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Techno-economic optimization of hybrid photovoltaic/wind generation together with energy storage system in a stand-alone micro-grid subjected to demand response

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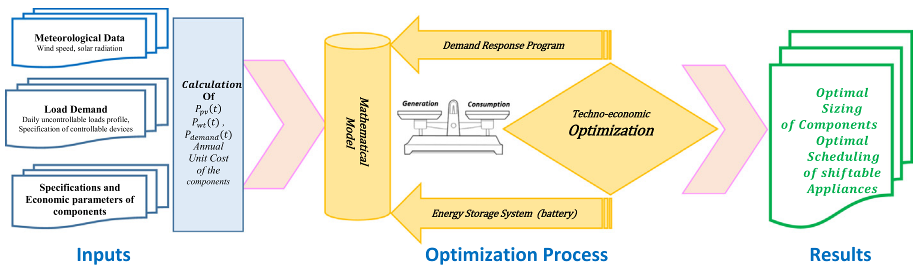
HIGHLIGHTS

- Ability of DR for component size optimization of a stand-alone micro-grid was examined.
- DR is implemented by reducing or eliminating the mismatch between the generation and consumption profiles.
- DR utilization, reduce the number of batteries, inverters, photovoltaic cells, and total net present costs.
- DR implementation reduces the peak of consumed loads and increased the consumed load factor and correlation factor.

GRAPHICAL ABSTRACT



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ABSTRACT

Regarding the importance of supplying energy to regions that are far from power systems, this study is devoted to analyzing and modeling of a stand-alone micro-grid. In spite of many studies in the case of demand response programming for optimal management and operation cost reduction of the micro-grids, and regarding the importance of size optimization of micro-grids, this paper seeks to examine and investigate the ability of demand response programming in the case of component size optimization of a micro-grid. Due to deficiency or unavailability of dispatchable energy recourses, only the nondispatchable renewable energy resources (wind and solar energy) are considered to supply the required energy. Applied strategy for effective component size optimization as well as relevant costs reduction is implemented by reducing or eliminating the mismatch between the generation and consumption profiles by time shift and schedule of dispatchable loads. Furthermore, the effect of demand response utilization on loss of generated energy reduction is studied. The optimized results with and without demand response are extracted and compared to each other.

For each case, the optimum configuration was determined. Obtained results indicated that application of the demand response program, reduced the number of required batteries, the required inverter and photovoltaic cells capacity, and, consequently, the total net present costs. Furthermore, demand response implementation reduced the peak of consumed loads and increased the consumed load factor and correlation factor. The micro-grid components have been modeled mathematically within the framework of the mixed integer linear programming method. The optimization program has been performed by HOMER software together with GAMS software via the CPLEX solver.

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1. Introduction

Nowadays, Interest in the use of renewable energy resources has been increased. This is due to rising of energy demand, limited resources of fossil fuels, energy market instability, as well as environmental threats on the one hand, and the free availability and limitlessness of renewable energy resources on the other hand. Moreover, the need to supply energy to remote regions from power distribution networks has further increased the importance of on-site renewable energy generation systems [1].

In the recent years, increased interest in the use of small-scale hybrid energy sources in electricity distribution networks has led to the appearance of smart micro-grids (MGs).

Wind and solar energy are considered as major renewable resources [2]. The amount of energy generated by these resources varies over time and does not usually match the consumption profile. This mismatch necessitates the use of batteries in an off-grid system. Also, if photo-voltaic (PV) systems or wind turbines (WT) are used separately, system size and investment cost will increase. Hybrid use of these sources can improve system reliability, performance, decrease generation fluctuations, investment costs, and the size of the storage system [3,4].

Notable studies have addressed the optimal design of hybrid power generation systems in micro-grids. In [5], Multi-objective Genetic Algorithms are used to optimize three stand-alone hydrogen storage systems. Application of meta-heuristic algorithms to optimize the size of hybrid systems has been reported in Refs. [6–8].

Technological development in the field of renewable resources makes these resources more usable for supplying power to small and remote sites. Numerous plans have been reported to meet the whole energy demand of off-grid systems using renewable energy resources and storage systems [9]. Panayiotou et al. [10] designed and employed an optimal standalone PV system and a standalone hybrid PV-WT system in Nicosia, Cyprus and Nice, France. Enevoldsen and Sovacool [11] examined the feasibility of implementing a standalone hybrid system (renewable energy only) in one of the Faroe's Islands. In Ref. [12], a storage system was used to increase reliability in an isolated micro-grid. In this study, various methods and tools for optimizing the design and selecting the components of a wide range of isolated micro-grids were examined. Zakeri and Syri [13] designed a standalone system equipped with a storage system to moderate the effects caused by the varying nature of energy supply/demand.

Considerable researches have been conducted in the case of size optimization of stand-alone micro-grids [14–16]. In Ref. [17], the metaheuristic method has been applied for the size optimization of the battery energy storage system in the hybrid power systems. In Ref. [8], colony optimization method has been implemented for size optimization renewable energy. Fadaee et al. [18] thoroughly examined the different methods for optimizing the size of hybrid renewable energy systems. In Ref. [19], a new formulation for optimizing the design of a photovoltaic (PV)-wind hybrid energy home system, incorporating a storage battery, was developed, using genetic algorithm. In Ref. [20], the capacity of an isolated micro-grid (PV/wind/battery bank) was optimized using iterative methods. In Ref. [21] size optimization of a micro-grid evolutionary algorithm was accomplished. In Ref. [22], the techno-economical optimization of an isolated system (PV/wind/diesel/battery) was addressed. This optimization was based on total unsupplied energy, total net present cost, and energy generation cost. In [23], size of an isolated system (PV/wind/diesel/battery) were minimized using harmony search algorithm. Mukhtaruddin et al. [24] optimized an autonomous hybrid system using iterative-Pareto-fuzzy methods. In Ref. [25] size optimization of a biomass-based PV power plant to supply the electrical power was done.

From previous studies, it has been found that a considerable amount of works have been performed on size optimization of micro-grids without DR programing.

In on-grid systems, demand response (DR) is often used to reduce operating costs. DR involves a change in consumption pattern in response to a change in electricity price over time or to cost incentives aimed at reducing consumption or shifting it to another time during hours when the market price of electricity is high or system reliability is in danger [26–29].

Recently, many studies have addressed the DR strategy for optimum power management in on-grid networks [30–33]. In Ref. [34] a new approach for solving the multi-area electricity resource allocation problem with considering both intermittent renewables and DR was proposed. Babonneau et al. introduced a linear programming framework to model distributed generation, flexible loads and distributed energy resources [35]. Tsui and Chan [36] proposed a method of minimizing electricity consumption cost using price-based DR for optimum operation of appliances in a smart home. Li and Hong [37] implemented a DR strategy for a smart home based on user-expected price with the aim of reducing total electricity cost. Yan et al. presented a novel demand response estimation framework for residential and commercial buildings using a combination of energy plus and two-state models for thermostatically controlled loads [38]. In Ref. [39] the promotion impact of demand response on distributed PV penetration was investigated. The DR strategy implemented in the study involved charging the electricity storage system (ESS) during off-peak times and discharging it during peak times. Previous studies are used DR only for optimal management and operation cost reduction without component size optimization.

To the best knowledge of the authors, no study has been done in the case of examining DR ability for size optimization.

Regarding the importance of size optimization of micro-grid, this paper seeks to examine the energy generation in a stand-alone micro-grid using DR programing. Due to deficiency or unavailability of dispatchable energy recourses, in the present study, only the available nondispatchable renewable energy resources (wind and solar energy) are considered to supply the desired energy (it must be noted that power management with nondispatchable energy recourses is more complicated than dispatchable ones). For the realistic modeling, consumed loads were considered as statistical normal distribution with mix of hourly and daily variation of loads. The studied micro-grid is a forestry camp, located in the northwest of Iran at longitude of $45^{\circ}, 5'$ and latitude of $37^{\circ}, 2'$. Consumed loads comprise dispatchable and nondispatchable loads. Applied strategy for effective component size optimization is implemented by reducing or eliminating the mismatch between the generation and consumption profiles by time shifting and schedule of dispatchable loads. In addition, the effect of applying this program on reducing the loss of generated energy is studied. Finally, the obtained optimization results with and without DR are compared to each other. The micro-grid components have been modeled mathematically within the framework of the mixed integer linear programming method. The applied software for modeling, simulating, and optimizing the studied micro-grid are GAMS and HOMER.

2. Model of the hybrid micro-grid system

Fig. 1 shows a schematic view of the studied isolated micro-grid. In this micro-grid, energy is generated using PV and WT. As shown in this figure, the micro-grid has an energy storage system (battery) to store energy generated in excess of consumption. Furthermore, the micro-grid has a smart system to manage