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Minimizing the energy cost for microgrids integrated with renewable energy resources and conventional generation using controlled battery energy storage

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A B S T R A C T

This paper presents a methodology to minimize the total cost of buying power from different energy producers including renewable energy generations particularly within the context of a microgrid. The proposed idea is primarily based on the controlled operation of a battery energy storage system (BESS) in the presence of practical system constraints coupled with our proposed cost optimization algorithm. The complex optimization problem with constraints has been solved using the well-known concept of dynamic programming. The methodology has been assessed using actual power and price data from six different power generation sites and cost reduction has been calculated for a number of BESSs by varying their energy and power capacities. Twofold benefits of the proposed methodology lie in minimizing the total cost along with the constraint-based efficient operation of the BESS. Simulation results depict that the given power demand at a particular region can be fulfilled properly at all times using a BESS and multiple power generation.

1. Introduction

Microgrid (MG) has become promising component for future smart grid deployment [1–4]. A MG is a distributed electric power system that can autonomously co-ordinate local generations and demands in a dynamic manner. Modern MGs often consist of distributed renewable energy (RE) generations like wind and solar and conventional co-generation technologies. MGs can operate in either grid-connected mode or islanded mode. Recently, there have been worldwide deployments of pilot MGs. MGs are more robust and cost-effective than traditional approach of centralized grids. They represent an emerging paradigm of future electric power systems that address the two critical challenges of power reliability and integration with RE due to the increasing penetration of clean energy resources as a result of the growing environmental awareness [5–7].

RE resources are non-dispatchable resources that are variable, intermittent and uncertain in nature [5]. This variability can pose significant challenges in the operation of the MG especially at large penetration levels. In traditional centralized grids, the actual locations of conventional energy generation, RE generation, and energy consumption are usually distant from each other. Thus, the need to coordinate conventional energy generation and consumption based on the instantaneous variations of RE generation leads to challenging stability problems. A variety of different solutions have been proposed in the existing literature [8–15] including renewable power forecasting. Given the non-controllable and stochastic nature of the RE resources, a potential solution is the use of a battery energy storage system (BESS), which allows one to accumulate the surplus energy in those periods in which RE production is higher than the plant power commitment and delivering it back in the opposite situation. It is expected that storage would be an integral part of the future smart grids [16–18].

In contrast, in MGs RE is generated and consumed in the local distributed network. Thus, the uncertainty of RE is absorbed locally, minimizing its negative impact on the stability of the central transmission networks. However, to realize the maximum benefits of MGs, intelligent scheduling of both local generation and demand

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Nomenclature

α_M	maximum allowed BESS capacity in per unit
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$b(k)$	amount of energy that a buyer needs to buy at time k
C	BESS capacity
$d(k)$	net energy demand at time k
$e(k)$	amount of energy that a producer is willing to sell at time k
i	index of energy producers; $1 < i < n$
k	sampling instant (discrete time)
N	prediction horizon
n	number of energy producers
$p(k)$	price per energy unit at time k
r_c	maximum allowed rate of charge of the BESS
r_d	maximum allowed rate of discharge of the BESS
$u(k)$	control signal at time k
$u^0(k)$	optimal control signal at time k
V	cost function for a prediction horizon N
$x(k)$	state of charge of the BESS at time k

must be established [19–22]. Hence, intelligent generation scheduling, which orchestrates both local and external generations to satisfy the time-varying energy demand, is indispensable for the viability of MGs. Such generation-side scheduling must simultaneously meet two goals: 1) maintaining grid stability, the aggregate supply from all generation systems must meet the aggregate electricity demand, and 2) it is highly desirable that the MG can coordinate local generation and external energy procurement to minimize the overall cost of meeting the energy demand. Therefore, it has become very important to develop innovative optimization algorithms to minimize the cost of energy in the context of a MG especially with larger penetration of RE [23–26]. However, it is very difficult to incorporate intermittent energy resources in such problems in a straightforward manner. Several careful investigations and optimization strategies are required to solve this problem. Several efforts have been made in this regard (see, e.g., [27–32]).

The present work describes an optimization algorithm to minimize the total cost of buying power from multiple power generations by jointly considering RE penetration such as wind and solar photovoltaic (PV), and co-generations like hydro-electric, gas-fired, and thermal power generations within the framework of a MG. In particular, the minimum in the proposed optimization problem is achieved through the constraint-based controlled operation of the BESS. A control system model has also been proposed for the operation of a BESS and resulting constrained optimal control problem has been solved using the concept of dynamic programming (DP). The methodology is quite general, which can be useful particularly serving an Island or a remote locality using RE resources coupled with the BESS, conventional generations, and a mircogrid with the minimum cost. The proposed methodology has been investigated for different sizes of BESSs and the cost reduction has been reported. It has been observed that the presented method leads to significant cost reductions over a given period of time. As a case study, the proposed methodology has been tested with real data obtained from six generations sites from different states in Australia.

The remainder of the paper is structured as follows. The proposed methodology is described in Section 2 and its subsections. The information about databases is given in Section 3. Section 4 presents the simulation results and discussions. The Section 5 concludes the paper.

2. The proposed methodology

The proposed methodology consists of 1) defining a constrained optimization problem, 2) developing a control system model, and 3) finding the solution of problem. All steps are described in the following sub-sections.

2.1. Problem statement

We consider the power supply and consumption in the context of a MG. A general structure of a typical MG is shown in Fig. 1. The supply and demand matching of electric energy in real-time is one of the most important requirements of the MG power management system [34]. Due to the increasing deployment of distributed RE resources, a MG provides a localized cluster of RE generation, storage, distribution and local demand, to achieve reliable and effective energy supply with simplified implementation of smart grid functionalities.

Furthermore, consider Fig. 2 where energy demand at a particular geographical location can be fulfilled from the available power generation of different types including RE resources. The MG control center aims to minimize the MG operation cost while maintaining the supply-demand matching at all times. The problem can be formulated as a constrained optimization problem with the objective of minimizing the total cost of buying power from multiple generations using the controlled charging/discharging of the BESS while maintaining the perfect demand and supply balance.

The problem can be briefly stated as: *to propose an optimization algorithm of minimizing the total operation cost of the MG system with multiple distributed energy generations coupled with the BESS in the presence of physical system constraints while maintaining the perfect balance of supply and demand at a particular geographical location at all times.*

2.2. Proposed optimization algorithm

We consider n electrical energy producers labelled 1,2,…,n. Furthermore, we consider a buyer who buys the energy from these n producers. Let $e_i(k)$, $1 \le i \le n$ denote the amount of energy the producer i is ready to sell at time k. Furthermore, $p_i(k)$, $1 \le i \le n$ denotes the price per energy unit at which the producer i is agreed to sell its energy to the buyer at time k. We assume that

$$p_1(k) \le p_2(k) \le \cdots \le p_n(k). \quad (1)$$

In other words, we present the producers are listed in an ascending order of their prices at time k. This assumption does not imply any loss of generality, if relationship of prices of actual producers changes with time, we just change their numeration. The buyer needs to make the decision regarding the energy amounts $b_1(k)$,$b_2(k)$,…,$b_n(k)$ that the buyer buys from the producers 1,2,…,n at time k. Obviously, the constraints are

$$0 \le b_i(k) \le e_i(k) \quad \forall i = 0, 1, 2, \dots, n. \quad (2)$$

The total amount of energy the buyer needs to have at time k is $d(k)$. Furthermore, the buyer has a battery energy storage that has capacity $C > 0$. Let $u(k)$ be the energy amount sent to the battery energy storage at time k. If $u(k) > 0$ the battery energy storage is charged, if $u(k) < 0$ the storage is discharged. Since the buyer should provide the energy amount $d(k)$ at time k, the following constraint