A new optimized control system architecture for solar photovoltaic energy storage application

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Abstract: Aiming at the high-efficiency charging application requirements of solar photovoltaic (PV) energy storage systems, a novel control system architecture for solar photovoltaic energy storage applications is presented. The system dynamically adjusts its working state according to the real-time power generation data of solar photovoltaic output, thus realizing the hierarchically combined operating mode and operation state changes when applying different environmental parameters. In addition, the corresponding algorithm was proposed to achieve efficient control. Compared with the conventional control system architecture, the developed circuits can realize high-efficiency solar charging and multi-mode flexible applications. An experimental prototype is implemented and the test results are derived to verify the effectiveness and superiority of the proposed system, which provides the new ideas and references for the application of solar photovoltaic energy storage systems.

Keywords: solar photovoltaic energy storage, control system architecture, multi-mode flexible applications, high efficiency charging

Classification: Power devices and circuits

1. Introduction

Due to the volatility and intermittent characteristics of solar photovoltaic power generation systems, the energy storage can increase the applicability and flexibility of solar photovoltaic power generation systems [1, 2, 3]. An energy storage system involves the charge/discharge control and energy management units. How to efficiently control the solar charge storage has become the core and key of entire system design. At present, many researchers have conducted extensive research on this kind of solar photovoltaic system, and developed the corresponding products.

In [4], a photovoltaic battery energy storage system for low-energy buildings is analysed, and the corresponding control strategy is proposed. Besides, the modal analysis and study of a solar photovoltaic system coupled with lead acid battery is studied in [5]. In addition, a typical photovoltaic energy storage system is introduced in [6], which can use the coupled photovoltaic battery energy storage charging system at the DC side, with the corresponding dynamic control strategies proposed. In [7], a bidirectional DC-DC conversion-based DC-bus charging controller was designed to realize the management and control of batteries, and explained its control system and power management in different states of irradiance and SOC [7]. Most of the existing photovoltaic energy storage systems are based on a single centralized conversion circuit, and many research activities concentrate on the system management and control circuit improvement.

For the purposes of avoiding and dealing with the shortages of using a single control circuit, and increasing the system volume, the parallel- and series-connected circuit-based solutions are proposed and designed. The authors in [8, 9, 10, 11, 12] designed a type of parallel-connected energy storage module to increase the storage volume and discharging power requirements [8].

In some specific applications, the parallel modular architecture exhibits better scalability and reliability [10, 11]. It can be seen that the parallel-connected architecture has advantages over the single electric circuit one in terms of either the circuit applicability or reliability. However, most existing research activities in this field focus on the discharging process of storage batteries, without paying much attention to the charging applications. Especially for the critical application scenarios such as photovoltaic renewable energy, it has great value to develop optimized charging storage technologies. Aiming at the high-efficiency charging application requirements of solar photovoltaic energy storage systems, a novel control system architecture for solar photovoltaic energy storage applications is presented.

The structure of this paper is arranged as follows. Section 2 introduces the system constitution and its design. In Section 3, the illustrations and analysis of the proposed control algorithm are presented by combing the characteristics of PV energy storage systems. Moreover, the verification of the designed system and its control algorithm is carried out through experiments and engineering applications in Section 4.Finally, the conclusions are given in Section 5.

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2. System constitution and architecture

2.1 Solar PV energy storage system
A solar PV energy storage system outputs DC electric power by utilizing the PV effect of solar energy. System constitution of solar PV energy storage system as shown in Fig. 1, the DC power is output to the storage battery for the charging purpose after DC-DC conversion control. The storage battery is used as the charging load to store, transform and take advantage of the solar power. Such a system is one of the main formats of utilizing solar power generation, which is widely applied in the engineering field.

2.2 Conventional system constitution
A conventional solar energy storage-charging system is composed of a single DC/DC conversion circuit, which is displayed in Fig. 2. The electric power output through PV conversion of solar PV components charges the storage batteries after the conversion circuit. According to different power generation states of solar batteries and working conditions of storage batteries, the conversion circuit works in different operation conditions. Therefore, the power converter may not work at the optimal power-matching state, which affects the efficiency of power converter and decreases the system flexibility.

When the system operates with low power, the power conversion efficiency decreases. At the output terminal of the power converter, the required charging voltage and current change according to the different states of the connected storage batteries, which also affects the working efficiency and states of the power converter. The above-mentioned factors cannot guarantee the power converter and the whole system are at the optimal working state. In addition, for medium and large application systems, multiple storage batteries need to be series or parallel connected.

However, because of the differences in the parameters and performance of individual batteries, mixing individual conversion circuits will result in the phenomena such as charging imbalance, which affects the efficiency, battery balance and application flexibility of the whole system.

2.3 Novel system architecture
In address to the deficiencies of the existing system circuit structure, a novel solar power application circuit that can be detailed hierarchically is designed, which is shown in Fig. 3. Compared to the centralized conversion circuit architecture, the novel circuit structure can realize hierarchically detailed management and control.

Therefore, real-time and dynamic adjustment of the circuit working states can be obtained by precisely matching the real-time power generation states of solar PV components with the states of terminal storage batteries. Besides, the optimal electric circuit state matching can be realized, increasing the circuit working efficiency and the energy efficiency of the whole system.

After adopting the designed novel solar PV energy storage charging management and control system, the detailed and accurate management of the PV power generation and storage sides can be realized through the designed multi-level cascaded circuit. In addition, the different states of real-time power generation and storage batteries are combined to implement reasonable and accurate allocation and management, achieving the optimization of high efficiency and reliability for solar energy charging management.

3. Proposed control system strategy
Aiming at the designed novel circuit topology, the corresponding control strategies and algorithmic solutions are proposed to realize the highly efficient and precise control of the novel circuit topology. Combine the real-time solar power generation parameters and battery states, the optimization can be implemented to determine different working states and control outputs.

The equivalent circuit of a typical solar PV battery is displayed in Fig. 4. The output $U_{PV}$ and $I_{PV}$ relationship of the equivalent electrical circuit are expressed as Eq. (1) and Eq. (2), respectively:

$$I_{PV} = I_{ph} - I_{pd} - I_{sh}$$ (1)
where $I_{pv}$ is light-generated current, $I_{sh}$ is short-circuit current, and $I_d$ is the current shunted through the intrinsic diode, $V_{oc}$ is the voltage across the solar cell.

According to $U_{pv}$ and $I_{pv}$, the relationship of power $P_{pv}$ for a solar cell is expressed as [12, 13, 14, 15, 16]:

$$P_{pv} = U_{pv} \cdot I_{pv}$$

Where $G$ is random irradiance, $G_{ref}$ is standard irradiance, $\alpha_{sc}$ is the temperature coefficient of short-current, $T_{ref}$ is the reference temperature of the PV cell, $T$ is the junction temperature, $q$ is the electron charge, $k$ is Botzmann’s constant, $A$ is diode ideality factor.

According to Eq. (3), it can be seen that the output power of PV power generation is affected by the environmental factors such as illumination intensity and temperature, which has relatively strong environmental volatility. The solar PV power generation is affected by the environmental parameters such as illumination intensity and real-time temperature [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Under different illumination intensities, different seasons and time periods, certain volatility and randomness occur in the generated PV power as shown in Fig. 5 [14, 15].

For a PV-storage engineering application system as shown in Fig. 6, since the efficiency of the whole storage-charging conversion circuit is affected by the differences in battery manufacturing techniques and parameters for the storage battery at the load side, the detailed classification of charging management circuits can be implemented from the energy utilization and storage sides.

In address to the detailed classification and control of different states of storage batteries, the proposed control algorithm is shown in Fig. 7. The circuit state control decision is made according to different power generation parameters and the states of storage batteries, and then the final charging strategy is obtained.

Based on solar energy optimization and management, the specific steps are as follows:

**Step 1: Judge the charging requirement**

After system completing initialization, the controller collects and calculates the charging requirement status of storage batteries, reading the SoCs of batteries, then calculating the minimum total charging power requirement ($P_{Total_{BAT}}$) and judge if the energy storage system needs to be charged, either the standby mode or the charge mode. If $P_{Total_{BAT}} > 0$ charging is needed, the system enters the PV power generation charging control mode. On the other hand, the storage system doesn’t need to be charged, then it enters the standby mode state.

**Step 2: Collect real-time photovoltaic power generation data**

When the energy storage system is determined to enter the charging mode, collect the real-time data of PV power generation and analyze/calculate the real-time solar power generation data ($P_{PV}$), then calculate the minimum charging power requirement ($P_{BAT_{ch}_{min}}$) for energy storage according to Eq. (4).

$$P_{BAT_{ch}_{min}} = \text{Minimum}\{P_{BAT_1}, P_{BAT_2}, \ldots, P_{BAT_n}\}$$

If $P_{PV} \geq P_{BAT_{ch}_{min}}$, then charge according to the preset priority and determine the charging sequence, otherwise enter return status.

**Step 3: Calculate the charging sequence at the storage battery side**

Sort the charging sequence, and carry out charging management based on the principle of first charging the battery unit with the lowest electric quantity as Eq. (4).

$$\text{SoC}_{Lowest} = \text{Minimum}\{\text{SoC}_{L_1}, \ldots, \text{SoC}_{L_n}\}$$

Open the corresponding DC/DC charging modules and...
channels and realize on-demand charging.

**Step 4: Determine if there is information of remaining electric quantity**

\[
P_{PV} - \sum P_{BAT, ch,i} \geq P_{BAT, ch, min} \tag{6}
\]

According to Eq. (6), calculate the information of remaining PV power output \((P_{PV, R})\), if there is information of remaining electric quantity, then remove the sequence of charging battery sets based on the above equation, and derive the new charging sequence \(SoC\_Lower\) and charge after sorting again. Charge the batteries according to the new charging sequence.

Compared with the conventional charging method, a single conversion circuit is used for charging regardless of the size of the photovoltaic power generation, and the batteries is not subdivided and optimized according to their respective states. Especially under low photovoltaic output power condition, the converter maintains operate at light-load state, the efficiency is relatively low and the single battery inconsistency also affects the charging of the entire system, which limits the application of charging optimization. In addition, in the entire charging process, the conventional converter circuit needs to keep working will affect the operating life.

**4. Experimental verification and analysis**

Experimental verification platform shown in Fig. 9 is built, the outputs of PV modules are simulated by the Chroma PV program control, and the storage load is composed of three sets of individual 12V/12AH batteries. The charging control circuit is made up of individual Buck circuit modules, and the MCU uniform control is adopted for the controller.

The SoC can be obtained according to the commonly used method. Specifically, the dynamic estimation of SoC is carried out through collecting the real-time charging current \(i(t)\) and efficiency \(\eta\) [17, 18, 19, 20] as shown in Eq. (7), then the control decision is made.

\[
SoC_{\_i0}(t) = SoC_{\_i0}(t_0) + \frac{1}{C_{\_i, N}} \int_{t_0}^{t} \eta(t) \times i(t) dt \tag{7}
\]

According to the control algorithm of Fig. 9, measure and calculate the \(P_{Total, BAT}\) in the initial state is 90 W and \(P_{BAT, ch, min}\) is 20 W, their initial SoCs are respectively 20%, 30%, 50% and 70%. The experiment waveforms simulating different operating states are shown in Fig. 10.

Fig. 10(a) shows the control and output experiment waveforms of a single battery module in the charging control mode. The \(P_{Total, BAT} = 90\) W > 0, the system enters charging mode, the emulated PV power output increases at \(t_1\), and the output current increases. The system first detects the increase of output current, when the \(P_{PV} = 20\) W equal to \(P_{BAT, ch, min}\), and then the optimal charging is implemented according to the scheduled charging priority, sorting initial state, the \(SoC\_Lowes\) single battery module 1# is charging and \(K1\) is ON.

Fig. 10(b) shows the experimental results for the PV output power increases from 20 W to 42 W at \(t_2\), in which case, the \(P_{PV, R}\) is 22 W, which can charge for two sets of storage battery modules and \(K2\) is ON. Fig. 10(c) shows the working characteristics at full power \(P_{PV}\) is increased and more than \(P_{Total, BAT}\). Consequently \(K3\) and \(K4\) are respectively turned on at \(t_3\) and \(t_4\) to charge the battery at full power, and it can be seen that four sets of storage battery modules can charge synchronously.

It can be seen that the normal operation can be obtained based on the preset control algorithm in different PV output

![Fig. 8](image)

**Fig. 8** Charging efficiency curves: (a) conventional control; (b) proposed optimal control strategy.

![Fig. 9](image)

**Fig. 9** Experimental verification and test platform.

![Fig. 10](image)

**Fig. 10** Experimental results of different PV output power: (a) \(K1\) ON; (b) \(K1, K2\) ON; (c) \(K1, K2, K3, K4\) ON.
power conditions, and the synchronous charging of a single module or multiple modules in different power ranges can be realized.

In order to further verify the control effects of the designed optimal charging control circuit, the engineering application experiment for an outdoor practical PV-storage system is implemented in Fig. 11. The maximum output power of PV components in engineering applications is 100 Wp, and its rated working voltage and current are 17.5 V and 5.71 A, respectively.

According to the real-time measured PV module output, the storage battery 1 is constantly charged, and the storage battery 3 starts being charged in sequence with the increases of illumination and PV output current. After a certain period of time of engineering experimental operation, it can be seen that excellent engineering application effects are achieved for the designed system architecture.

In Table I, the comparison between the conventional system architecture and optimized control system is reported, in contrary to a single DC-DC converter system, which has a low working efficiency under the low-power small-current working condition (most PV-battery system engineering scenarios), the designed system optimally distributes the power, thus ensuring a relatively high overall average working efficiency.

5. Conclusions

According to the environmental variation characteristics of PV power generation and the engineering application requirements of energy storage and charging, a novel PV charging circuit is designed, which adopts the group and split charging strategies. The real-time parameter characteristics of PV power generation and dynamic SoC state parameters of storage batteries are fully considered to charge with respect to the requirements, thus effectively avoiding the disadvantages of low working efficiency and utilization flexibility of a single conversion circuit in all working conditions. Meanwhile, it can match the engineering applications of the batteries with different volumes, resolving the charging balancing issue caused by using different batteries. Besides, group charging can be applied to different batteries, which eliminates the mutual effects and disturbances between battery sets, increasing the flexibility and reliability of application systems. Additionally, because multiple groups of charging circuit structures are adopted, the equivalent working time of a single conversion circuit is reduced, thus increasing the reliability of the whole system. Combining the proposed charging control algorithm that considers real-time PV power generation parameters, the energy efficiency of the whole PV utilization system is optimized, and the utilization efficiency of PV power generation. The designed circuit and scheme are verified by experiments, which provides new ideas and solutions for the design of novel PV storage and charging systems.

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