Mix-mode energy management strategy and battery sizing for economic operation of grid-tied microgrid

Shivashankar Sukumar\textsuperscript{a}, Hazlie Mokhlis\textsuperscript{a,*}, Saad Mekhilef\textsuperscript{a}, Kanendra Naidu\textsuperscript{c}, Mazaher Karimi\textsuperscript{b}

\textsuperscript{a} Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
\textsuperscript{b} School of Electrical and Electronics Engineering, The University of Manchester, United Kingdom
\textsuperscript{c} Electrical Technology Section, Universiti Kuala Lumpur, British Malaysian Institute, Malaysia

\textbf{Abstract}

This paper presents a novel 'mix-mode' energy management strategy (MM-EMS) and its appropriate battery sizing method for operating the microgrid at the lowest possible operating cost. The MM-EMS is developed by combining three proposed operating strategies, namely "continuous run mode", "power sharing mode" and "ON/OFF mode" for a 24 h time period. The objective functions for the proposed strategies are solved using linear programming (LP) and mixed integer linear programming (MILP) optimization methods. A sizing method using the particle swarm optimization (PSO) technique to determine the optimal energy capacity of battery energy storage (BES) in kWh is also presented. Since the size of the BES influences the microgrid's operating cost, the energy management strategy (EMS) and BES capacity are simultaneously optimized. The proposed MM-EMS and battery sizing method were first validated. Then, the variation of optimal battery capacity for different battery state of charge (SOC) levels is analyzed. The variation of microgrid's associated costs for different battery's initial state of charge (SOC) levels is analyzed as well. Finally, a recommendation on the choice of initial SOC level during the start of the day for the economic operation of microgrid is also suggested.

\section{1. Introduction}

The conventional power system distribution network is currently undergoing a major change due to the addition of microgrids. The benefits of using microgrids include the fact that it is capable of supplying loads with negligible losses, reduce fossil fuel consumption, and postpone investment in a distribution system. Connecting intermittent sources such as solar photovoltaic (PV) generators and wind turbines in the grid-connected microgrid introduces challenges in various technical aspects, such as power quality, protection, generation dispatch control, and reliability. Challenges caused by these intermittent sources render the battery energy storage (BES) an indispensable source \cite{1}. When a grid connected microgrid consists of two or more dispatchable sources, it is necessary for the grid operator to run it economically. If battery energy storage (BES) is one of the dispatchable sources, it is essential that an appropriate size of BES is installed for the optimal microgrid operation.

A power management and battery sizing algorithm is proposed for a grid connected microgrid, consisting of PV, diesel generator, and BES in Ref.\cite{2}. However, the battery size is not optimum, because the algorithm does not consider economic operation of microgrid. A smart energy management system based on matrix real-coded genetic algorithm is proposed in Ref.\cite{3} for economic operation of grid connected microgrid. The optimal operation of grid connected microgrid is presented in Refs.\cite{4,5}, where the microgrid’s economic dispatch problem is solved by minimizing the microgrid’s operational cost using mesh adaptive direct search (MADS) algorithm. Mixed integer linear programming (MILP) is used to solve the economic dispatch of microgrid sources in Ref.\cite{6}. An optimal energy management is presented in Ref.\cite{7}, where the objective is to minimize the generation cost of the grid connected microgrid. The economic dispatch problem is solved using mixed integer quadratic programming (MIQP). Similarly, the sizing of battery energy storage is carried out in Ref.\cite{8}, where the economic dispatch problem is solved using linear programming (LP). Apart

\* Corresponding author. Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail address: hazli@um.edu.my (H. Mokhlis).

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from solving the energy management problem using numerical methods, metaheuristic methods are used to solve energy management problem found in Refs. [9–12]. The energy management problem from the aforementioned references is based on one particular strategy. Moreover, in few papers, the optimal sizing of battery storage is not taken into account.

Energy storage devices play a crucial role in the economic operation of microgrid. Battery storage can take advantage of time of use tariffs, where it can be an effective option when the power purchasing price from the utility grid is high. Therefore, the accurate sizing of battery source is essential to ensure a microgrid’s economic operation. The sizing of BES involves determining the optimal energy capacity in kWh with the aim of reducing microgrid’s daily operating cost. An optimal sizing of battery storage for microgrid is presented in Ref. [13]. The optimal sizing of battery energy storage using improved bat algorithm is presented in Ref. [14]. Genetic algorithm based method for sizing battery storage is proposed in Ref. [15]. The energy management system in this paper is based on fuzzy expert system. In Ref. [16], matrix real-coded genetic algorithm (MRCGA) is used to determine the optimal energy capacity of BES. In a recently published article [17], the battery size is evaluated in order to minimize the microgrid’s operational cost. The sizing problem was solved using Grey WolfOptimizer (GWO). The energy management problem solved in aforementioned references is based on a single operating strategy. The battery sizing methods presented in these references is focused on one particular energy management strategy, which may not incur the lowest operating cost.

The prominent focus of most work in literature pertaining to this subject was on solving economic dispatch for microgrid sources using a single operating strategy. It is possible that the microgrid might operate at lower operating cost in the case of a newly designed operating strategy. There are only a few works in literature that accounted for the sizing of battery storage, which is an important aspect of economic operation of a microgrid. In addition the papers in the literature discuss battery sizing methods that considers the economic operation of microgrid for one particular strategy. Therefore, in this paper an energy management strategy to operate the grid connected microgrid at the lowest possible operating cost is discussed. A method to estimate optimal BES size in kWh will also be presented. This work involves the development of an energy management using mix-mode operating strategy to operate the microgrid at the lowest possible operating cost. The proposed mix-mode operating strategy is developed by combining three proposed operating strategies, namely “continuous run mode”, “power sharing mode” and “ON/OFF mode” for a 24 h time period. The objective functions for these operating strategies were minimized using linear programming (LP) and mixed integer linear programming (MILP) methods. The mix-mode operating strategy is based on combining the aforementioned strategies keeping the operating cost in mind. The non-linearity of the PV output power and load demand, daily grid electricity price profile, the price of the natural gas, as well as battery state of charge (SOC) limits were all taken into account in the development of this model. In this paper, the BES’s energy capacity for the microgrid under the proposed mix-mode operating strategy is solved using the PSO optimization technique. Due to the fact that the operating cost produced using mix-mode strategy depends on the characteristics of battery storage, both the EMS and BES capacity needs to be simultaneously optimized. The discussion section will detail the, validation of the proposed MM-EMS and battery sizing method.

2. Proposed 'mix-mode' energy management strategy (MM-EMS)

Operating the microgrid in more than one operating strategy is referred to as the mix-mode operating strategy. Three operating strategies, namely the continuous run mode, power sharing mode, and ON/OFF mode are proposed and explained in the following subsections.

2.1. Proposed operating strategies

The optimal generation dispatch for energy sources is calculated on an hourly basis to satisfy the load requirements considering hybrid system limits and constraints. The proposed operating strategies are explained in the subsequent sections.

2.1.1. Strategy 1: continuous run mode

In this operating mode, the power drawn from the utility grid is always zero. The fuel cell operates continuously during a 24 h time period. The output power from the fuel cell depends on the load demand and output powers from the PV and battery storage. During this strategy, initially the output power from PV and battery is used to supply the load demand. If demand is not met, the fuel cell is optimally dispatched to satisfy the load demand. There are chances where the output power from the PV exceeds the load demand, and in this case, the battery is charged, and the fuel cell is forcibly switched OFF. The objective function for this mode is to reduce the daily operating cost, which can be expressed as:

\[
\text{obj1} = \text{Minimize} \left[ C_{\text{gi}} \sum_{i=1}^{N} P_{\text{FCi}} + \beta (P_{\text{BATi}}) \right] \tag{1}
\]

where,

- \( C_{\text{gi}} \) is natural gas price to supply the fuel cell in dollars per kilowatt-hour
- \( P_{\text{FCi}} \) is fuel cell power at time interval ‘i’
- \( \beta \) is taken as \( 1 \times 10^{-6} \) to obtain the dispatch solution of \( P_{\text{BATi}} \)
- \( P_{\text{BATi}} \) battery power at time interval ‘i’;
- \( \eta_{\text{FC}} \) cell efficiency of SOFC at time interval ‘i’ which is given as,

\[
\eta_{\text{FC}} = \frac{V_{\text{stack}}}{E^*} \tag{2}
\]

\( E^* \) is standard electrochemical potential which is 1.482 V/cell
\( V_{\text{stack}} \) is fuel cell output stack voltage at instant ‘i’
\( N \) is number of cell in fuel cell stack

At any given time instant ‘i’, the sum of the power generated from the distributed sources should be equal to the load, which can be expressed as:

\[
P_{\text{PVi}} + P_{\text{BATi}} + P_{\text{FCi}} = P_{\text{li}} \quad i = 1, 2, \ldots, 24 \tag{3}
\]

The power produced from PV is uncontrollable. The fuel cell and battery is modeled as a variable controllable source, which should be operated within the prescribed limits for a 24 h time period. The
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