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Energy management in a microgrid with distributed energy resources

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ABSTRACT

A smart grid power system with renewable energy resources and distributed energy storage shows significant improvement in the power system's emission reduction, reliability, efficiency, and security. A microgrid is a smart grid in a small scale which can be stand-alone or grid-tied. Multi microgrids form a network with energy management and operational planning through two-way power flow and communication. To comprehensively evaluate the performance of a microgrid, a performance metric is proposed with consideration of the electricity price, emission, and service quality, each of them is given a weighting factor. Thus, the performance metric is flexible according to the consumers' preference. With the weighting factors set in this paper, this performance metric is further applied on microgrids operated as stand-alone, grid-tied, and networked. Each microgrid consists of a solar panel, a hydrogen fuel cell stack, an electrolyzer, a hydrogen storage tank, and a load. For a stand-alone system, the load prediction lowers down the daily electricity consumption about 5.7%, the quantity of H_2 stored fluctuates in a wide range, and overall performance indexes increase with the solar panel size. In a grid-tied MG, the load prediction has a significant effect on the daily consumed electricity which drops 25% in 4 days, some day-time loads are shifted to the night time, and the capacity of hydrogen tank is lower than that in a stand-alone MG. In a network with multiple MGs, the control of the power distribution strongly affects the MG's performance. However, the overall performance index instead of any specific index increases with the MG's power generated from renewable energy resources.

1. Introduction

According to the U.S. Energy Information Administration, around 29.3 PWh of energy was consumed in 2008. 37% of the energy was from petroleum while 50% of the petroleum was imported – around 1.32 million tons/day. From 2006 to the present, the price of gasoline has fluctuated due to the instability in the Middle East, manipulation of energy supplies, competition over energy sources, attacks on supply infrastructure, and natural disasters. To improve the nation's energy independence and security, the best solution is to efficiently utilize renewable energy resources including solar, wind, hydro, geothermal, and tidal energy. Renewable sources of energy are plenty and vary widely in their availability across the United States. In addition, these energy resources are environmentally friendly with zero emission. In order to utilize renewable energy, wide-scale distributed renewable energy resources (DRERs) are more widespread than the large-scale centralized installations [1]. However, the traditional power grids heavily rely on the centralized power generation, around 16,000 power plants in the U.S, for instance [2,3]. Therefore, a new power grid, Smart Grid (SG), was proposed through the updating of the current grid and this SG includes technologies in the distributed energy generation (DEG), distributed energy storage (DES), advanced measurement and sensing, communications, controls, cyber security, and customer power management systems [4–7]. DEG is small-scale power generation with power less than 50 kW. It includes micro turbines (μturbine), micro combined heat and power (μCHP) systems, photovoltaic systems (PV), wind turbines, and solar thermal systems [8,9]. Electricity and on-site heat can be produced near the point of demand, allowing for production of energy with high efficiency and avoidance of the transmission and distribution losses in the conventional centralized generation model [10–12]. However, the widespread emergence of the DEG on the consumer side will significantly increase the variability of generation due to the intermittent nature of generators, especially wind turbines and photovoltaic (PV) systems. To balance supply and demand and to minimize the DEG-induced power fluctuations in the grid, compensating changes are required in the demands, DES, and output from flexible generation sources [13,14]. Here, DEG and DES are parts of distributed energy resources (DERs) [15]. Voltage and frequency within tight bands can be maintained with real-time and continuous physical adjustments to electricity generation and demand subject to complex constraints. A conservative SG approach is expected to reduce the environmental impact of the whole electricity supply system and improve the existing services efficiently [16].

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Nomenclature

S	solar panel size (m^2)
Q	overall performance index
F	price index
E	emission index
S	service quality
w_i	weighting factor
P_{supply}	energy supplied to the load
P_{demand}	power demand
e_{avg}	average atmospheric emission for electricity consumed in a MG
e_{plant}	emission from a coal-fire power plant
$\bar{P}_{dd}$	average daily day-time power demand (kW)
$\bar{P}_{dn}$	average daily night-time power demand (kW)
h_d	hours of day time
$\bar{I}$	average solar irradiance (kW/m^2)
η	efficiency

A microgrid (MG) is a small power system with a set of DEG, DES, a grid connection for two-way power flow and message exchange, heat and power distribution infrastructure, and an energy management system. In a MG, electricity and on-site heat can be produced near the point of demand, allowing for production of energy with high efficiency and avoidance of the transmission and distribution losses in the conventional centralized generation model [10–12]. Multiple MGs can form a network with a connection to the utility grid and this shows a great potential to increase the penetration of renewable and distributed energy resources. The control architecture in a MG network is distributed instead of centralized in the traditional grid and this architecture is scalable. Software with different controls, strategies, or architectures has to be developed as a management system to improve the SG's performance [17–19]. One MG can run in two modes: grid-tied and islanded [20]. In the first mode, power flows in two ways between a MG and the other MGs or the utility grid. A MG may consume the power from the outside or it may supply power for credits according to the agreement among the MGs and utility companies. An energy router, such as solid state transformers, will be developed to control power flow among MGs [21]. In an islanded or stand-alone mode, a MG is isolated from the network and this intentional "islanding" under certain circumstances, provides local reliability, stability, and security. At the same time, this operation, mode change, does not change or disrupt the integrity of the network as a whole [20]. The operation of a single MG or MG network is based on the MG energy management which includes a power generation program, an energy storage program, and a load management program. In a MG with multiple generators, such as microturbine, fuel cell stack, or PV system, power generation program will choose appropriate generators to meet the electrical and thermal load demands. The energy storage program provides an energy reserve with a stable output power, voltage and frequency, in the presence of renewable energy fluctuation [22]. The load management or demand response program determines the reduction or shift of the load demand to reduce peak-to-average ratio [23]. Demand can be categorized into different types based on whether it is can be shifted, interrupted, decreased, or cancelled. It also has different priorities in the presence of limited supply. Generally, demand is a random variable with a probability distribution in an operation time window, and it can be regarded as a series of separated and fine-grained tasks, which means each task can be completed in a sequence but not in continuous time slots. MGs should collaborate to schedule the demand shift to avoid a new peak formed in a typical nonpeak hour. The electricity price is definitely considered in this scheduling. In a grid, the price is established by the market to balance sellers' supply and buyers' demand. This balancing process should be continuous and instantaneous; since electricity must be produced at nearly the same instant it is consumed. Market trades in electricity can be: (i) bilateral transactions – short-term forward market trading in the form of a day-ahead market, and (ii) spot market trades in real-time. The first is conducted between wholesale consumers and power plants, and it provides price certainty. But consumers with DEG, DES, and AD must pursue a combination of short-term trading and spot trading. Thus, in order to maximize their benefits from the generation and consumption, consumers can balance their portfolios and adjust their generation or demand under some short-term predictable and unpredictable circumstances [13,24].

A SG with multiple MGs is a distributive system. There are different criteria to evaluate the performance of a MG. Current evaluation methods and indicators only consider one particular aspect of the system, such as economic benefits, energy use efficiency, and environmental benefits [25].

The objective of this paper is to introduce MG performance metrics for the MG performance evaluation from comprehensive aspects: cost, environmental effect, and the service quality. Here, service quality is supply/demand ratio. With the performance metrics, the optimum design and operation of the MG can be achieved. Models of a stand-alone MG, a grid-tied MG, and a MG network with multi-agents are designed for the simulation on the power generation, distribution, consumption, and storage on the energy level while the topology of these models does not limit the simulation. The whole system is developed with Java and each unit is implemented as a thread.

2. The MG model

Fig. 1 shows the structure of a MG with a radial distribution type and the location is assumed to be in the city of Bridgeport, Connecticut, U.S.A (longitude 73, latitude 41). Each MG consists of a solar panel, an electrolyzer, a hydrogen (H_2) fuel cell (FC) stack, a H_2 tank, and loads with different priorities. In addition, there are two circuit breakers and one local agent. The MG can be connected to an external distribution system, grid, through a point of common coupling (PCC). There is also a separation device, a static switch, which has the capability to island the MG when faults or events described in the standard IEEE 1547 occurs, or for maintenance purposes [16,26]. Line 1, 2, and 3 are for bi-directional power distribution and their directions depend on the local load, supply, and electricity price. The local agent is responsible for the energy management: it monitors the grid and the MG status through smart meters with two-way communication; it schedules the power/heat generation, energy storage, and load demands; it also determines the power flow within the MG and between the MG and the outside. In Fig. 1, electricity can be generated from the solar panel to be supplied to the local loads. The spare can either be stored as H_2 in a compresses tank through an electrolyzer or be supplied to the utility grid. When more electricity is needed later, the FC stack will run with the stored H_2 or the power can be