



Optimal placement of solar farm on the power system network

Nopporn Leeprechanon* and Prakornchai Phonrattanasak

Department of Electrical and Computer Engineering, Thammasat University, Pathumthani, Thailand 12120

* Corresponding Author: E-mail nopporn@ieeee.org, Tel:02 5643001-9 Ext.3050, Fax:02 902 3948

Abstract

Nowadays, solar energy is a main green energy source which can reduce green house gas emission. Solar panel produces electricity by using the natural light power from sun and convert solar energy to direct electricity current during daytime. The solar energy is a clean and sustainable source, it does not produce emission of pollutants and it will never run out as it is constantly replenished by energy from nature.

Small scale solar panel can be used in domestic, community and smaller solar energy projects can be stand-alone or grid-connected systems. Stand-alone systems are used to generate electricity for charging batteries to run small electrical applications, often in remote locations where it is expensive or not physically possible to connect to a mains power supply. With grid-connected from PV solar farm can directly connect to the existing mains electricity supply by using modern inverter circuit which is known as STATCOM. It is composed of six insulated gate bipolar transistor (IGBTs) in a matrix with its snubber circuits and is used to generate real power output during daytime. A grid-connected solar farm can be a good proposition if consumption of electricity is high during daytime, and it is clean energy resource.

In this paper, PV solar farm is utilized as a STATCOM which perform voltage control to improve system performance and can directly connect into a power system topology. An optimal placement of solar farm on the power system topology is proposed aiming to minimize fuel and emission costs of overall system. The multiobjective bees algorithm (MOBA) is used to minimize simultaneously fuel cost and emission of thermal units by changing location and varying sizes of solar farm with security constraints of power system. We employ IEEE 30 bus system to verify the proposed method. The results show that the proposed method found the optimal position of solar farm with minimum cost of fuel and environmental pollution.

Keywords: Solar Farm, Power System, Multiobjective bees algorithm (MOBA).

1. Introduction

A photovoltaic system (or solar farm) is a system which uses one or more solar panels to convert sunlight into electricity. It consists of multiple components, including the photovoltaic

modules, mechanical and electrical connections. Thus it can supply more electrical energy. Solar power has become increasing practical over the last several years [1]. The advantages of solar power are many, including practical,



environmental as well as economic. One of the main advantages of a solar power system is the lack of pollution given off by solar panels when generating electricity. Another advantage of solar power in economic is very low operation and maintenance cost. When solar farm is built to generate electricity, it can produce electricity into power system during daytime. Moreover; solar energy system operations do not generate air or water emissions pollutant and do not produce hazardous waste like coal, oil, or gas [2].

Transient stability and transmission limit in power system is studied to find utilization of an existing solar farm [3]. But the result of solar farm in economic and environment benefit is not still developed. And high penetration of solar farm on power system is mysterious.

The goal of this paper is to find best location and sizing of solar farm in power system with minimum fuel cost and emission in test system with many real constraints. The multiobjective bees algorithm is developed to find minimum fuel cost and emission when the solar farm varies in its location and sizing. The IEEE 30 bus is selected to test proposed method. The result show that the best location and sizing of solar farm with minimum fuel cost and emission in test system.

2. Problem Formulation

The objective of environmental/economic power dispatch with varying location and sizing of solar farm is to minimize the economic and environmental cost function of power system while satisfying various equality and inequality constrains.

2.1 Objectives

Objective1: *Minimization of generator cost*

The total US\$/h fuel cost $f(P_G)$ can be expressed as

$$f(P_{G_i}, P_S) = \sum_{i=1}^N a_i + b_i P_{G_i} + c_i P_{G_i}^2 + d_i P_S \quad (1)$$

where a_i, b_i, c_i and d_i are the cost coefficients of the i^{th} generator thermal units and solar farm, and P_{G_i} and P_S are the real power output of the i^{th} generator thermal units and solar farm at bus w . N is the number of generators. It can be defined as

$$P_{G_i} = [P_{G_1}, P_{G_2}, \dots, P_{G_N}, P_S]^T \quad (2)$$

Objective2 : *Minimization of environmental emission*

The total ton/h emission $E(P_G)$ of atmospheric pollutants such as sulfur oxides SO_x and nitrogen oxides NO_x caused by fossil-fueled thermal units can be expressed as

$$e(P_{G_i}, P_S) = \sum_{i=1}^N 10^{-2} (\alpha_i + \beta_i P_{G_i} + \gamma_i P_{G_i}^2) + \xi_i \exp(\lambda_i P_{G_i}) + \rho P_S \quad (3)$$

where $\alpha_i, \beta_i, \gamma_i, \xi_i, \lambda_i$ and ρ are coefficients of the i^{th} emission characteristics of thermal units and solar farm .

2.2 Constraints

Generation capacity constraints: For stable operation, real power output of each generator is restricted by lower and upper limits as follows:

$$P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max}, \quad i = 1, \dots, N \quad (4)$$

$$P_S^{\min} \leq P_S \leq P_S^{\max}, \quad 1 \leq s \leq N_B \quad (5)$$

where N_B is the number of buses.

Power balance constraints: Power balance is an equality constraint. The total power generation must cover the total demand P_D . Hence,



$$\sum_{i=1}^N P_{Gi} + P_S - P_D - P_L = 0 \quad (6)$$

Then, power loss in transmission lines can be calculated as

$$P_{loss} = \sum_{k=1}^{NL} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad (7)$$

where V_i and V_j are the voltage magnitudes at bus i and j . δ_i and δ_j are the voltage angles at bus i and j .

The system operating constraints $h(x, u)$ include:

(1) Generation constraints:

For stable operation, generator voltages, real power outputs and reactive power outputs are restricted by the lower and upper limits as follows:

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max}, i \in NG \quad (12)$$

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, i \in NG \quad (13)$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, i \in NG \quad (14)$$

(2) Transformer constraints:

Transformer tap settings are restricted by the minimum and maximum limits as follows:

$$T_i^{\min} \leq T_i \leq T_i^{\max}, i \in NT \quad (15)$$

(3) Security constraints:

These incorporate the constraints of voltage magnitudes of load buses as well as transmission line loadings as follows:

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}, i \in NB \quad (16)$$

$$S_{Li} \leq S_{Li}^{\max}, i \in NL \quad (17)$$

where S_i and N_L are transmission line loading and the number of transmission lines.

2.3 Formulation of multiobjective optimization

Aggregating the objectives and constraints, the problem can be mathematically formulated as a nonlinear constraint multiobjective optimization problem as follows[4].

$$\text{Minimize } [f(x, u), e(x, u)] \quad (18)$$

Subject to:

$$g(x, u) = 0 \quad (19)$$

$$h(x, u) \leq 0 \quad (20)$$

where $g(x, u)$ is the equality constraints, $h(x, u)$ is the system inequality constraints.

3. Multiobjective optimization principles

For a multiobjective optimization problem, any two solutions x_1 and x_2 can have one of two possibilities: One dominates the other or none dominates the other. In a minimization problem, without loss of generality, a solution x_1 dominates x_2 if the following two conditions are satisfied [5]:

$$1. \forall i \in \{1, 2, \dots, N_{obj}\}: f_i(x_1) \leq f_i(x_2) \quad (21)$$

$$2. \exists i \in \{1, 2, \dots, N_{obj}\}: f_j(x_1) < f_j(x_2) \quad (22)$$

If any of the above condition is violated, the solution x_1 does not dominate the solution x_2 . If x_1 dominates the solution x_2 , x_1 is called the nondominated solution. The solutions that are nondominated within the entire search space are denoted as Pareto-optimal and constitute Pareto-optimal set. This set is also known as Pareto-optimal front.

4. THE MOBA TECHNIQUE

4.1 OVERVIEW OF BA METHOD

Bees algorithm was proposed by Pham D.T [6] which was widely used for optimizing numerical problems in 2006. The algorithm mimics the food foraging behavior of swarms of honey bees. Honey bees use several mechanisms such as waggle dance to optimally locate food sources and to search new one. This makes them a good candidate for developing new intelligent search algorithms. It is a very simple, robust and population based stochastic



optimization algorithm. However, changing conventional single objective BA to a multiobjective BA requires a rational redefinition. In MOBA, there is no absolute one global best, but rather a set of nondominated solutions. Hence there is a need to compromise the quality of the outcome by a fuzzy technique as it is proposed in this paper.

4.2 MOBA and Computational process

In the proposed MBO, the population has n_s scout bees and each bee is an m -dimensional vector, where m is the number of optimized parameters. The computation flow of the MBO technique is briefly stated and defined as follows:

Step 1: Generate randomly the initial populations of n_s scout bees as following equation.

$$n_s = l_i + rand(0,1) \times (u_i - l_i) \quad (23)$$

where u_i and l_i are upper and lower bound of the n_s scout bees. These initial populations must be feasible candidate solutions that satisfy the constraints. Set $NC = 0$.

Step 2: Evaluate the fuel cost and emission fitness value of the initial populations.

Step 3: Search for nondominated solutions from initial solution by using nondominated function in order to get the Pareto set and find m best solutions for neighborhood search by using fuzzy c-mean clustering (FCM)[7].

Step 4: Separate the m best solutions to two groups, the first group are e best solutions by using fuzzy compromise

and another group is other selected $m - e$ solutions.

Step 5: Determine the size of neighborhood search of each best solutions (n_{gh}).

Step 6: Generate neighborhood solution (n_{ngh}) around the selected solutions within neighborhood size as following equations.

$$n_{ngh,e} = n_e + rand(0,1) \times n_{gh} \times (u_i - l_i) \quad (24)$$

For best solutions and

$$n_{ngh,m-e} = n_{m-e} + rand(0,1) \times n_{gh} \times (u_i - l_i) \quad (25)$$

For other selected solutions.

Step 7: Evaluate the fuel cost and emission fitness value of the generated solution.

Step 8: Search for nondominated solutions from all solution by using nondominated function in order to get the Pareto set. If nondominated solution is over the limit, then uses FCM.

Step 9: Check the stopping criterion. If satisfied, terminate the search, else $NC = NC + 1$.

Step 10: Assign the $n - m$ population to generate new solutions and add it with last best solution. Go to Step 2.

Upon the Pareto-optimal set of nondominated solution, fuzzy-based mechanism is imposed to extract the best compromised outcome.

4.3 Best compromised solution

After obtaining the Pareto-optimal solution, the decision maker may need to choose one best compromised solution according to the specific preference for different applications. Thus, fuzzy set [5] is introduced here to handle

the dilemma. Here a linear membership function u_i is defined for each of the objective functions F_i :

$$u_i = \begin{cases} \frac{F_i^{\max} - F_i}{F_i^{\max} - F_i^{\min}} & F_i^{\max} > F_i > F_i^{\min} \\ 1 & F_i \leq F_i^{\min} \\ 0 & F_i \geq F_i^{\max} \end{cases} \quad (26)$$

In the above definition, F_i^{\max} and F_i^{\min} is the value of the maximum and minimum in the objective functions, respectively. It is evident that this membership function indicates the degree of achievement of the objective functions. For every nondominated solution k , the membership function can be normalized as follows:

$$u^k = \frac{\sum_{i=1}^O u_i^k}{\sum_{k=1}^S \sum_{i=1}^O u_i^k} \quad (27)$$

where O and S are the number of objective functions and the number of non-dominated solutions, respectively. The solution with the maximum membership u^k can be seen as the best compromise solution.

4.4 Implementation

The parameter of MOBA can be set as follow. The population of bees is set to be 40. The number of selected sites and elite site is 3 and 1 respectively. Patch size is 0.01. Number of bees around elite site and Number of bees around other selected sites is 10 and 5 respectively. Maximum iteration = 200. The maximum size of the Pareto-optimal set was selected as 50 solutions. The MOBA is tested to 100 runs to obtain best solution.

4.4.1 IEEE 30 bus test system

The proposed MOBA technique was tested on IEEE 30-bus 6-generator test system. The detail data are given in [8]. The values of fuel cost and emission coefficients are given in Table 1. The MOBA is computed by Intel core i5 2.0 GHz processor 2 GB ram under Matlab program.

Table 1. Generating thermal unit fuel cost and emission coefficients.

Unit	G ₁	G ₂	G ₃	G ₄	G ₅	G ₆
P _{min} (MW)	50	20	15	10	10	12
P _{max} (MW)	200	80	50	35	30	40
Cost						
a	0	0	0	0	0	0
b	2	1.75	1	1.25	3	3
c	0.00375	0.00175	0.00625	0.00834	0.02500	0.02500
Emission						
α	4.091	2.543	4.258	5.326	4.258	6.131
β	-5.554	-6.047	-5.094	-3.550	-0.5094	-5.555
γ	6.490	5.638	4.586	3.380	4.586	5.151
ξ _i	2.0E-4	5.0E-4	1.0E-6	2.0E-3	1.0E-6	1.0E-5
λ _i	2.857	3.333	8.000	2.000	8.000	6.667

4.4.2 Solar farm

Solar farm consist of a large number of solar panel connected to bus of power system topology through power transformer. Solar farm use STATCOM for generating power into power system network [3].

Solar farm is modeled as a voltage sourced which is fed to the DC bus to inject real power to the inverter during daytime operation. The amount of real power from STATCOM to the grid depends upon the level of DC voltage magnitude. STATCOM is composed of six IGBTs with its snubber circuits A large size DC capacitor is combined to maintain voltage magnitude. Each phase has a pair of IGBT devices which convert DC voltage into a series of variable width pulsating voltages according to the switching signal to the matrix. For instance, solar farm is shown in Fig.1

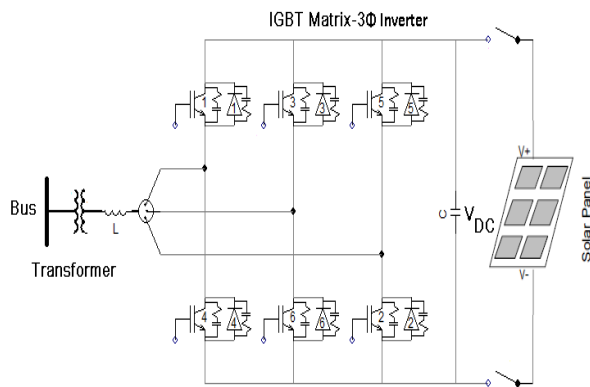


Fig.1 solar farm with STATCOM connect to bus of power system through power transformer

In this paper, cost and emission coefficients of solar farm are zero. Large solar farm is selected to produce electric power up to 200 MW. The solar farm is operated during daytime.

5. RESULTS AND DISCUSSION

Case 1: best fuel cost and emission of power system without solar farm

Fuel cost and emission objective are optimized to find the best solution by using MOBA Algorithm when solar farm is not penetrated into power system network. Its result is shown in Table 2.

Table 2. Results of best solution of the proposed approach without solar farm

Unit (MW)	Best solution
P_{G1}	114.165
P_{G2}	63.942
P_{G3}	20.289
P_{G4}	30.381
P_{G5}	28.192
P_{G6}	33.782
Total of thermal units (MW)	290.751
Fuel Cost(\$/h)	847.430
Emission(ton/hr)	0.2450

Case 2: best fuel cost and emission of power system with solar farm penetration

Solar farm is penetrated into IEEE 30 bus test system. Its result can be shown in Table 3. and Fig 2.

Table 3. Results of best solution of the proposed approach with solar farm on IEEE 30 bus test system

Unit (MW)	Best solution with solar farm
P_{G1}	50.521
P_{G2}	32.992
P_{G3}	33.262
P_{G4}	11.732
P_{G5}	29.889
P_{G6}	38.220
Total of thermal units (MW)	196.616
Fuel Cost(\$/h)	592.262
Emission(ton/hr)	0.2052
Solar farm	
Location (Bus)	7
Size (MW)	90.393

Table 3 shows the power generation and solar farm position optimized by the MOBA technique. The result in this case has cost and emission lower than previous case. Solar farm penetrated into IEEE 30 bus test system can reduce fuel cost and emission of pollution as 255.16 \$/hr and 0.0448 ton/hr respectively.

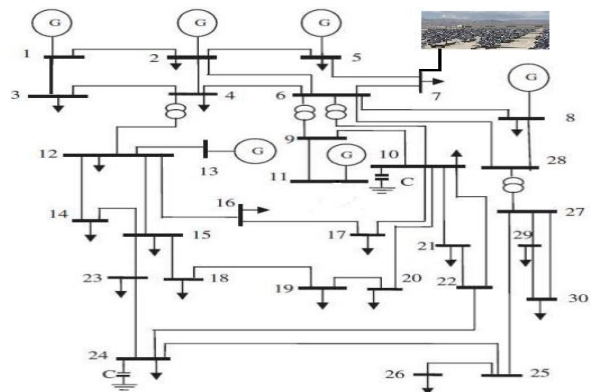


Fig.2 position of solar farm on power system

Solar farm is connected to power system at bus

7 in Fig 2. Capacity of solar farm is 90.393 MW.

This value is high penetration of solar farm on test system.

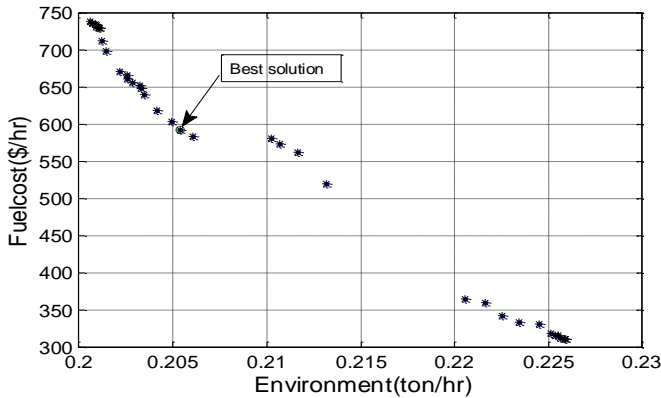


Fig.3 Best solution on tradeoff surface with solar farm in power system

The best solution in tradeoff surface is selected by fuzzy compromise method in Fig 3.

The fuel cost and environment cost is 592.26 \$/hr and 0.2052 ton/hr respectively.

7. Conclusion

In this paper, MOBA algorithm has been proposed to find best location and sizing of solar farm on power system topology with minimum economic and emission of generations. Solar farm is formulated as inverter with voltage control (STATCOM) to inject real electric power into power system network during daytime. The simulation result demonstrates that solar farm in optimum sizing and location can reduce fuel cost and emission pollutant of generations with many real constrains of power system. In addition, the result indicated that MOBA have effectiveness to search optimum point of solar farm on power system topology.

8. Reference

- [1] <http://www.seriouslysolar.com/advantages.php>
- [2] J.R. Williams, Advances in Solar Energy: K. W. Boer and J. Duffie (Editors), American Solar Energy Society, Inc., Solar Energy, Volume 33, Issue 2, 1984, Page 231
- [3] www.worldenergy.org/documents/congresspapers/428.pdf
- [4] Abido, M. A. (2009). "Multiobjective particle swarm optimization for environmental/economic dispatch problem." *Electric Power Systems Research* 79(7): 1105-1113.
- [5] Tahir Sag, Mehmet Cunkas, A tool for multiobjective evolutionary algorithms, *Advances in Engineering Software*, Volume 40, Issue 9, September 2009, Pages 902-912
- [6] D.T. Pham, A. Ghanbarzadeh, E. Ko, S. Otri, S. Rahim, M. Zaidi, D.T. Pham, E.E. Eldukhri, A.J. Soroka, The bees algorithm -- A novel tool for complex optimisation problems, *Intelligent Production Machines and Systems Oxford: Elsevier Science Ltd.* (2006) 454-459.
- [7] F. Mendoza, J.L. Bernal-Agustin, J.A. Dominguez-Navarro, NSGA and SPEA applied to multiobjective design of power distribution systems, *IEEE Trans. on Power Systems* 21 (2006) 1938-1945.
- [8] Alsac O, Stott B. Optimal load flow with steady-state security. *IEEE Trans Power Apparatus Syst* 1974;93(3):745-51.