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The Elitist Non-dominated Sorting GA for Multi-objective Optimization of Standalone Hybrid Wind/PV Power Systems

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Abstract: In the design of standalone hybrid wind/photovoltaic power systems, the optimal sizing is an important and challenging task. The coordination among renewable energy resources, generators, energy storages and loads is very complicated. The sizing of standalone hybrid wind/PV power systems can be taken as a multi-objective optimization problem involving two conflicting objectives being maximization of power reliability and minimization of cost. The Loss of Power Supply Probability (LPSP), which is the index of power reliability, is obtained by simulation. The Pareto-optimal solutions are found using the elitist non-dominated sorting GA (NSGA-II) and this has been validated by solving the multi-objective problem with the tangency method, which also belongs to the-constraint method. The decision variables are not only the size of Photovoltaic (PV) panels and the capacity of batteries included in traditional methods, but also the type and size of Wind Turbine Generators (WTGs) and the tilt angle of PV panels.

Key words: Renewable energy, standalone power systems, sizing, multi-objective optimization, evolutionary algorithms

INTRODUCTION

Global environmental concerns and the ever-increasing need for energy, coupled with a steady progress in renewable energy technologies are opening up new opportunities for utilization of renewable energy resources. Hybrid wind/photovoltaic (PV) power systems are one important type of standalone renewable energy power systems. The hybrid combination of PV panels and Wind Turbine Generators (WTGs) improves overall energy output and reduces energy storage requirements (Habib *et al*., 1999).

Proper design of standalone renewable energy power systems is a challenging task, as the coordination among renewable energy resources, generators, energy storages and loads is very complicated. Generally the main objectives of the optimization design are maximization of power reliability and minimization of cost, so this is a multi-objective optimization problem. There are a few single-objective optimization methods, which convert one objective into constraint, for sizing standalone renewable energy power systems (Habib *et al*., 1999; Borowy and Salameh, 1996; Willis and Scott, 2000; Kaldellis, 2004; McGowan and Manwell, 1999; Ai *et al*., 2003; Elhadidy and Shaahid, 1999; Al-Ashwal and Moghram, 1997; Kellogg *et al*., 1998). One representative method, the tangency method, is to optimize the size of PV panels and the capacity of batteries for given type and size of WTGs and tilt angle of PV panels (Borowy and Salameh, 1996; Willis and Scott, 2000). But the problems remained are that how to determine the optimal type and size of WTGs and the optimal tilt angle of the PV panels and how to solve the multi-objective optimization problems.

We propose a method in this study, which can not only take the type and size of WTGs, the tilt angle and size of PV panels and the capacity of batteries as decision variables, but also give the Pareto-optimal solutions for higher-level decision. We employ one of the multi-objective evolutionary algorithms (MOEAs), the elitist non-dominated sorting genetic algorithm (NSGA-II) (Deb, 2001), to size standalone renewable energy power systems.

LOSS OF POWER SUPPLY PROBABILITY

System configuration: The configuration of standalone hybrid wind/PV power systems is shown in Fig. 1. The present study, we investigated the case that a system has only one type of WTGs.

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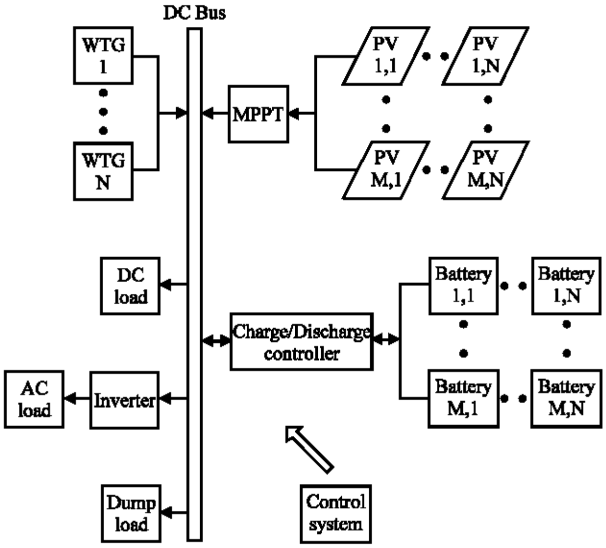

Fig. 1: Schematic of standalone hybrid wind/PV power systems

Calculation of wind and solar energy: The wind speed to a particular hub height is calculated by the equation in (Borowy and Salameh, 1996). It is necessary to estimate the solar radiation incident on a tilted solar panel surface when only the total radiation on a horizontal surface is known. The Hay-Davies-Klucher-Reindl (HDKR) anisotropic model described by Duffie and Beckman (1991) is employed to calculate the incident radiation on the tilted PV panel surface.

Models of system components: The power curve is represented by a piecewise cubic spline interpolation in the calculation. The output power from a PV panel can be calculated by an analytical model given by Lasnier and Ang (1990), in which a Maximum Power Point Tracker (MPPT) is considered.

Lead acid batteries are main energy storage devices in standalone power systems. The battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 1. The maximum battery life can be obtained if the Depth Of Discharge (DOD) is set equal to 30-50%.

The MPPT, the battery controller, the inverter and distribution lines are assumed to have constant efficiencies. Assume the efficiencies of the MPPT, the battery controller and distribution lines as 1 and that of the inverter as 0.9.

Loss of power supply probability: The Loss of Power Supply Probability (LPSP) (Borowy and Salameh, 1996), which is defined in terms of the battery State Of Charge (SOC), is the power reliability index of a system. The LPSP can be defined as the long-term average fraction of the load that is not supplied by the standalone power system. In terms of the SOC, the LPSP can be defined as:

$$\mathrm{LPSP} = \Pr\left\{E_{B,t} \le E_{B\min};\ \text{for } t \le T\right\} \tag{1}$$

where $E_{B,t}$ is energy stored in batteries at any hour t and $E_{B\min}$ is battery minimum allowable energy level.

Operation simulation: The logistic model and time series method (Manwell *et al.*, 1998) are employed for simulation studies. Logistical models are used primarily for long-term performance predictions, for component sizing and for providing input to economic analyses. An essential feature of the time series method is that it employs an energy balance approach within each time step. This assures that energy is conserved throughout the entire simulation and that the model is internally consistent. In particular the sum of all energy sources must equal the sum of all sinks.

The simulation period is 1 year and the time step is 1 h. The load, wind energy and solar energy are assumed to be constant during a time step. When the available energy generated and stored in batteries is insufficient to satisfy the load demand $E_{L,t}$ for hour t, the deficit is called Loss of Power Supply (LPS). The LPSP for a considered period T is the ratio of all LPS_t values for that period to the sum of the load demand, as defined by:

$$\mathrm{LPSP} = \sum_{t=1}^{T} \mathrm{LPS}_t \bigg/ \sum_{t=1}^{T} E_{L,t} \tag{2}$$

MULTI-OBJECTIVE OPTIMIZATION USING NSGA-II

Problem description: Maximization of power reliability and minimization of cost are two conflicting objectives of sizing standalone hybrid wind/PV power systems. The total capital cost of WTGs, PV panels and batteries, C_{WPB}, can be taken as the cost index (Borowy and Salameh, 1996; Duffie and Beckman, 1991; Lasnier and Ang, 1990). The type and size of WTGs, the tilt angle and size of PV panels and the capacity of batteries have a considerable influence upon the power reliability and capital cost and can be optimized. The multi-objective optimization problem is as follows:

$$\begin{cases} \text{minimize} & \mathrm{LPSP} \\ \text{minimize} & C_{WPB} = C_{WTG_{Type}} N_{WTG} + C_{PV} N_{PV} + C_{bat} N_{bat} \\ \text{where} & N_{WTG} = 0,1,2,\cdots \\ & N_{PV} = N_{PV\_s} N_{PV\_p},\ N_{PV\_p} = 0,1,2,\cdots \\ & N_{bat} = N_{bat\_s} N_{bat\_p},\ N_{bat\_p} = 0,1,2,\cdots \\ & \text{Type} = \text{I, II, III}, \cdots \end{cases} \tag{3}$$

where:

C_{bat}	Cost of the battery,
C_{PV}	Cost of the PV panel,
C_{WTG}	Cost of the WTG,
N_{bat}	Number of the batteries,
N_{bat_p}	Number of the batteries in parallel,
N_{bat_s}	Number of the batteries in series,
N_{PV}	Number of the PV panels,
N_{PV_P}	Number of the PV panels in parallel,
N_{PV_s}	Number of the PV panels in series,
N_{WTG}	Number of the WTGs,
Type	Type of WTGs.

In the optimization model, the tilt angle is a variable of the HDKR model that is used in computing LPSP. The fixed tilt angle (Hartley *et al.*, 1999) β is set as an integer in degrees. The optimal fixed tilt angle rests on geographical and meteorological conditions of the location and the load characteristics as well as the system configuration. The range of optimization of β is [0°, 90°] for south-facing panels.

NSGA-II: Although the field of research and application on multi-objective optimization is not new, the use of MOEAs in various engineering and business applications is a recent phenomenon (Deb *et al.*, 2004). MOEAs have an edge over the classical methods in that they can find multiple Pareto-optimal solutions in one single simulation run. Deb and his students suggested NSGA-II in 2000, which has been shown to outperform other current elitist MOEAs on a number of difficult test problems (Deb *et al.*, 2000). NSGA-II uses (i) a faster non-dominated sorting approach, (ii) an elitist strategy and (iii) no niching parameter. Diversity is preserved by the use of crowded comparison criterion in the tournament selection and in the phase of population reduction (Deb, 2001).

APPLICATION EXAMPLE

The location of Boston, Massachusetts with Latitude 42°22'N is chosen. The load curve of a typical house (Borowy and Salameh, 1996) is shown in Fig. 2. The typical meteorological year data sets (TMY2s) contain hourly values of solar radiation and meteorological elements for a one-year period (Marion and Urban, 1995). The data of extraterrestrial horizontal radiation, global horizontal radiation, diffuse horizontal radiation, temperature and wind speed of station Boston are utilized. Generally, the ground reflectance is 0.2.

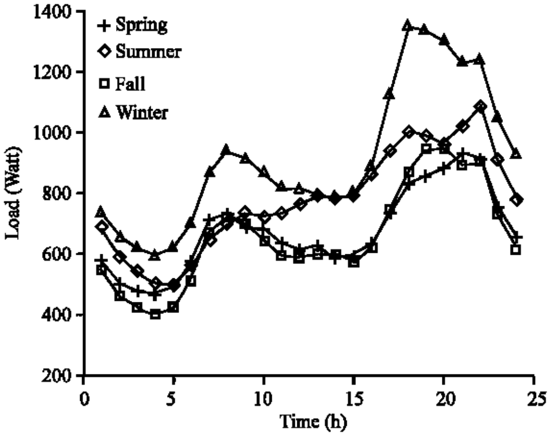

Fig. 2: A typical load profile in Boston

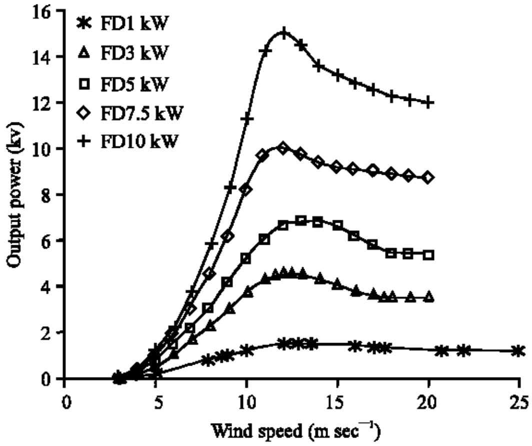

Fig. 3: The power curves of the WTGs (The symbols represent data sampled from the power curve graphs given by the manufacturer)

The FD series WTGs with rated power of 1, 3, 5, 7.5 and 10 kW made by Tianfeng Green Energy Company of China were considered. The power curves of the WTG are shown in Fig. 3. A 50 W_{peak} PV panel made by Yunnan Semiconductor Device Factory in China was used for this simulation study. The capacity of a single battery used was 200 Ah. That battery has a round-trip efficiency of 0.7 and DOD = 50%.

The form of the individual of the population is [Type N_{WTG} β N_{PV_p} N_{bat_p}], a integer-valued vector of 5 values. The LPSP of every individual is calculated by simulation of 8760 h. For the real-coded NSGA-II, the discrete version of Simulated Binary Crossover (SBX) operator and the real-parameter mutation operator are used (Deb *et al.*, 2000). When a pre-specified iteration count ($N = N_{max}$) is reached, NSGA-II is terminated. N_{max} = 200 and a population size of N_{pop} = 50 are used. The crossover and mutation probability of p_c = 0.9 and p_m = 0.1 are used for the real-coded NSGA-II.

According to the voltage, let NPV_s = 3 and Nbat_s = 24. The solutions termed as Initial in Fig. 4

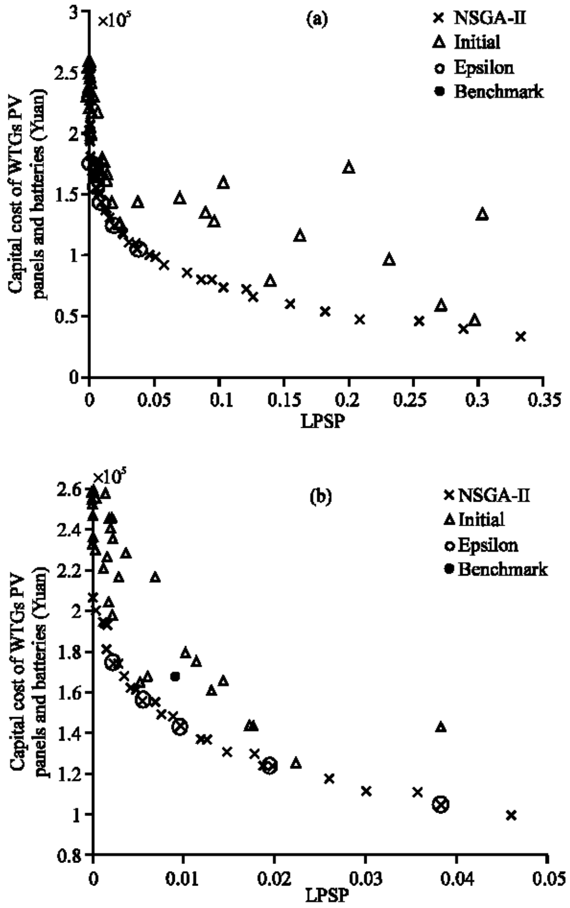

Fig. 4: Obtained NSGA-II solutions for the C_{WPB} and LPSP optimization are compared with the constraint method (Epsilon) solutions. Initial solutions of NSGA-II and the benchmark solution are also shown. (b) is part of (a)

denote the objective vectors with which the NSGA-II search process is started. The figure indicates that the random solutions (within the chosen variable bounds) are far from being close to the optimized front (marked as NAGA-II). The figure clearly shows that a wide range of distribution in LPSP and C_{WPB} values are obtained. Part of the resulting LPSP-C_{WPB} trade-off is nonconvex and it can be inferred that compared to the benchmark solution (marked as 'Benchmark' in the figure) there exist better solutions.

In order to verify whether the obtained NAGA-II solutions are actually close to the true Pareto-optimal front of this problem, we use the tangency method. The method also belongs to the-constraint method that can find Pareto-optimal solutions whether the objective space is convex or nonconvex. The method is to convert the first objective (Minimization of LPSP) into an additional

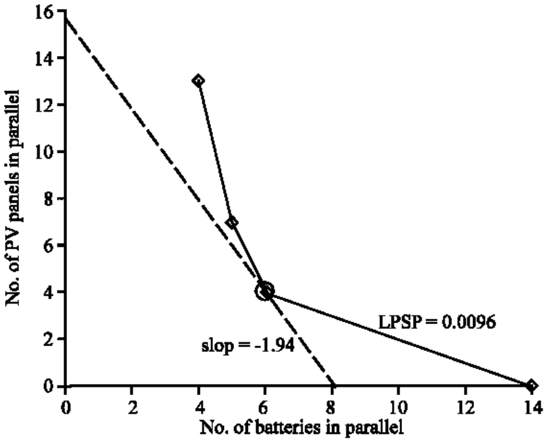

Fig. 5: The optimal configuration of $[N_{PV\_p}\ N_{bat\_p}] = [4\ 6]$ for the given conditions as Type = 1, $N_{WTG} = 6$, $\beta = 28°$ and $LPSP_{epsilon} = 0.0096$

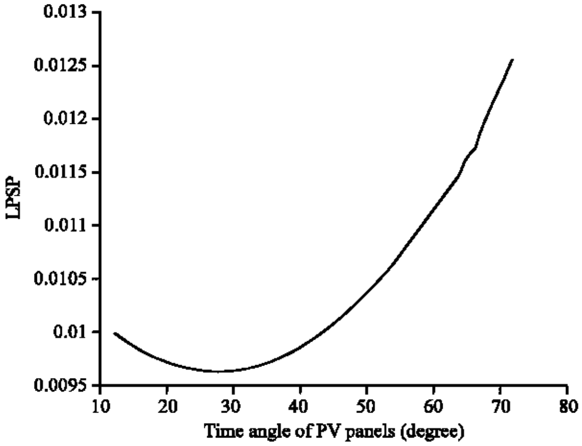

Fig. 6: $\beta = 28°$ is optimal for the configuration [Type N_{WTG} N_{PV_p} N_{bat_p}] = [I 6 4 6]

constraint as LPSP = $LPSP_{epsilon}$ and minimize only the second objective. The procedure is:

```
For every Type do;
  for every $N_{WTG}$ do;
    For every $\beta$ do;
      find the optimal $N_{PV\_p}$ and $N_{bat\_p}$ ($LPSP = LPSP_{epsilon}$);
    end for;
  end for;
end for.
```

We take an NSGA-II solution [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6], LPSP = 0.0096, C_{WPB} = 143160 (Yuan) for example. Let Type = 1, $N_{WTG} = 6$, $\beta = 28°$ and $LPSP_{epsilon} = 0.0096$, we get $[N_{PV\_p}\ N_{bat\_p}] = [4\ 6]$, as shown in Fig. 5. The minimum cost is at the tangent point of the

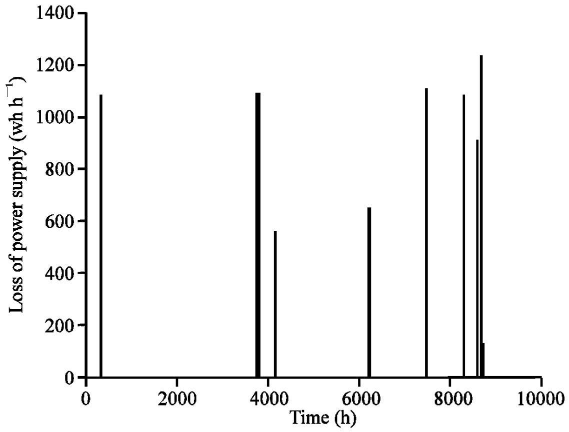

Fig. 7: The LPS of the configuration [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6]

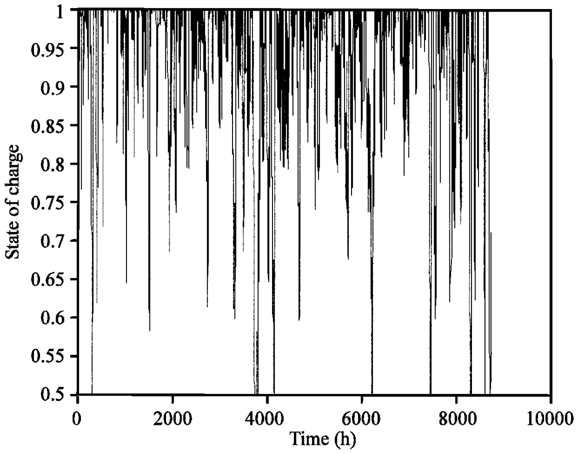

Fig. 8: The SOC of the battery bank of the configuration [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6]

cost line and the curve that represents the relationship between the size of PV panels and capacity of batteries. The slope of the cost line is:

$$-\frac{C_{bat}N_{bat\_s}}{C_{PV}N_{PV\_s}} = -\frac{520\times 24}{2150\times 3} = -1.94 \quad (4)$$

Enumerate the cases of every Type, N_{WTG} and β, we get the optimal configuration [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6], C_{WPB} = 143160 (Yuan) for $LPSP_{epsilon}$ = 0.0096. So [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6] is a Pareto-optimal solution to this optimization problem. Figure 4 marks the 5 solutions as 'Epsilon' solutions obtained by 5 independent runs of the constraint method, each performed with a different $LPSP_{epsilon}$ value. Since these solutions are found to lie on or near the non-dominated front obtained by NSGA-II, it can be stated that the non-dominated front found by NSGA-II is the true Pareto-optimal front.

For the configuration [Type N_{WTG} N_{PV_p} N_{bat_p}] = [I 6 4 6], the optimal tilt angle is 28°, as shown in Fig. 6. The LPS of the configuration [Type N_{WTG} β N_{PV_p} N_{bat_p}] = [I 6 28° 4 6] is shown in Fig. 7 and the SOC of the battery bank is shown in Fig. 8. The optimal tile angle is less than the Latitude value means that the PV panels can generate more power to complement the insufficient power output of the WTGs in summer.

Usually, one larger WTG is chosen. We select one FD3KW WTG with rated power 3 kW and use the tangency method to size the power system. Let β = 42°. The result is [N_{PV_p} N_{bat_p}] = [8 7], LPSP = 0.0091, C_{WPB} = 167460 (Yuan). This configuration, which is taken as the benchmark, is not a Pareto-optimal solution to this optimal design because the FD3KW WTG is not as economical as the FD1KW WTG.

CONCLUSIONS

Sizing of standalone hybrid wind/PV power systems is a multi-objective optimization problem with two objectives being maximization of power reliability and minimization of cost. The LPSP is obtained by operation simulation of the system. A multi-objective evolutionary algorithm, NSGA-II, is utilized and it can find solutions on or near the true non-dominated front of the problem. This has been validated by solving the multi-objective problem with a constraint method. When using NSGA-II, the decision variables are the type and size of WTGs, the tilt angle and size of PV panels and the capacity of batteries. The advantage of using NSGA-II is that it can find multiple optimized solutions in a single run.

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