ capacity of installed ESS (MW);

The first objective function in (3) is to calculate the total expected operation cost by optimally allocating ESS and determining the output of all the different types of generators factoring in the wind distribution. However, the voltage will fluctuate sharply with the change of the wind power generation, so the voltage deviation equation in the second objective function of (3) is proposed to develop the voltage profile.

B. *Problem Constrains*

There are two types of constraint considered in this research: Equality and inequality.

1) Equality Constraints: These constraints (5) are related to the nonlinear power flow equations

$$\begin{aligned} P_i - V_i \Sigma_{j=1}^{N} V_j\left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) &= 0 \\ Q_i - V_i \Sigma_{j=1}^{N} V_j\left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) &= 0 \end{aligned} \qquad (5)$$

In this paper, a Newton–Raphson method for power flow is used to solve the equality constraints.

2) Inequality Constraints: The inequality constraints are those associated with the bus voltages, the reactive powerof generation, and the tap of the transformer. The inequality constrains are shown as

$$V_{min} \le V_i \le V_{max} \qquad (6)$$

$$T_{min} \le T_i \le T_{max} \qquad (7)$$

$$Q_{Gmin} \le Q_{Gi} \le Q_{Gmax} \qquad (8)$$

Where

V_i rms value of the bus i voltage;

T_i tap of transformer i;

Q_{Gi} reactive power of generator i.

IV. SOLUTION METHOD

1. PSO

PSO is a heuristic optimization technique first developed in 1995 by Kennedy and Eberhart [12]–[15]. The fundamental idea behind the PSO algorithm is that a population called a swarm is randomly generated, consisting of individuals called particles. Each particle, representing a potential solution of the optimization problem, flies through an N –dimensional search space at a random velocity and updates its position based on its own best exploration, best swarm global experience, and its previous velocity vector according to the following equations:

$$V_i^{k+1} = Wv_i^k + C_1 r_1 \left(Pbest_i^k - x_i^k\right) + C_2 r_2 \left(gbest^k - x_i^k\right) \quad (9)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (10)$$

Where

ω Inertia weight;
c_1 and c_2 Acceleration constants;
r_1 and r_2 Two random numbers in the range of [0 ,1];
$Pbest_i^k$ best position particle I achieved based on its own experience
$gbest^k$ best particle position based on overall swarm experience

In order to improve the efficiency and accuracy, a linearly decreasing inertia weight from maximum w_{max} value to minimum w_{min} is applied to update the inertia weight [13]

$$W^k = W_{max} - \frac{W_{max} - W_{min}}{K_{max}} . k \quad (11)$$

Where w_{max} and w_{min} are the initial and final inertia weights, K_{max} is the maximum iteration number.

2. Hybrid PSO

By incorporating a fast and elitist multi-objective algorithm and probabilistic load flow calculation, an HMOPSO algorithm is developed to search for the best combination of the placements and sizes of energy storage devices in power system, which is programmed and implemented in MATLAB. MOPSO is applied to optimally locate and rate the storage. As a part of the probabilistic load flow, Newton–Raphson power flow calculates the power equations shown in (5) and the inequality constraints shown in (6,7,8). The developed HMOPSO algorithm starts with random generated population P with N particles for initializing all generators' voltage, output power, and position and size of ESS. The random selections of swarm of particles considering constrains and corresponding velocity for each particle are initialized. By discretizing wind power distribution. Through probabilistic power flow, particles are evaluated by fitness functions, and recalls their best positions associated with the best fitness value. After checking and preserving thePbest and Gbest. If the algorithm has not yet searched the minimum cost and voltage deviation , the position and velocity of each particle are continuously updated.

The Flowchart of HMOPSO algorithm is represented in Figure1.

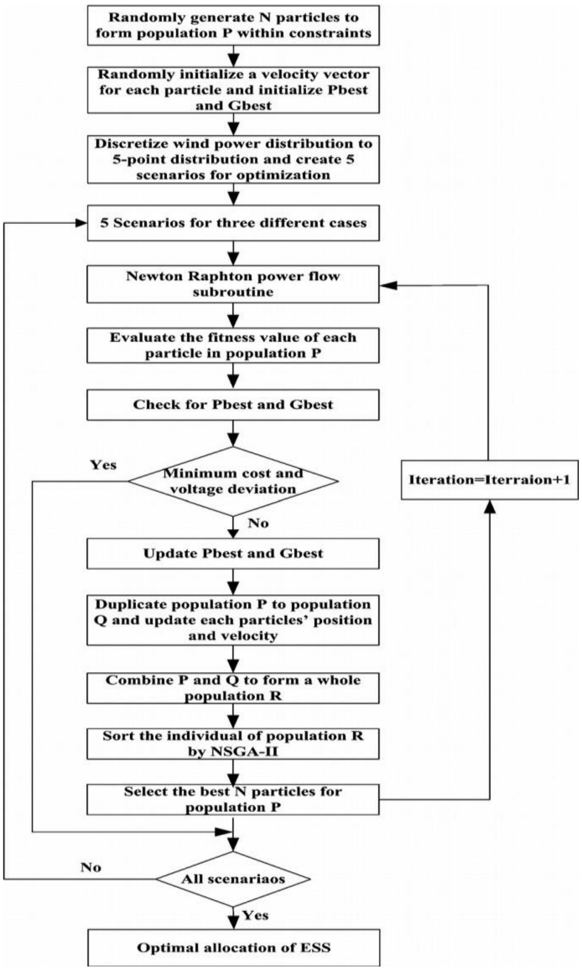

Fig ure 1:Flow Chart of HMOPSO

V. RESULTS AND DISCUSSION

System Configuration

The proposed HMOPSO algorithm has been applied to IEEE 30 bus and IEEE 118-bus systems and compared with several other methods in order to test its quality and robustness. The impacts of the integration of wind power and energy storage systems in three cases are studied and compared to demonstrate the effectiveness of the proposed HMOPSO method.

1.For IEEE-30 bus system:

Case 1) A conventional probabilistic load flow analysis for the system consider the entire wind power distribution, without ESS installation.

Case2) An optimal load flow analysis to determine the best ESS allocation under the worst case scenario assuming zero wind power.

Case3) HMOPSO and ESS considering the entire wind profile

Table 1 : The voltage Profile for 30 bus system in all cases

	LOSSES $(P_i + jQ_i)$	OPTIMAL PLACEMENT	ESS SIZE IN (MW)	COST in $/hr
CASE1	2.95+j10.84	---	---	---
CASE2	2.74+j10.08	[6 19 22 28]	[2.5 18.2 5.6 16]	8927.2
CASE3	2.44+j8.99	[7 16 30]	[12.1 9.7 7.4]	8599.3

Table 2: Econamic allocation of ESS for 30 bus system

BUS NO	Case1	Case2	Case3
1	0.92	0.95	1
2	0.92	0.95	1
3	0.901	0.932	0.983
4	0.898	0.929	0.98
5	0.9	0.931	0.982
6	0.89	0.921	0.973
7	0.883	0.915	0.967
8	0.876	0.908	0.961
9	0.898	0.929	0.981
10	0.903	0.933	0.984
11	0.898	0.929	0.981
12	0.904	0.934	0.985
13	0.92	0.95	1
14	0.894	0.925	0.977
15	0.898	0.929	0.98
16	0.895	0.926	0.977
17	0.894	0.925	0.977
18	0.898	0.916	0.968
19	0.882	0.913	0.965
20	0.886	0.917	0.969
21	0.913	0.943	0.993
22	0.92	0.95	1
23	0.92	0.95	1
24	0.907	0.938	0.989
25	0.909	0.94	0.99
26	0.89	0.921	0.972
27	0.92	0.95	1
28	0.891	0.923	0.975
29	0.898	0.928	0.98
30	0.885	0.916	0.968

2. IEEE-118 BUS SYSTEM:

The IEEE-118 bus system line data, and bus data have been presented in Appendix-A. The layout of the system is shown in Figure2. The system consists of 186 transmission lines, out of which 54 are generators buses and 99 load buses and the generator bus-1 is selected as slack bus.

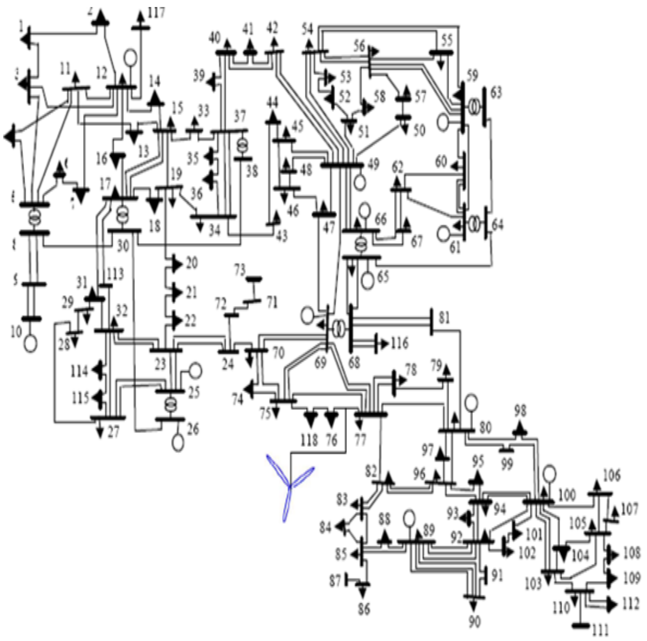

Figure2:Block Diagram of IEEE-118 bus system.

The performance study of this system is also done in three cases similar to the 30-bus system.

Case1:
In this case, we are considering the wind generation which is connected at bus 2. Due to the addition of wind energy it will share the load on the generators and the burden on the remaining generators will be reduced. On the other hand due to the uncertainty nature of wind waves the production of wind power is also varies in between 0 to 113 MW. At this time the system experiences both low voltage and high voltage problems. It will also affect the stability of the system.

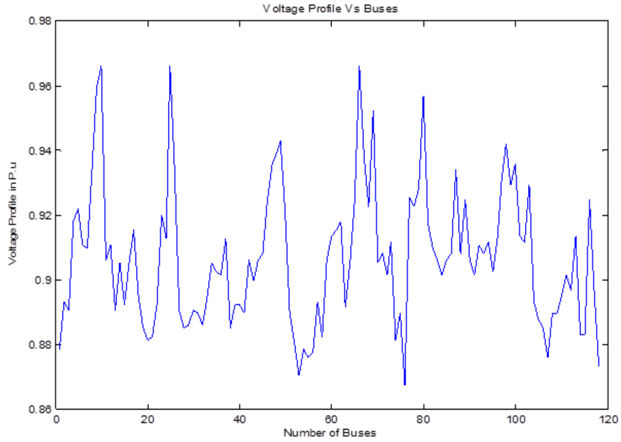

Figure3: Voltage profile for case1

By seeing the voltage profile of the system we have clearly observed that the system will be experiencing both high voltage and low voltage problems due to the adding of wind energy. These types of variations will drag the system into unstable state.

Case2: In this case, the optimal load flow analysis is implemented to determine the locations and the corresponding sizes of ESS under the poor wind power situations. The voltage profile of the system can be represented in figure 4.

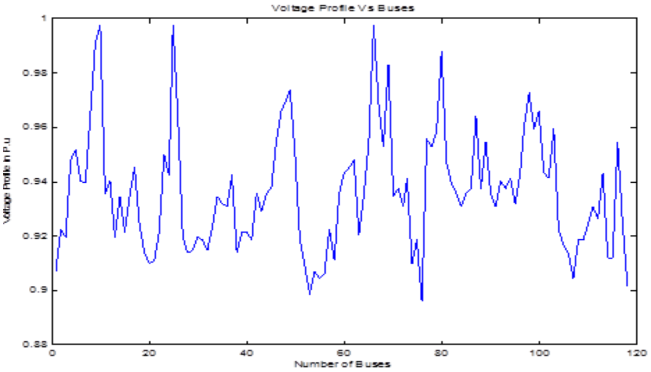

Figure4: Voltage profile for case2

This case is called as the worst case why because here we are taking the poor wind profile so the amount of power generation from the wind turbine is very small so the burden on the generators are increased and the voltage profile is also low for improving the voltage profile we are installing the ESS. The placement and sizes of the ESS can be determined by load flow calculations and the proposed algorithm. The required size of ESS in this case is high due to the absence of wind power. In this case, the optimal places of ESS are at buses 31, 63, 74, and 85 are to be found with sizes of 12.6, 22, 46, and 35MW, respectively. Comparing with Case 1, the total operation cost and real power loss are significantly reduced.

Case3:

In this case, the optimal ESS allocation considers the entire wind distribution. Due to the uncertainty in wind power, the optimal power flow used in the case 2 cannot be applied here. Instead, the proposed HMOPSO is implemented to find the optimal ESS allocation and generator outputs. In HMOPSO, each particle initializes a random ESS size for each bus and the size. At the end, the size of ESSs at some buses becomes zero, which means that these buses do not need to install any ESS. The remaining ESSs converge to their optimal allocations.

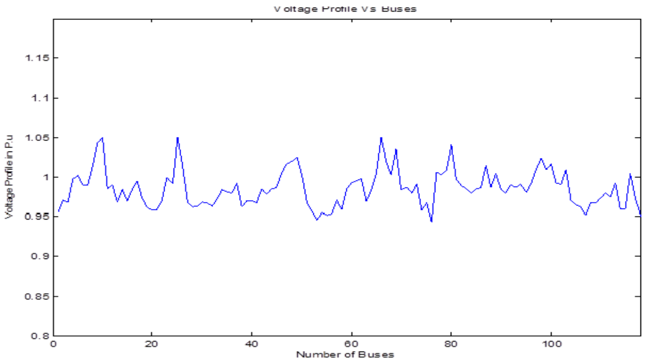

Figure5: Voltage profile for case3

In this case the total operation cost and power loss is reduced, and voltage profiles are improved, compared with Case 1 and case2. It should be noticed that the normal operation cost which is 9033.9 $/hr. in the case3 is substantially less than that on that off case2 and case3. This shows that the placing and sizing of ESS chose by the proposed HMOPSO calculation is improved.

The results for the 118 bus system can be shown in table--.it consists of generation of power from the all generators, active power loss, optimal placement and sizing of ESS, reactive power compensation and operating cost of the system for all three cases.

Table 3: Result for 118 bus system

Case study	P+JQ	Power Loss (MW)	Optima placing	Size of ESS (MW)	Cost ($/hr).
Case1	4389.17+j 918.05	156.17	------	-------	97215.8
Case2	4388.55+ 862.53	146.53	[31 63 74 85]	[12.6 22 46 35]	96922
Case3	4374.9+7 83.79	132.86	[31 74 84]	[15 23 37]	95323.1

By observing the above result it is clear that due to the adding of wind power the power generation will be reduced from 4389.17 to 4374.9 MW so the amount of fuel cost will be reduced. By integration of wind energy with the ESS the reactive power will compensated and the losses of the system will reduced from 156.17 to 132.86 MW. The operating cost of the system will also reduced from 97215.8 to 95323.1$/hr.

VI. CONCLUSION

As wind energy is continuous in nature so integration of wind energy on power grids is increases .Beside of advantages of wind energy it becomes important to consider the uncertainty of wind power. when optimizing the placement and size of energy storage systems the voltage profile will stabilized. In the paper, an HMOPSO algorithm is proposed to determine the optimal ESS allocation in wind integrated power systems. An IEEE 30 and IEEE 118-bus systems are adopted to perform case studies. The results show that the proposed HMOPSO is able to find proper placement and size of ESS as well as minimize the total operation cost and better voltage profiles.

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