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Fuzzy Logic Controller for Lithium-ion Battery in Standalone DC Microgrid

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***Abstract*—An isolated dc microgrid for a residential building is proposed, with a solar photovoltaic array as its primary power source during daytime when insolation is sufficient and a backup dc generator during other times. A lithium-ion battery is used as the energy storage device in this system, and a fuzzy logic-based charge/discharge controller for this battery is designed and implemented. The model is simulated in MATLAB/Simulink to verify the efficacy of the controller. The performance of the fuzzy controller is evaluated based on the proper supply of power to the load at all times and maximizing the life of the battery by minimizing high charge or discharge.**

Keywords—microgrid; fuzzy; lithium-ion; battery; photovoltaic; energy storage

I. Introduction

The host of issues with conventional energy sources such as fossil fuels seems to indicate that energy systems of the future will rely on distributed generation from a number of different types of energy sources. In recent times, researchers are particularly interested is the study of microgrids with high penetration of renewable energy (RE) resources such as wind and solar power due to the potentially limitless supply of energy. Commonly used RE sources are solar power, biomass, wind power and hydroelectricity. However, the implementation of RE systems has economic drawbacks due to high installation costs. Nevertheless, RE as a percentage of total energy consumption seems likely to increase in the future [1]. Large-scale exploitation of RE sources will be especially beneficial to developing countries which possess such sources in abundance but are prevented from using them widely due to economic realities. Bangladesh, which has great potential for solar power, is a good example.

However, RE resources are subject to the changing conditions of nature and are therefore unpredictable to a certain degree, unlike convention resources such as fossil fuels, which depend mostly on the efficiency of human effort. An overcast day might dramatically lower the power output of a solar PV array, and a sudden drop in wind speeds may cause wind turbines to fall short of their target output power. Using such intermittent sources instead of a predictable and reliable fuel supply raises a number of issues such as the availability of power during high loads, the quality of power and the wastage of generated power due to mismatch of supply and demand. The issues can be partly resolved by the inclusion of an energy storage device in the grid which, in the event of the load exceeding the total generation, supplies the deficit power. When the load is lower and there is surplus generation, the grid supplies power to the energy storage device. The device can be a lithium-ion or sodium sulphur (NaS) battery for short-term storage, or a pumped-storage hydroelectric plant for long-term storage, depending on the requirements of the system. In this paper, a lithium-ion battery is considered for the purpose of energy storage in a dc microgrid.

The microgrid considered here is a simple case, with a solar PV array for generation and a Li-ion battery system for storage. Besides supplying the generation shortfall, there are two additional issues to consider in case of the battery. Firstly, the life of the Li-ion battery must be extended as far as possible, for economic reasons, by ensuring that the state-of-charge (SOC) remains within certain bounds. Secondly, since there is an upper limit to the amount of energy the battery is allowed to store, the surplus power generated by the PV array should be sold to external grids for both economic optimization and energy efficiency. It is the aim of this paper to develop a controller using fuzzy logic that provides the optimal solution to the issues, making it possible to maintain high efficiency and functionality despite unpredictable variations in solar power generation.

An energy management system (EMS) based on fuzzy logic control has already been shown to work for a hybrid energy system with renewable energy sources [2][3]. It has also been demonstrated that the performance of a fuzzy logic controller (FLC) in case of a similar hybrid system is superior to a traditional model such as a PI controller [4]. Fuzzy algorithms have the advantage of being feasible in cases where exact mathematical models do not exist, and are also relatively cheap and simple to implement as they do not require expensive and sophisticated hardware [5].

II. Modelling of Components

In order to observe the proposed controller in action, it is necessary to obtain dynamic models of the four components shown in Fig. 1. Since only the case of an standalone microgrid

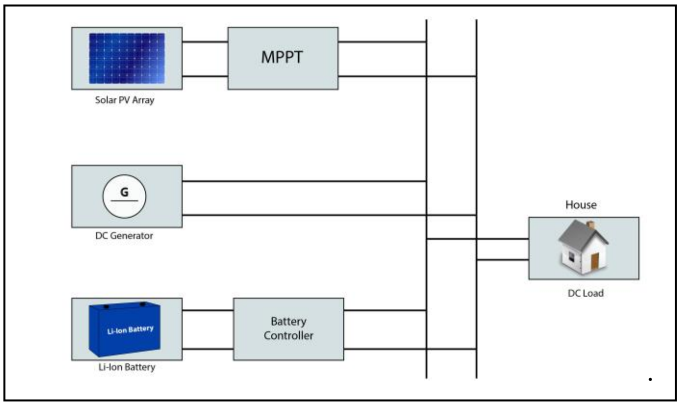

Fig. 1 The dc microgrid system configuration.

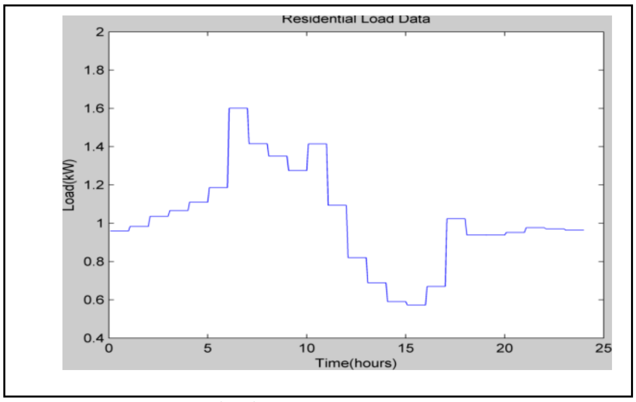

Fig. 3 Modelled load profile for a residential building in Sacramento, CA.

has been considered, these four models are sufficient for a complete simulation. However, the selling of surplus power to external grid would require additional components for interfacing with another grid, usually a bidirectional inverter for interfacing with an ac system. But that is beyond the scope of this paper. Except in case of the Li-ion battery, detailed mathematical models have been avoided in favor of modelled data generated through sophisticated algorithms. Such data is deemed to be significantly more accurate than data generated through simpler mathematical models, particularly in case of the solar PV power output.

A. *Solar PV System*

The primary power source in the microgrid is a solar photovoltaic system rated at 5 kW. The solar power output data was obtained from the National Renewable Energy Laboratory (NREL), which selected plant locations based on previous integration studies in order to optimize the solar power generation [7]. The particular dataset used here pertains to California, because it is thought that a region of high insolation would be the most practical location for a PV-based microgrid. It must be emphasized that this data, which gives the power output for five-minute intervals for a 24-hour period, was not taken from actual measurements, but generated by NREL using the Sub-Hour Irradiance Algorithm. Employing the model developed by Perez et al., hourly irradiance data derived from satellite images is used to generate values for PV power output.

As shown in Fig. 2, solar power is a highly intermittent source with zero output for much of the day, and even when there is an output, large variations occur due to shading effects.

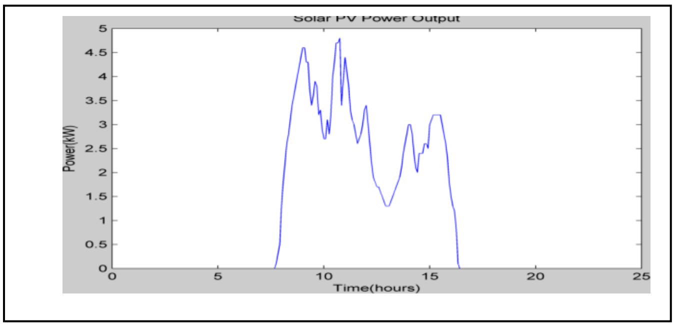

Fig. 2 Modelled solar PV power output data for California.

It is observed from the data table that insolation begins at 7:40 am and stops at 4:20 pm. The actual times will vary depending on geographical location, but this is sufficient for modelling purposes.

B. *DC Load*

The load considered here is a residential building, with a power demand within 2 kW at any particular time. The peak demand is important from a design point of view, and the sizing of the other components has to take this into account. As in the case of the solar photovoltaic system, the data used has been modelled from simulations, not actually measured. The simulated hourly load profile for residential buildings was authored by the Office of Energy Efficiency and Renewable Energy, a branch of the US Department of Energy, and takes into account variables such as differences in construction due to geography and climate [8]. The hourly load data was used assuming that the load remains constant for each hour. As seen in Fig. 3, there are typical variations in power consumptions throughout the day.

C. *Li-ion Battery*

A 700 Ah lithium-ion battery was used as the energy storage device in this dc microgrid. A comparison between lead-acid and lithium-ion battery technologies shows that the difference in results is small, but Li-ion batteries have a higher calendar life [6] which is why it was chosen. The battery capacity was decided after a compromise between three considerations: sufficient storage to supply load at all times, cost and weight of the battery and the ability to maintain a certain SOC less than 100%. For the microgrid to be functional, the battery must be able to supply the demand at all times, but the cost and weight of the battery increases with capacity, and so does the difficulty in procuring and transporting it. The third consideration relates to maximizing the life of the battery. Keeping a Li-ion battery fully charged (SOC close to 100%) or fully discharged (SOC close to 0%) for long periods of time is detrimental to its life. Therefore, the battery capacity must be such that the SOC can be maintained around 50% with the available power sources.

$$f_1(it\ i^* i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \quad (1)$$

$$f_2(it\ i^* i) = E_0 - K \cdot \frac{Q}{it+0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \quad (2)$$

The discharge and charge models of the battery are described by (1) and (2) respectively, where the maximum capacity is represented by Q. In (1) i* is positive (discharging) and in eq. (2) i* is negative (charging). Eq. (3) gives the state-of-charge of the battery in terms of the charge/discharge current.

$$SOC = 100\left(1 - \frac{\int_0^t i dt}{Q}\right) \qquad (3)$$

D. DC Generator

A commercially available petrol-powered 1 kW DC generator is modelled here as a constant dc power source that is switched on and off at certain times. The generator is essentially used to supplement the power supply from the battery at times when there is no sunlight and the PV power output is zero. It is modelled as a single unit, although due to the long hours of continuous operation involved, it might be more practical to use two units alternately.

III. Battery Control

A. Fuzzy Control of Battery

Fuzzy logic relies on the concept of "degrees of truth", as opposed to the Boolean concept of absolute truths. Since the original idea was proposed in 1965 in the form of fuzzy set theory, fuzzy logic has become an integral part of control engineering and has been developed for several applications such as control of electrical machines, robotics and various intelligent systems. The usefulness of fuzzy logic is that it does not make the impractical assumption of a binary system with two absolute states, but rather assumes two extreme states with a certain number of intermediate states between them.

Fuzzy logic is applied in the design of the charge/discharge controller for the lithium-ion battery. The battery is discharged when the load is higher than the generation, and charged when there is surplus generation. Negative feedback loop control is used to maintain the battery SOC at the desired level (50%), as shown in Fig. 4. The FLC has two input variables, ΔP and ΔSOC, as described by (4) and (5). The output variable is the battery charging/discharging current. The input and output are divided into five different grades based on magnitude and polarity. The grades in ascending order are: high negative (H-), low negative (L-), zero (Z), low positive (L+) and high positive (H+).

$$\Delta SOC = SOC_{ref} - SOC \qquad (4)$$

$$\Delta P = P_L - \left(P_{solar} + P_{gen}\right) \qquad (5)$$

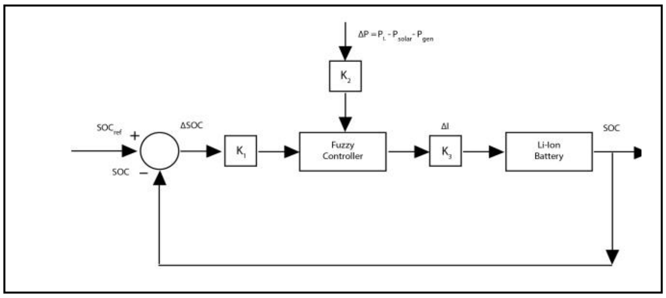

Fig. 4 Block diagram of system with fuzzy controller.

Effectively, the fuzzy controller performs three tasks: supply power during high load, maintain battery SOC at 50%, and save surplus power for sale. The highest priority is to keep the loads in the microgrid well supplied, as shown by the fact that when ΔP is highly positive (demand far exceeds the generation), the controller outputs a highly positive (discharging) current regardless of the value of ΔSOC. However, when ΔP is negative (surplus power generated), the controller only outputs a negative current (battery charging) when ΔSOC is positive (battery SOC lower than 50%). If the battery SOC is above 50%, the current will be discharging, and zero if SOC is equal to 50%. This will save the excess power for sale.

B. Implementation of Fuzzy Controller in MATLAB

The Fuzzy Inference System (FIS) Editor and the Fuzzy Control Toolbox in MATLAB were used to implement the FLC in a dynamic model of the microgrid. Uniformly distributed triangular and trapezoidal membership functions were used with 40% interval for each grade. The resultant set of rules is mapped as a surface plot in Fig. 5, where each of the three axes correspond to one of the three variables. Fig. 6 shows the complete Simulink model of the microgrid.

IV. Simulation Results

Fig. 7 shows the simulation results for proposed microgrid system which is modelled and simulated using Simulink in MATLAB. Since the paper focuses on the fuzzy controller for

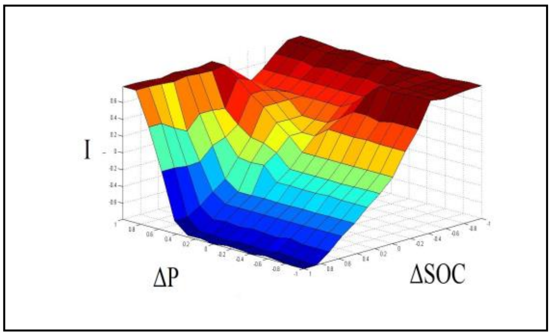

Fig 5 Three-dimensional surface plot of fuzzy rule.

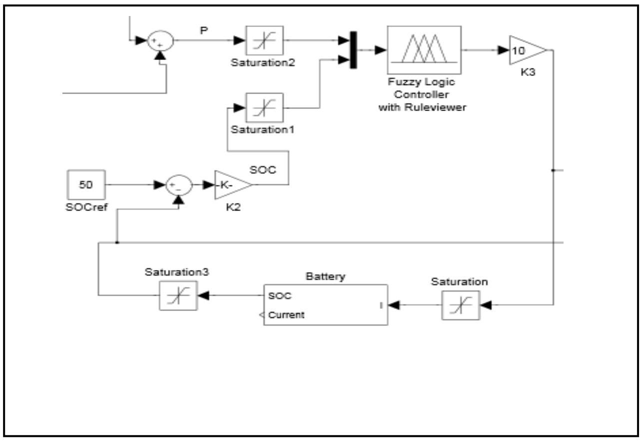

Fig. 6 Part of the Simulink model showing the FLC with input and output.

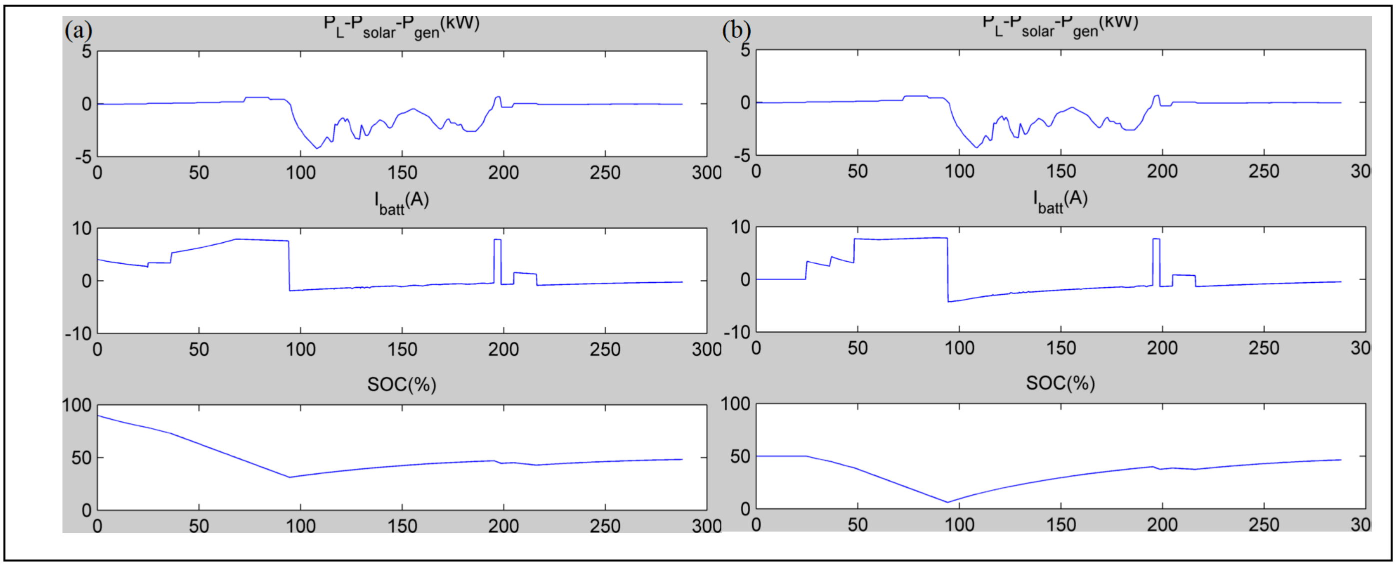

Fig. 7 Simulations results showing ΔP, I_{batt} and ΔSOC for (a) initial SOC = 90% (b) initial SOC = 50%.

the Li-ion battery, only the variables involved in the controller are of interest. The modelling of individual components such as the maximum power point trackers (MPPT) and dc-dc converters is ignored as it is deemed unnecessary, although the inclusion of such models could conceivably produce more accurate results. The simulation is run for two cases, varying only the initial SOC of the battery, which is 50% in once case and 90% in the other.

From Fig. 7, it is observed that the controller is capable of maintaining the battery SOC at 50% in both cases. The wave shapes of I_{batt} and SOC in the two cases are similar, the only major difference being the high initial discharge current in the case where initial SOC is 90% which is required to bring the SOC down to the desired level. Despite occasional dips in SOC level when backup power is required, but the controller always charges the battery up to half-capacity when surplus power becomes available. When half-capacity is reached, the current returns to zero until the next time the load exceeds the generation. From the results, it can be seen that the most challenging time is the morning, around 8:00 am. The SOC drops below 30% in both cases due to continuous high discharge, as the load rises above the power output of the dc generator. After that, there is sufficient sunlight for the solar PV system to start generating power, and the battery SOC becomes stable even after the generator is switched off at 9:40 am.

V. CONCLUSION AND FUTURE WORKS

The fuzzy controller for the battery proposed here successfully supplies the necessary power and maximizes the life of the battery in a simple standalone dc microgrid. It also saves a significant portion of the surplus generation from the solar PV system, which can be used elsewhere. In order to make such a closed system more cost-effective, a bidirectional inverter could be used to connect the microgrid to a larger ac grid which would purchase the surplus power remaining after supplying the load and charging the battery. It is also the intention of the authors to run the simulations with PV power output and hourly load data from Bangladesh, in order to obtain a better understanding of the system's effectiveness in the local context. The availability of such data would significantly enhance our understanding of the feasibility of the proposed system in a country with high potential for solar power.

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