A MPC Operation Method for A Photovoltaic System with Batteries

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Abstract: The schedule dispatch of batteries and operation of photovoltaic(PV) systems can create significant economic benefits for residents. This paper presents a model predictive control method to optimize the charge and discharge of batteries and operation of a PV system. The objective is to minimize the bill cost for customers with the prediction information of solar power generation, load consumption and unit electricity price from grid. Experiment results taken in Nansha, Guangzhou, China are analyzed and prove the creditability of the model and effectiveness of the optimal operation method.

Keywords: Renewable energy systems, Model predictive control (MPC), Optimization

1. INTRODUCTION

Photovoltaic(PV) systems develop fast in recent years due to the rapid increase of PV materies and the reduction of the cost. One of the major challenges for PV systems remains in the matching of the intermittent energy production with the dynamic power demand. A solution is to add batteries as an alternative to ensure greater availability of electricity supply in PV systems [1]. And this results in the research of management of the batteries and operation of the PV system.

There have been many studies about control algorithms and management policies for such a residential PV and energy storage system. Ha Pham et al. proposed an optimal operation method of a PV-based multi-source system with two principal mechanisms of control [2]. Riffonneau et al. present a predictive control system to perform peak shaving and reduce daily electricity bills, with the consideration of battery aging effect [3]. Wang et al. proposed a hierarchical algorithm with a novel PV power generation and load power consumption prediction method [4].In ref.[5], a model predictive control approach combined with mixed-integer linear programming (MILP) is used to solve the problem of efficiently optimizing microgrid operations while satisfying a time-varying request and operation constraints. In most of these papers, the PV system can provide extra solar power back to grid and no solar power is wasted.

This paper deals with a PV systems with storage for residents, which can not send power back to grid. Compared with the work mentioned above, the model of the system in this work is novel. To optimize the operation of the system, it compares a rule-based operation method and model predictive control operation method. The model and MPC operation method are proved to be reliable with the experiment data taken in Nansha, Guangzhou, China. Table.1 explains some important parameters in the paper.

The rest parts of the paper are as follows: Section 2 presents the System modeling. Section 3 presents Operation Strategy and Experiment. Section 4 presents the simulation result. Section 5 concludes the study and introduces the future work.

Table 1. PARAMETERS

Parameters	Description
η_g	efficiency of rectifier
η_i	efficiency of inverter
$\triangle t$	time interval [h]
$P_{loadmax}$	the maximum load power[kW]
$P_{loadmin}$	the minimum load power[kW]
$P_{solarmax}$	the maximum solar power [kW]
SOC_{max}	the maximum level of SOC
SOC_{min}	the minimum level of SOC
P_{bat}	battery power [kW]
I	battery current[A]
V_{bat}	battery voltage[V]
P_{batmax}	the maximum charge power[kW]
$P_{batdmin}$	the maximum discharge power[kW]
P_{sys}	power cost by system without load[kW]
P_w	wasted solar power[kW]
P_{grid}	power form grid [kW]
σ	binary variable
δ	binary variable

2. SYSTEM MODELING

2.1 Presentation of the System

We consider a small, residential level energy system. A scheme of the studied system is presented in Fig. 1. There are several loads in the system and each of them can choose two power sources: power from grid or power from inverter. In this work, the inverter is off-gird and cannot be connected with the grid, thus the system is unable to send extra power back to the grid. And for each load, it cannot use the power from grid and power from inverter at the same time.
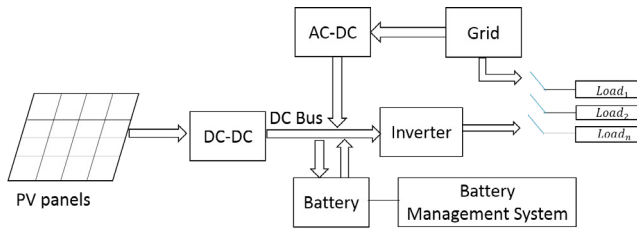
Fig. 1. System Framework

The PV panels are controlled by a solar controller, which is a DC-DC converter to maximize the output power of the PV panels. The grid is connected via a AC-DC rectifier to the DC bus. The battery management system is a monitor and controller for batteries and collect the information of current, voltage, state of charge(SOC)of batteries. Based on these information, we can decide the strategy of charging and discharging of batteries and operation of system to optimize the profit for customers.

Note 1: The inverter and gird can provide power to load seperately, however, as the inverter cannot be conneted with the grid, they can not provide power at the same time. Generally speaking, if the solar power is sufficient or the SOC(state of charge) of battey is high enough, such as at daytime in sunny days, we can choose to use the inverter to provide power to load. If the solar power is minor and battery SOC is low, we should switch to use the grid alone to provide power to load. However, this may not always be the optimal operation strategy. The operation strategy will be discussed in details in Section 3.

Note 2: Since the power flow can only go from grid to inverter, we may wonder what will happen if the battery is fully charged and the PV generation exceeds the load requirement. In practice, the voltage of DC bus is determined by the battery voltage, which is related to the state of charge of the battery. When the battery is fully charged, the voltage of the DC bus is higher than the threshold of DC-DC converter and the output of the solar panel will be limited. For example, in our experiment, the threshold of the DC-DC converter is 54.4V, when the battery voltage is close to 54.4V, the solar controller(DC-DC converter) will limit the output current of the solar panel to protect batteries. However, this will result in a waste of the solar power $P_w(t)$. In our optimal operation strategy, we will try to find an optimal battery charge/discharge and operation strategy to prevent the waste of solar power.

In accordance with the two operation mode, for each load, there exists two power balance function:

1) When we choose to provide power to load $P_{load_m}(t)$ by inverter, the laws of physics require the power balance in the system described as follows:

$$\eta_g P_{grid}(t) + P_{solar}(t) = P_{bat}(t) + P_{load_m}(t)/\eta_i$$
$$+ P_{sys} + P_w(t)$$

$P_{bat}(t)$ is positive when batteries are charged and negative when batteries are discharged.

2) When we choose to provide power to load $P_{load_m}(t)$ by grid alone, the two power balance in the system are as follows:

$$P_{grid1}(t) = P_{load_m}(t)$$

$$\eta_g P_{grid2}(t) + P_{solar}(t) = P_{bat}(t) + P_{sys} + P_w(t)$$

$P_{grid1}(t)$ is the power provided to the load from grid. P_{grid2} is the power provided to charge the battery from grid. The total power from grid $P_{grid}(t)$ is

$$P_{grid}(t) = P_{grid1}(t) + P_{grid2}(t)$$

Thus,

$$\eta_g P_{grid}(t) + P_{solar}(t) = P_{bat}(t) + \eta_g P_{load_m}(t) + P_{sys} + P_w(t)$$

When the battery is fully charged and the PV generation exceeds the load requirement, we will get the wasted power $P_w(t)$, thus

$$P_w(t) \geq 0$$
$$P_{solar}(t) - P_w(t) \geq 0$$

When we choose to provide power to load by grid alone,

$$P_{grid}(t) - P_{load_m}(t) \geq 0$$

Definition: when we choose to provide power to load by grid alone, $\sigma(t) = 0$; when we choose to provide power to load by inverter alone, $\sigma(t) = 1$.

Then the power balance function is as follow:

$$\eta_g P_{grid}(t) + P_{solar}(t) = P_{bat}(t)$$
$$+ ((1/\eta_i - \eta_g)\sigma_m(t) + \eta_g)P_{load_m}(t) + P_{sys} + P_w(t)$$

If there are n loads in the system, then the power balance function and the constraints are as follows:

$$\eta_g P_{grid}(t) + P_{solar}(t) = P_{bat}(t) + \sum_{m=1}^{n}((1/\eta_i - \eta_g)\sigma_m(t)$$
$$+ \eta_g)P_{load_m}(t) + P_{sys} + P_w(t)$$
$$P_w(t) \geq 0$$
$$P_{solar}(t) - P_w(t) \geq 0$$
$$P_{grid}(t) - \sum_{m=1}^{n}(1 - \sigma_m(t))P_{load_m}(t) \geq 0$$

In this work, we don't consider the capital cost of the system. Thus, the only cost of the system is the bill of electricity we buy from the grid. It's easy for us to get the electricity price from grid at time t, assume it's Price(t). For instance, in our experiment in Guangzhou, China, if we choose the time-of-use electricity, the daily price for electricity in 24h can be divided into five period as Table 3. Then the energy bill at time t from the grid should be

$$C(t) = Price(t)P_{grid}(t)$$

In the following paper, we will adopt a slotted time model, all the system constraints as well as decisions are provided for discrete time intervals of equal length. More specifically, each day is divided into T time slots, each of duration is $\triangle t$. We use T=24 hours and $\triangle t = 1$ hour. The goal of our optimal operation strategy is to minimize the total cost for customers.

2.2 Battery model

Common commercial Storage elements include lead-acid batteries, Lithium(Li-ion) batteries, metal air batteries NiMH batteries, and super capacitors. This study has been performed with Lithium(Li-ion) batteries. There are many models used to simulate the electric behavior of a battery. For example, chemical reaction process, equivalent circuit models [6]. In this work, an open-circuit-voltage (OCV) and ohmic resistance based battery model is chosen for the scenario simulation, where OCV can be measured and established as a function of battery SOC [7].