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Imperial competitive algorithm optimization of fuzzy multi-objective design of a hybrid green power system with considerations for economics, reliability, and environmental emissions

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ABSTRACT

In addition to economics, reliability and environmental emissions are of great importance for designing a power generation system. The objective of this study is to optimally design an autonomous and non-autonomous hybrid green power system (HGPS) to supply a specific load demand with considerations for economics, reliability indices, and environmental emissions. The HGPS includes wind turbine (WT) units, photovoltaic (PV) arrays, electrolyzer and fuel cell (FC). The data used for simulation are actual annual solar irradiation and wind speed for the northwest region of Iran. For reliability analysis, it is assumed that WT, PV, DC/AC convertor, and electrical network can have failure in supplying power. Imperial competitive algorithm is utilized for optimization. To address different levels of importance for economics and environmental emission, fuzzy multi-objective problem formulation is used for non-autonomous HGPS. For the optimally designed non-autonomous HGPS, for maximum purchased power of 50 kW, based on current rates, the costs are 92.6% less than that of the autonomous HGPS, in exchange for 5778 tons of CO_2 emissions. In general, it is determined that allowance for purchasing power results in lower overall efficiency of the non-autonomous HGPS.

1. Introduction

In nearly all developing countries, the increasing population growth and industrialization have resulted in the slow expansion of electrical distribution networks and formation of regions with high load density creating reliability problems such as diminished power quality and voltage instability [1]. At the same time, the non-urban areas suffer from problems, such as, voltage drop and high losses across distribution lines. Distributed generation based on green power sources is considered as a suitable option for utility operators to address the aforementioned electrical network problems [1]. However, the correct estimation of economical gain can be achieved only when reliability is taken into account [2]. In addition, the influence of environmental aspects must be considered when green power sources are employed [3]. The limitations in available energy from wind and solar irradiation and their discontinuous behavior cause a decrease in the level of system reliability [2], which could be solved by employment of green power sources in hybrid form [4–15].

While, currently, it may be economically unattractive to invest in an autonomous hybrid green power system (HGPS) (power not allowed to be purchased from grid), a non-autonomous HGPS may ensure the required reliability and could be a good backup for the HGPS system [15–19].

For an autonomous and non-autonomous HGPS, the planning problem can be handled with minimizing a single-objective cost function including various costs but sometimes it is necessary to consider an additional objective function, as some optimization variables may not be of the same type and goals of the optimization may not be in the same direction. In other words, minimizing costs by one objective function may not result in minimized environmental emissions and a second objective function must therefore be considered. As a result, a multi-objective procedure must be developed for analysis of HGPS, where the solution to the problem leads to minimization of cost and environmental emissions. Further, for better flexibility of arriving at non-dominated optimal solutions, fuzzy logic approach can be used [16], [20].

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1.1. Contributions of this study

The examination of literature review shows that treatment of environmental emissions that results from various levels of purchased power from the network in the case of utilizing a non-autonomous HGPS is not addressed in conjunction with reliability and economics of owning and operating such systems.

Hence, the objective of this study is to optimally design an autonomous and non-autonomous HGPS to supply a specific load demand with considerations for economics, reliability indices, and environmental emissions. To address different levels of importance for economics and environmental emission, fuzzy multi-objective problem formulation is used for non-autonomous HGPS.

The HGPS includes WT units, PV array, electrolyzer and FC and, actual data used for simulation are annual solar irradiation and wind speed for the northwest region of Iran. For optimization, due to the large number of variables and their discontinuity, imperial competitive algorithm (ICA) is used.

Next, the problem formulation including HGPS and reliability modeling is discussed. Then, multi-objective problem solving and fuzzy logic approach for the applied ICA are outlined followed by the simulation result and discussions section. Finally, the conclusions and recommendations are given.

2. Problem formulation

For the autonomous HGPS, the system operates independent from electrical network and there is no purchased power. As shown in Fig. 1, the non-autonomous HGPS operates in parallel with the electrical network as a backup and consists of WT units, PV array, electrolyzer, HST, FC units, and DC/AC inverter. All variables and symbols are explained in the nomenclature section.

The total produced power by the HGPS is the sum of WT and PV outputs. In each hourly time step, one of the following conditions exists:

(a) All generated power by HGPS is sent to DC/AC bus to supply load demand,

$$P_{HGPS}(t) = \frac{P_{load}(t)}{\eta_{inv}} \tag{1}$$

(b) Excess power is delivered to electrolyzer to produce hydrogen, then whenever transferred power to electrolyzer is more than its rated capacity or HST reaches its maximum capacity, excess power is dissipated by means of a dump load,

$$P_{HGPS}(t) > \frac{P_{load}(t)}{\eta_{inv}} \tag{2}$$

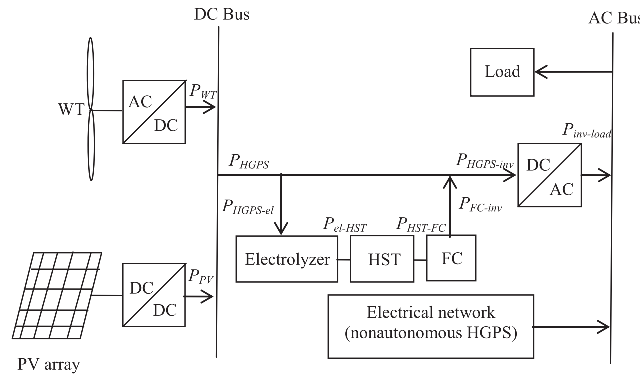

Fig. 1. HGPS structure used in this study.

(c) Portion of load demand not supplied by WT and PV is met by FC and electrical network,

$$P_{HGPS}(t) < \frac{P_{load}(t)}{\eta_{inv}} \tag{3}$$

Note that whenever the sum of FC and maximum purchased power from electrical network is not adequate to supply load demand, there is an increase in loss of reliability, as discussed and analyzed in details later. A simplified flowchart of simulation activities in this study is presented in Fig. 2.

2.1. HGPS components modeling

2.1.1. Wind turbine

Wind speed at a given installation height is modeled by the exponent law [10].

$$v_W^h = v_W^{ref} \times \left(\frac{h}{h_{ref}}\right)^{\psi} \tag{4}$$

where ψ is a coefficient between 0.14 and 0.25 (0.14 in this study).

The relations for calculation of WT output power are [21].

$$P_{WT} = \begin{cases} 0 & ; v_W \le v_{cutin}, v_W \ge v_{cutout} \\ P_{WT,\max} \times \left(\dfrac{v_W - v_{cut\ in}}{v_{rated} - v_{cut\ in}}\right)^z & ; v_{cutin} \le v_W \le v_{rated} \\ P_{WT,\max} + \dfrac{P_{furl} - P_{WT,\max}}{v_{cut\ out} - v_{rated}} \times (v_W - v_{rated}) & ; v_{rated} \le v_W \le v_{cutout} \end{cases} \tag{5}$$

where v_{cutin}, v_{cutout} and v_{rated} are 3, 25, and 13 m/s, respectively. In addition, P_{furl} and $P_{WT,max}$ are considered 5.8 and 8.1 kW, respectively. Parameter z is a constant (assumed = 3) [22].

2.1.2. PV array

The power from PV array is modeled as [23].

$$P_{PV} = \frac{G(t, \theta_{PV})}{1000} \times P_{PV,rated} \times \eta_{PV,conv} \tag{6}$$

where

$$G(t, \theta_{PV}) = G_V(t) \times \cos(\theta_{PV}) + G_H(t) \times \sin(\theta_{PV}) \tag{7}$$