INTRODUCTION

The tension between power supply and demand is exacerbated for the increasing global refrigeration demand year by year. Therefore, refrigeration system driven by solar energy becomes one of the promising approaches to reduce or partially replace conventional refrigeration systems driven by power grid under the pressure of environmental protection and building energy conservation. Classified by operation mode, solar refrigeration is mainly composed of solar thermal refrigeration, solar photovoltaic refrigeration, and hybrid system consisting of solar thermal and photovoltaic energy. Nowadays, the cost-effective advantage of photovoltaic (PV) refrigeration is prominent for the low PV module price. Therefore, PV refrigeration can attract many scholars for not only its considerable economic. More importantly, PV refrigeration reduces the dependence on power grid so as to effectively alleviate the contradiction between power supply and demand. Besides, vapor compression refrigerator and air conditioning are important household appliances to improve people’s living standards, so most of the research work were focused on the PV refrigeration system.
First, the possibility of refrigeration system driven by photovoltaic energy was put forward and the thermodynamic properties were analyzed too. Results revealed that the energy matching relationship between PV arrays and refrigerator, refrigerator operation mode, and evaporator structure should be further optimized. To reduce energy loss in storage process, three independent compartments were designed and the cooling distribution automation of each storage space was optimized by automatic control. Moreover, component energy loss of refrigerator was studied and results showed that power cable and wire brought a certain amount of energy loss. In order to optimize the energy matching relation among PV refrigeration components, energy conversion and transformation characteristics were dynamic simulated under variable load current condition and experimental test was also carried out. In order to ensure the stable operation of refrigerator, all of the energy systems were assisted with battery bank or power grid.

There were also many researches about PV air conditioning. Household power grid-connected photovoltaic air conditioning system was built, and the comparative study on the basic building and energy saving building was investigated. Results showed that photovoltaic air conditioning system played an important role in building energy conservation. In order to save investment cost, the optimization on energy supply, control strategy, and air conditioning motor operating speed were carried out. Moreover, the simulation carried in Jaipur with RETScreen software showed that the expensive battery bank employed as energy storage installation was the huge obstacle for the large-scale application of PV refrigeration. So, the inconvenience of grid-connected PV air conditioning and high cost of battery bank assisting PV air conditioning should be further studied.

On the other hand, many researchers are constantly trying to explore other technology, which was mature, simple, and low cost to eliminate the fluctuation impact on PV refrigeration system. Cherif first proposed a refrigeration system directly driven by photovoltaic energy without battery bank. Experimental results showed that refrigerator could operate under different weather conditions. The refrigeration power consumption was 1 kWh(-day)\(^{-1}\), and the annual solar assurance rate was 87%, but the refrigerator could not operate during night for the absence of energy storage device. Here, ice thermal storage, widely used in conventional refrigeration field to transfer the peak power load of power grid for its mature technology and low price, attracted researchers’ attention. So, phase change material (PCM), especially ice thermal storage, was employed in air conditioning in recent years.

Ice thermal storage was first applied in PV directly driving refrigerator by Axaopoulos. Results showed that refrigerator compressor was of variable speed and ice produce of the refrigerator reached 17 kg, but the refrigerator started and stopped frequently for the instantaneous variation of solar irradiance. System COP was low, and a part of the solar energy in low irradiance was abandoned. Ming Li team also focused on the studies about component energy matching, efficiency improvement and directly driven control of PV refrigeration, but the researches on the influence caused by instantaneous solar irradiance on compressor motor and refrigeration characteristics have not been reported.

The previous researches confirmed the feasibility of the coupling of the application of PV directly driven and PCM energy storage in the field vapor compression refrigeration, but some research work have not been reported so far on the energy storage and refrigerating characteristics of household PCM energy storage air conditioning system directly driven by the distributed PV arrays under different operation modes, the influence of instantaneous and intermittent solar energy, and the comparative analysis of the refrigeration characteristics of different drive mode. So, a 3HP household PCM air conditioning system directly driven by photovoltaic energy is designed and constructed, and the refrigeration characteristics of household PCM air conditioning operating in four typical conditions are tested by experiment in this paper. The simulation model is designed to analyze the directly driven characteristics. After that, based on the irregular instantaneous variation characteristics of solar irradiance, the optimization of MPPT control strategy for photovoltaic arrays and the matching performance between MPPT control and variable frequency (VF) control of compressor motor speed are analyzed in order to obtain shorter response time of MPPT and smaller fluctuation amplitude of motor speed. Finally, the control strategy of compressor motor is optimized, so that more solar energy was converted and transferred into thermal energy stored by PCM. Research results will provide support for the popularization and application of PCM storage air conditioning system directly driven by distributed photovoltaic energy.

## 2 | ICE THERMAL STORAGE AIR CONDITIONING SYSTEM DIRECTLY DRIVEN BY DISTRIBUTED PV ARRAYS

### 2.1 | Working principle

Distributed photovoltaic energy, ice making refrigerator, and large temperature difference cold water cooling system were three main subsystems of ice thermal storage air conditioning system directly driven by distributed PV arrays, and the working principle was given in Figure 1.
As shown in Figure 1, the distributed photovoltaic energy system converted solar energy into electricity to drive the refrigerator directly without battery bank. Because the sun’s rays shining on the earth’s surface are blocked and scattered by clouds and dust in the air, the solar irradiation received by PV arrays was instantaneous and intermittent. Therefore, the PV arrays’ output power fluctuated at all times in the directly driven system, which had a certain impact on the stability and reliability of load operation. The variable frequency (VF) load just adapted to the fluctuation of the output power of PV arrays. In the distributed photovoltaic energy system, inverter & controller-integrated machine, coupled with maximum power point tracking (MPPT) and frequency control technology, was employed to ensure that the refrigerator could adaptively operate on the maximum power point of PV arrays. The inverter also converted the DC power output by PV arrays into AC power to drive the power consumption units. In order to adapt to the fluctuation characteristics of PV arrays output power, VF refrigerator was adopted, the refrigerator and cold storage system consisted of VF compressor, condenser, throttle valve and, immersed coil evaporator. In refrigeration cycle, saturated gaseous refrigerant was compressed to high pressure and high temperature gaseous refrigerant. After that, vapor refrigerant was sucked into condenser and vapor was condensed into liquid refrigerant by air forced through condenser surface with fan. Meanwhile, refrigerant fluid was throttled into low temperature and low pressure by throttle valve. Next, refrigerant fluid flowed into coil evaporator immersed in PCM material tank to absorb heat. After that, heated liquid refrigerant vaporized in evaporator and was sucked into gas-liquid separator and compressor. During refrigeration, the PCM material temperature around immersed evaporator gradually dropped. When the temperature dropped below the freezing temperature, PCM material solidified. The cold was stored in the phase change process. Many materials such as inorganic substances, organic alcohols, and hydrated salts can be used as phase change materials for cold storage. Water with stable performance, high latent heat value, and low price was selected as phase change materials in this paper. In water tank, water transformed into ice wrapping around evaporator in cold storage process. With the refrigerating time increase, the ice thickness and storage cold were gradually increased along with time, and the cold was stored with ice in tank. In cooling process, the cold water stored in tank was transferred into fan coil to service for user by water pump. The water then returned to the water tank. At this time, a cooling cycle was completed. The water temperature at the inlet of water tank is higher than that at the outlet, so the stored ice gradually absorbed heat and melted. According to the working principle, a 3HP ice storage air conditioning directly driven by distributed PV arrays was constructed, and the experimental platform was shown in Figure 2.

2.2 Main component parameters

The main component parameters were shown in Table 1. 3HP is the most used in household refrigeration system,
which was adopted in this paper; the maximum design capacity of the ice thermal storage tank was the ice making capacity of the 3HP refrigerator continuously and stably operating for 12 h. The calculated tank capacity was about 653 L. So, the 658L water tank was employed. Moreover, in order to prevent all of the water from freezing, the automatic protection device was adopted. In photovoltaic energy, PV arrays consisted of 32 monocrystalline PV modules with two PV arrays in parallel and sixteen PV modules in series, and every PV module peak power was 190 W. PV arrays output voltage and current ranges were 580~700 V and 0~11 A, respectively. All of the characteristic parameters of main component parameters were tested and monitored by experiment. First, climatic conditions, such as solar irradiance $G$, ambient temperature $T_1$, and wind speed $v$, were measured by pyranometer, temperature sensor, and wind speed transducer, respectively. Meanwhile, electrical performance parameters of PV arrays and refrigerator were tested and monitored by Solar 300N. In addition, refrigerator operation conditions were

![Diagram of the system](image-url)

**Figure 2** 3HP ice storage air conditioning directly driven by distributed PV arrays

| TABLE 1 Main component parameters |
|-----------------------------------|
| **System**                      | **Component**  | **Model**   | **Main components**                          |
|----------------------------------|----------------|-------------|-----------------------------------------------|
| Distributed photovoltaic energy system | PV module     | ST*190      | $V_{oc}$: 44.5 V, $I_{sc}$: 5.52 A, $V_{mp}$: 36.5 V, $I_{mp}$: 5.21 A, $S_c$: 1.125 m². |
| Inverter-controller integrated machine | JN-5000 | | Power: 5 kW, DC input voltage: 600 V, AC output voltage: 380 V, output frequency: 0 Hz –50 Hz. |
| Refrigerator and cold storage system | Refrigerant | R22         | Molecular formula: CHClF₂, boiling point: −40.82 °C, critical temperature: 96.15 °C, critical pressure: 4.75 MP. |
| Refrigerator                      | QK-2.2        |             | Power: 2.2 kW, refrigerating capacity: 6.8 kW. Diameter: 0.66 m, height: 1.5 m, capacity: 500 kg. |
| Cold storage tank                 |               |             |                                               |
| Cooling supply system             | Water pump    | PUN-200EH   | Input power: 400 W, rated running speed: 2850 rmin⁻¹, lift: 15 m, flow: 38 Lmin⁻¹, pipe diameter: 25 mm. |
| Fan coil                          | FP-170LZ      |             | Power: 98 W, cooling capacity: 7.2 kW, heat capacity: 12.75 kW, water flow: 1480 kgh⁻¹, air flow: 1700 m³h⁻¹. |
controlled by inverter and controller integrated machine. Meanwhile, the running speed and frequency of refrigerator were also monitored and tested by inverter and controller integrated machine.

Besides, some other important parameters such as temperature $T$ and pressure $p$ were also measured by T-type thermocouples and piezometer. The installation positions of temperature sensors were also shown in Figure 1. $T_1$, $T_2$, $T_3$, $T_4$, $T_5$, $T_6$, $T_7$, $T_8$, $T_9$, and $T_{10}$ were, respectively, ambient temperature, compressor exhaust temperature, condenser outlet temperature, evaporator inlet temperature, evaporator outlet temperature, storage ice temperature, backflow water temperature of the tank, outflow water temperature of the tank, fan coil outlet temperature, and indoor air temperature. $p_C$ and $p_E$ were compressor outlet pressure and evaporator outlet pressure, respectively. Finally, the electric energy consumption $W$ was also measured by Solar 300N.

### 2.3 Operation conditions

According to the cold demand period of human living, two kinds of cooling modes, cooling service during daytime or night were proposed. In order to analyze refrigerator-operating performance, two driving modes, such as photovoltaic energy and power grid, were also studied by experiment. So, four operating conditions were designed as follows:

1. **Operating condition 1 (ice storage + photovoltaic energy)**. Directly driven by photovoltaic energy, refrigerator operated, and cold water was stored during daytime. When cold load increased in night, the stored was pumped out to service for user.
2. **Operating condition 2 (water chiller air conditioning + photovoltaic energy)**. Directly driven by photovoltaic energy, chiller operated and cold water was pumped to the fan coil to service for users at the same time. Meanwhile, the surplus cold water was stored in tank, which was also called out-of-the-box working condition.
3. **Operating condition 3 (ice storage + power grid)**. Driven by power grid, refrigerator operated and cold was stored, and this cooling mode could transfer cold in time and space to use valley power to fill peak power of power grid.
4. **Operating condition 4 (water chiller air conditioning + power grid)**. Driven by power grid, refrigerator and fan coil operated at the same time.

### 3 EXPERIMENT AND RESULTS

#### 3.1 Experiment

First, climatic conditions were tested and shown in Figure 3A, and refrigerator was then directly driven by PV arrays during daytime without supplementary energy battery bank. Some main components performance, such as compressor, condenser, and evaporator, were shown in Figure 3B. At the same time, the temperature variations of the evaporator surface and the condenser fan outlet were also shown in Figure 3B. During night, the cooling supply process was turned on.

Refrigerator operated at 08:31 and ice making process began at 11:00, ended at 16:20. In ice making process, it was observed that the evaporator inlet and outlet average temperatures were, respectively, $-6.4^\circ C$ and $-2.4^\circ C$ with $4.0^\circ C$ temperature difference. At the same time, the evaporator surface average temperature was about $-4.3^\circ C$, and the ice production was about 180 kg.

The cooling supply process began at 16:20 and ended at 08:31 the next day. This moment, indoor temperature
was the same as the tank temperature. Results revealed the stored cold was completely released. In cooling supply process, the cold water was pumped into the fan coil and the cold was exchanged by indoor air. Temperature difference between backflow water and outflow water of tank was about 12°C, which was called large temperature difference cooling. This moment, the indoor temperature $T_{10}$ dropped rapidly and the minimum temperature can reach 17.4°C. As shown in Figure 3B, the cooling supply process was made up with ice melting (16:20–18:06, 107 min), cold water (18:07–08:31, 564 min), which had about 11-h cooling supply capacity with about 25°C ambient temperature in Kunming China.

High solar irradiance region was high latitude and altitude with a large temperature difference between day and night. Usually, the cold demand during daytime was greater than night. So, operation condition 1 was not suitable for these regions. Therefore, the other condition 2, directly driven by photovoltaic energy, refrigerator, and cooling system operated at the same time in daytime, was employed and studied in these regions. Experimental results were also shown in Figure 4.

Water chiller air conditioning mode (condition 2) was made up with temperature descending stage (09:12–10:20, 68 min) and stable stage (10:21–16:30, 249 min) distinguished as shown in Figure 4B. In temperature descending stage, the temperatures of evaporator inlet, evaporator outlet, and storage water decreased along with time step by step. Before stable stage, the average temperature difference between evaporator inlet and outlet remained the same about 4.1°C, which indicated that most of the cold quantity produced by evaporator immersed in tank was taken away by water. In addition, experimental results also showed that chiller refrigeration capacity was higher than cold load. At the same time, the temperature difference between evaporator surface and evaporator inlet was almost unchanged, which revealed that most of the cold water around evaporator was pumped out of tank to service for user rather than frozen around evaporator.

In stable stage, the temperatures of evaporator inlet, evaporator outlet, and evaporator surface almost kept the same. Meanwhile, cold supply and cooling load reached the balance and some cold was stored with cold water or ice. When cold demand indoor was met, all of the temperatures basically remained stable. At this time, the refrigerating capacity was greater than the cold demand. Therefore, cold storage process began and water temperature reached the critical temperature of the liquid-solid phase of water.

Experimental results of refrigerator driven by power grid were shown in Figure 5. Ice making and cold storage mode (condition 3), water chiller mode (condition 4) were given by Figure 5A,B, respectively. Compared with photovoltaic driving mode, the operation performance of ice storage refrigeration system driven by power grid were more stable and the characteristic curves hardly fluctuated. In Figure 6A, the refrigerating time lasted 312 min (08:12–13:25) and 143 minutes (11:02–13:25) of which was the ice making time. The ice produce was 78 kg. Operating in condition 4, the water chiller was stable and efficient. In temperature descending stage, cooling capacity was higher than the load. In stable stage, cold supply and cooling load reached the balance and some cold was stored with cold water or ice. At this time, the refrigerating capacity was greater than the cold demand. Therefore, cold storage process began, and water temperature reached the critical temperature of the liquid-solid phase of water. So, between 13:00 and 14:08, the mixture of ice and water existed around evaporator.

![Figure 4](image-url)

**FIGURE 4** Ice storage refrigeration system directly driven by PV arrays with condition 2

**A** Climatic conditions

**B** Characteristics curves
3.2 Results analysis

Photoelectric conversion efficiency of PV arrays was calculated by:

$$\eta_{pv} = \frac{W_{pv}}{G_{Sc}} \cdot 100\%$$  \hspace{1cm} (1)

$W_{pv}$ was measured by Solar 300N.

Electric energy utilization efficiency of refrigerator was given by:

$$\eta_{r} = \frac{W_{r}}{W_{pv}} \cdot 100\%$$  \hspace{1cm} (2)

In formula (2), $W_{r}$ was measured by Solar 300N too.

The cold stored in tank was calculated by:

$$Q_{st} = C_{wm}m_{w}(T_{wb} - T_{wa}) + C_{mw}m_{w}(T_{wb} - T_{i}) + m_{i}h_{i} + C_{mi}m_{i}(T_{i} - T_{ia})$$  \hspace{1cm} (3)

Refrigerator refrigerating coefficient of performance was given by:

$$(COP)_{r} = \frac{\dot{m}h_{r}(h_{e} - h_{th})}{f_{R}W_{r}}$$  \hspace{1cm} (4)

Calculation formulas of $h_{e}$ and $h_{th}$ were given as follows:

$$h_{e} = 0.6143T_{5} + 398.05$$  \hspace{1cm} (5)

$$h_{th} = 1.4279T_{3} + 199.24$$  \hspace{1cm} (6)

Refrigeration coefficient of performance of refrigerator directly driven by photovoltaic energy was shown as follows:

$$(COP)_{pv} = \eta_{r}\cdot(COP)_{r}$$  \hspace{1cm} (7)

Refrigerator refrigerating coefficient of performance based on the solar energy accepted by PV arrays was calculated by:

$$(COP)_{s} = \eta_{pv}\cdot(COP)_{pv}$$  \hspace{1cm} (8)

In cooling supply process, the cooling capacity provided with cold storage tank was calculated by:

$$Q_{cs} = m_{w}C_{w}(T_{7} - T_{8})$$  \hspace{1cm} (9)

Energy utilization efficiency in cooling supply was shown as:

$$\eta_{cs} = \frac{Q_{cs}}{Q_{st}} \cdot 100\%$$  \hspace{1cm} (10)

Energy utilization efficiency of ice storage air conditioning system was given by:

$$\eta = (COP)_{s} \cdot \eta_{cs}$$  \hspace{1cm} (11)

When ice storage air conditioning system is driven by power grid, system energy utilization efficiency was calculated by:

$$\eta = (COP)_{r} \cdot \eta_{cs}$$  \hspace{1cm} (12)
Operation characteristic parameters, calculated by formulas (1) – (12), were shown in Table 2.

Experimental results showed that the average refrigeration coefficient of performance ($\text{COP}_r$) of refrigerator driven by power grid was at least 6.31% higher than that of refrigerator directly driven by distributed photovoltaic energy. Moreover, by comparing experimental results between conditions 1, 3 and conditions 2, 4, the refrigerator ($\text{COP}_r$s in conditions 2 and 4 were 1.38 times and 1.39 times of conditions 1 and 3, respectively. It was obvious that no matter whether driven by PV arrays in any weather condition or power grid, the ($\text{COP}_r$s of refrigerator operating in out-of-box mode was at least 1.38 times that of operating in ice storage mode. When refrigerator operated in conditions 1, the solar energy refrigeration coefficient of performance ($\text{COP}_s$), as known as solar energy ice making efficiency was 0.2183, which was 31.29% higher than the 0.15 ice making efficiency of solar adsorption reported in reference. The ice making efficiency was 2.37 times that of reported by Axaopoulos.30 Because the AC variable frequency compressor adopted in this paper had a wider frequency conversion range than the DC variable frequency compressor reported by Axaopoulos. When refrigerator operated in condition 2, system energy utilization efficiency $\eta_s$ was 27.71%, which was higher, 9.78%, than the 25% efficiency of the single-effect lithium bromide solar absorption air conditioning system reported in reference.36,37

4 | PERFORMANCE ANALYSIS

4.1 | Refrigerator characteristic analysis

In refrigerating process, refrigerating coefficient of performance ($\text{COP}_r$) and refrigerating capacity ($\bar{Q}$) of refrigerator were two very important parameters, usually used to evaluate refrigerator performance, which were mainly
affected by condensation temperature ($T_c$) and evaporation temperature($T_s$). So, refrigerator characteristics were usually expressed by the curves of coefficient of refrigeration performance changing with refrigerating power ($COP_r$), evaporator temperature ($COP_r$-$T_c$), and condenser temperature ($COP_r$-$T_s$). Tested by experiment, the dynamic performance of refrigerator operated with four conditions were shown in Figure 6.

No matter driven by power grid or distributed photovoltaic energy, the coefficient of performance ($COP_r$) of refrigerator increased with the increase of evaporation temperature and decreased with the increase of condensation temperature. It also revealed that ($COP_r$), was not affected by driven power. In other words, the refrigerator could operate stably and efficiently when it was directly driven by photovoltaic energy without energy storage devices of battery bank or power grid. But in Figure 6A, it was obvious that the ($COP_r$) curves of refrigerator driven by distributed photovoltaic energy had greater fluctuation compared to that driven by power grid. Because in low solar irradiance, refrigerator shutdown for the insufficient driving power provided by PV arrays. So, the frequent shutdown and start-up of refrigerator leaded the fluctuations of the ($COP_r$-$Q$ curves in operating conditions 1 and 2.

### 4.2 Directly driving characteristic analysis

The main reasons for low refrigeration efficiency of household PCM air conditioning directly driven by distributed PV arrays were the shutdown and operating fluctuation of compressor motor caused by the instantaneous fluctuation of solar irradiance. Because without buffer of energy storage equipment and power grid, the MPPT response time of PV arrays output power caused by the instantaneous solar irradiance directly transmitted to the compressor motor, which caused motor fluctuation. In addition, the fluctuation of load motor also affected the response time of PV array MPPT. So, the shutdown in low solar irradiance and fluctuating of compressor motor in fully solar irradiance were investigated.

#### 4.2.1 Fluctuation analysis of compressor motor impacted by instantaneous solar irradiance

Because the instantaneous fluctuation of solar irradiance was short time and no regularity, it was difficult to analyze the effect on compressor motor of refrigeration system by experimental test method. So, the software MATLAB/Simulink was employed to assess the effect.

First, the simulation model was established in MATLAB/Simulink, as shown in Figure 7, which was mainly composed of PV model, BOOST circuit, MPPT control circuit IGBT inverter circuit, three-phase AC asynchronous motor model, power feed-forward outer loop control circuit, and torque feedback circuit. The parameter values of PV arrays in Table 1 were then assigned to the PV model. The maximum power point tracking (MPPT) of PV arrays ensured the output power was always at the maximum power of PV arrays. The essence of MPPT control was to make the load impedance equal to the output impedance of PV arrays in a certain way. So, the response time of MPPT control system was the main factor affecting the fluctuation of compressor motor. Therefore, the control strategy and optimization of MPPT were studied.

Constant voltage method, disturbance observation method, and incremental conductance method were most commonly the MPPT control methods. Because the incremental conductance method had the advantages of fast response and high control accuracy, it was the best control strategy for the PCM air conditioning directly driven by PV arrays. The conductance in MPPT control was given by $dP/dV$. The relationships between the power point of PV arrays and its conductivity were showed in formulas (12) ~ (14).

\[
\text{MMP:} \frac{dP}{dV} = 0 \tag{12}
\]

Left side of MPP: $\frac{dP}{dV} > 0$. \hspace{1cm} \tag{13}

Right side of MPP: $\frac{dP}{dV} < 0 \tag{14}$

And because,

\[
\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \approx I + V \frac{\Delta I}{\Delta V} \tag{15}
\]
It was obvious that the fluctuation amplitude of output power decreased along with the increase of coefficient $K$, but the fluctuation time was affected more than the fluctuation amplitude in solar irradiance decreasing stage, which was the right side of MPP with voltage increasing stage, but the fluctuation time was affected more than the fluctuation amplitude in solar irradiance decreasing stage, which was the left side of MPP with voltage decreasing stage. So, in fully solar irradiance, the higher $K$ was better in irradiance increasing stage, but the lower $K$ was better in irradiance decreasing stage. The simulation results revealed that when $K$ was assigned 0.002, the fluctuation time in irradiance increasing stage and the fluctuation amplitude in irradiance decreasing stage were within a better range with solar irradiance irregularly changing in fully irradiance range no matter it was sunny, cloudy or rainy days.

Moreover, the power feed-forward outer loop control strategy was adopted in order to control the operation frequency of the compressor motor to improve the matching relation between the motor operation power and PV array output power. Three-phase asynchronous motor of refrigerator driven the moving scroll to rotate, which worked with the static scroll, to compress the low temperature refrigerant into high temperature and high pressure vapor refrigerant in the volume. Therefore, the characteristic of asynchronous motor directly driven by PV arrays was investigated. First, asynchronous motor control was the priority analysis. Three-phase static reference frame, two-phase static reference frame, and two-phase rotating reference frame were employed in the vector control of induction motor. These three reference systems were transformed to each other as needed, but two principles must be followed for coordinate change: the voltage transformation matrix matched the current transformation matrix, the magnetomotive force remained unchanged after coordinate transformation.

In static reference frame, when the stator phase A is selected as the $d$ axis, the two-phase static reference frame, $\alpha$-$\beta$ reference frame, was obtained, which was also called Formulas (16) ~ (18) were employed as the basis for judging whether the PV output power reached the maximum power point. The flow of incremental conductance method, MPPT simulation model and control strategy were showed in Figure 8.

In Figure 8E, it was obvious that the calculation step $K$ was the main factor affecting the response time of MPPT control strategy. Therefore, caused by the fluctuation of solar irradiance, the MPPT of PV arrays based on different $K$ was simulated, and the fluctuation time and amplitude of different $K$ were obtained by the model shown in Figure 8F, as shown in Table 3. Short fluctuation time and small fluctuation amplitude of output power of PV arrays were the judgment criteria for the optimal $K$ value. In the optimization of calculation step $K$, a fixed resistor with resistance value of 1000 ohm was chosen in the load.

Table 3 also showed that when solar irradiance increased from 100 Wm$^{-2}$ to 1000 Wm$^{-2}$, all of the fluctuation time and amplitude of output power increased along with the increase of coefficient $K$, but the fluctuation time and amplitude of output power decreased along with the increase of coefficient $K$ when solar irradiance decreased from 1000 to 100 Wm$^{-2}$. It was obvious that the fluctuation amplitude was affected by instantaneous solar irradiance more than the fluctuation time in solar irradiance increasing stage,
FIGURE 8

MPPT simulation model

(E) The flow of incremental conductance method

(F) MPPT simulation model

(G) Incremental conductance method control strategy
Clarke transformation. So, the instantaneous magnetomotive force relationship was as follows:

\[ N_2i_A = N_3l_A - N_3l_B\cos\frac{\pi}{3} - N_3l_C\cos\frac{\pi}{3} \]  
(19)

\[ N_2i_B = N_3l_B\sin\frac{\pi}{3} - N_3l_C\sin\frac{\pi}{3} \]  
(20)

where \(N_3\) and \(N_2\) were the effective turns of each phase of three-phase winding and two-phase winding, respectively. \(i_A, i_B, \) and \(i_C\) were the current of each phase of three-phase winding, and \(i_A, i_B, \) and \(i_C\) were the current of each phase of two-phase winding, respectively, and the matrix relation was as follows:

\[
C_{2s/3s} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & 0 \\
-1 & \frac{\sqrt{3}}{2} \\
\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\]  
(23)

So, the transformation matrix of \(2s/3s\) was given by:

\[
C_{3s/2s} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & 0 \\
-1 & \frac{\sqrt{3}}{2} \\
\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\]  
(21)

Because \(i_A + i_B + i_C = 0\):

\[
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & 0 \\
-1 & \frac{\sqrt{3}}{2} \\
\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
\]  
(22)

Next, the transformation of two-phase stationary to two-phase synchronous rotating reference frame, Park transformation, was carried out as:

\[
i_d = i_A \cos\phi + i_B \sin\phi
\]  
(24)

\[
i_q = -i_A \sin\phi + i_B \cos\phi
\]  
(25)

The transformation matrix from \(2s\) to \(2r\) was shown as follow:

\[
C_{2s/2r} = \begin{bmatrix}
\cos\phi \sin\phi \\
-\sin\phi \cos\phi
\end{bmatrix}
\]  
(26)

So, the transformation matrix from \(3s\) to \(2r\) was shown as follows:

\[
C_{3s/2r} = \frac{2}{3} \begin{bmatrix}
\cos\phi & \cos(\phi - 2\pi/3) & \cos(\phi + 2\pi/3) \\
-\sin\phi & -\sin(\phi - 2\pi/3) & -\sin(\phi + 2\pi/3)
\end{bmatrix}
\]  
(27)
The physical model of asynchronous motor in $\alpha-\beta$ coordinate system was shown as Figure 9. So, the formula (26) was given by:

$$
\begin{bmatrix}
  u_{sa} \\
  u_{s\beta} \\
  u_{ra} \\
  u_{r\beta}
\end{bmatrix} =
\begin{bmatrix}
  R_s + L_s p & 0 & L_m p & 0 \\
  0 & R_s + L_s p & 0 & L_m p \\
  L_m p & \omega L_m & R_r + L_r p & \omega L_r \\
  -\omega L_m & L_m p & -\omega L_r & R_r + L_r p
\end{bmatrix}
\begin{bmatrix}
  i_{sa} \\
  i_{s\beta} \\
  i_{ra} \\
  i_{r\beta}
\end{bmatrix}
$$

(28)

The rotor flux linkages on axes $\alpha$ and $\beta$ were as follows:

$$
\psi_{ra} = L_m i_{sa} + L_r i_{ra}
$$

(29)

$$
\psi_{r\beta} = L_m i_{s\beta} + L_r i_{r\beta}
$$

(30)

where

$$
i_{ra} = \frac{(\psi_{ra} - L_m i_{sa})}{L_r}
$$

(31)

$$
i_{r\beta} = \frac{(\psi_{r\beta} - L_m i_{s\beta})}{L_r}
$$

(32)

When $u_{ra}=u_{r\beta}=0$ in formula (28), the equations of rotor flux linkage of motor were given by:

$$
\psi_{ra} = \frac{L_m i_{sa} - \alpha T_r \psi_{r\beta}}{T_p + 1}
$$

(33)

$$
\psi_{r\beta} = \frac{L_m i_{s\beta} - \alpha T_r \psi_{ra}}{T_p + 1}
$$

(34)

Next, three-phase stator current was transformed from 3s to 2r, the excitation component current $i_q$ and torque component current $i_q$ were obtained. This time, the important parameters of three-phase asynchronous motor were calculated as follows:

$$
T_e = n_p \frac{L_m}{L_r} i_q \psi_r
$$

(35)

$$
\omega_s = \frac{L_m i_q}{T_r \psi_r}
$$

(36)

$$
\omega_1 = \omega_s + \omega
$$

(37)

$$
\psi_r = \frac{L_m}{T_p + 1} i_q
$$

(38)

where $u_{sa}$, $u_{s\beta}$, $u_{ra}$, and $u_{r\beta}$ were two-phase stator and rotor winding voltages, respectively. $i_{sa}$, $i_{s\beta}$, $i_{ra}$, and $i_{r\beta}$ were two-phase stator and rotor winding currents, respectively. $\omega$ was the rotor angular velocity. $R_s$ and $R_r$ were stator and rotor windings resistances. $T_r$ was the time constant of rotor electromagnetic force. $L_s$ and $L_r$ were the self-inductance coefficients of stator and rotor windings. $n_p$ was motor poles. $L_m$ was the mutual inductance between stator and rotor windings. $\omega_s$ was motor slip angular velocity.

The models of PV arrays and three-phase asynchronous motor in MATLAB/Simulink software were employed to simulate the influence of instantaneous fluctuation of solar irradiance on compressor operating parameters in full solar irradiance off-connected battery bank or power grid. So, the response time of MPPT was not only affected by instantaneous solar irradiance but also impacted by the variable frequency (VF) load compressor motor.

In order to compare with the experimental results, the solar irradiance first increased from 50 to 80 W/m$^2$ and then increased to 100 W/m$^2$. After that, solar irradiance gradually increased to 1000 W/m$^2$ with 100 W/m$^2$ growth rate, and solar irradiance then gradually decreased from 1000 to 100 W/m$^2$ with the same decrease rate. Another input parameter ambient temperature was given by the fixed value 25°C. Moreover, the simulation time step was set to 0.002 s. Simulation results were shown in Figure 10, and the experimental verification was shown in Table 4.

It was obvious that simulation results were in good agreement with the experimental data as shown in Table 4 and Figure 10. Results showed that the simulation model ran continuously in full solar irradiance range. In order to simulate the solar irradiance changes in whole day, the conditions of solar irradiance gradually increasing and decreasing were simulated. Moreover, the experimental
actual solar irradiance variations of sunny, cloudy, and rainy days were simulated by adjusting the solar irradiance variation. So, the calculated results were more accurate and reference value. The solar irradiance changes and calculated fluctuating time were shown in Table 5. Results showed that irradiance decrease, when sun was blocked, had more influence on the motor than irradiance increase. The fluctuation caused by low irradiance had greater influence than that of high irradiance. Moreover, compressor motor fluctuation time caused by the increase and decrease of solar irradiance in typical sunny, rainy, and cloudy days were about 65.22, 197.05, and 270.48 s, respectively.

Table 5 also showed that when solar irradiance reduced from 200 to 100 W/m², the fluctuation time of the compressor was the longest, up to 14.40 s. The main reason was that the compressor operated in the critical stage of shutdown and start-up in this irradiance range.

In order to study the influence of variable frequency operation of load motor on the response time of MPPT in photovoltaic directly driven system, the response time of PV arrays MPPT with rated load (1000 Ohm) and VF compressor motor were compared when the solar irradiance increased from 500 to 1000 W/m² and then decreased to 500 W/m² with the same time. The simulation results were shown in Table 6.

Table 6 revealed that the influence of motor frequency conversion on MPPT of photovoltaic energy was far less than that of the fixed load at the solar irradiance increasing stage. In solar irradiance decreasing stage, the fluctuation time of PV array output power, with VF motor as the load, was much longer than that of the fixed load. But the fluctuation amplitude in VF motor load was only about one-sixth of the fixed load. Comparing the simulating data in Table 5 and Table 6, it was obvious that in photovoltaic directly driven air conditioning system, the response time of motor frequency conversion operation caused by the instantaneous variation of solar irradiance was longer than the MPPT response time of photovoltaic energy system.
4.2.2 | Shutdown analysis of refrigerator impacted by instantaneous solar irradiance

The directly driving characteristics of refrigeration system were analyzed based on the experimental test data in low solar irradiance of condition 1 as shown in Table 7. Moreover, the operating characteristic curves of refrigerator were investigated as shown in Figure 11.

It was observed that total cumulative solar irradiance was 9.14 MJm\(^{-2}\) and instantaneous irradiation value changed between 200 and 400 Wm\(^{-2}\). Experimental results also showed that refrigerator could be directly driven by distributed photovoltaic energy, and the ice produce frozen around coiled tube evaporator was 65 kg.

Moreover, the output voltage \(V_{pv}\) of distributed PV arrays changed at 600~650 V and output current \(I_{pv}\) ranged between 2.0 A and 3.5 A, but when solar irradiance dropped too low to meet operation power requirement, refrigerator shutdown and output voltage and current declined to zero. Analysis results showed that the critical irradiation value for shutdown was about 150 Wm\(^{-2}\). In low solar irradiance, refrigerator stopped 23 times all

| Irradiance/Wm\(^{-2}\) | 50–80 | 80–100 | 100–200 | 200–300 | 300–400 | 400–500 | 500–600 | 600–700 | 700–800 | 800–900 | Total time/s |
|----------------------|-------|--------|---------|--------|---------|--------|---------|--------|---------|---------|-------------|
| 0.00                 | 9.00  | 5.00   | 2.20    | 1.95   | 1.65    | 1.55   | 0.10    | 0.05   | 0.12    |         |            |
| 0.12                 | 0.15  | 0.20   | 0.20    | 0.20   | 0.80    | 1.85   | 4.40    | 4.50   | 14.40   |         |            |
| 100–300              | 300–500| 500–700| 700–900 | 900–700| 700–500 | 500–300| 300–100 | 200–400| 400–600 |         | 29.12       |
| 4.00                 | 1.00  | 1.65   | 1.72    | 0.50   | 0.20    | 2.49   | 10.00   | 1.72   | 0.70    |         |            |
| 0.05                 | 0.10  | 0.50   | 0.80    | 1.75   | 1.94    |        |         |        |         | 6.00     | 20.00       |
| 100–400              | 400–700| 700–100| 1000–700| 700–400| 400–100 | 200–500| 500–800 | 800–500| 500–200 |         | 40.00       |
| 2.75                 | 0.40  | 1.70   | 0.40    | 1.60   | 20.00   | 1.30   | 0.25    | 0.30   |         |         | 34.42       |
| 300–600              | 600–900| 900–600| 600–300 | /      | /       | /      | /       | /      | /       |         |             |
| 0.50                 | 0.40  | 0.40   | 3.04    | /      | /       | /      | /       | /      | /       |         |             |
| 200–600              | 600–1000| 1000–600| 600–200 | 100–500| 500–900 | 900–500| 500–100 | 300–700| 700–300 |         | 34.20       |
| 1.40                 | 1.37  | 0.60   | 4.00    | 1.15   | 0.60    | 0.40   | 20.00   | 0.60   | 2.50    |         |             |
| 400–800              | 800–400| /      | /       | /      | /       | /      | /       | /      | /       |         | 32.20       |
| 0.30                 | 1.50  | /      | /       | /      | /       | /      | /       | /      | /       |         |             |
| 100–600              | 600–1000| 200–700| 700–200 | 300–800| 800–300 | 400–900| 900–400 | 500–1000| 1000–500|         | 34.20       |
| 1.60                 | 20.00 | 1.55   | 4.65    | 1.20   | 2.00    | 0.60   | 1.60    | 0.40   | 0.60    |         | 32.20       |
| 100–700              | 700–1000| 200–800| 800–200 | 300–900| 900–300 | 400–1000| 1000–400| /      | /       |         | 35.15       |
| 1.20                 | 20.00 | 0.60   | 4.50    | 0.60   | 2.50    | 0.80   | 2.00    | /      | /       |         | 35.15       |
| 100–800              | 800–1000| 200–900| 900–200 | 300–1000| 1000–300| /      | /       | /      | /       |         | 24.90       |
| 1.20                 | 20.00 | 2.90   | 6.00    | 3.55   | 1.50    | /      | /       | /      | /       |         | 24.90       |
| 100–900              | 900–1000| 200–1000| 1000–200| /      | /       | /      | /       | /      | /       |         | 24.90       |
| 1.50                 | 15.00 | 1.40   | 7.00    | /      | /       | /      | /       | /      | /       |         | 24.90       |
| 100–1000             | 1000–1000| /      | /       | /      | /       | /      | /       | /      | /       |         | 24.90       |
| 1.65                 | 16.50 | /      | /       | /      | /       | /      | /       | /      | /       |         | 18.15       |
TABLE 6  Fluctuation time and amplitude of PV output power with different load

| Load       | 300–1000 Wm$^{-2}$ | 1000–3000 Wm$^{-2}$ |
|------------|-------------------|---------------------|
|            | Fluctuation time s | Fluctuation amplitude | Fluctuation time s | Fluctuation amplitude |
|            | Avg s             | W                   | Avg s             | W                   |
| 1000 Ohm   | 0.085             | 42.75               | 0.012             | 32.00               |
|            | 0.080             | 33.25               | 0.0018            | 31.88               |
|            | 0.090             | 64.75               | 0.013             | 31.84               |
| VF motor   | 0.0052            | 7.00                 | 0.198             | 3.95                |
|            | 0.0030            | 4.95                 | 0.192             | 6.10                |
|            | 0.0029            | 6.82                 | 0.191             | 5.40                |

TABLE 7  Experimental results

| Load       | q $\text{MJm}^{-2}$ | $m_w$ kg | $m_i$ kg | $t_{wa}$ °C | $t_{wb}$ °C | $t_{ia}$ °C | $\dot{m}_w$ kgs$^{-1}$ | $\eta_{pv}$ | $\eta_{r}$ | COP $\text{r}$ | COP $\text{pv}$ | $\eta_{cs}$ | $\eta$ % |
|------------|---------------------|----------|----------|--------------|--------------|--------------|------------------------|------------|-----------|----------------|----------------|-----------|---------|
| Intermittent operation | 9.14 | 435 | 65 | 20 | 4 | −3 | 0.63 | 14.18 | 81.81 | 1.65 | 1.35 | 0.1915 | 83.26 |
| Continuous operation | 10.91 | 390 | 110 | 8.2 | 2.1 | −5.7 | 0.63 | 13.72 | 86.13 | 1.85 | 1.59 | 0.219 | 85.41 |

FIGURE 11  Operating characteristic curves of distributed photovoltaic energy and refrigerator
day and the shutdown time was 13,095 s about 3.6 h accounting for total refrigerator operating time of 35.06% according to statistical analysis. In other words, the total accumulated solar irradiance was abandoned during refrigerator shutdown time. Figure 11 also showed the variation curves of refrigerator consumption power $P$ and the output power of distributed photovoltaic energy $P_{pv}$. Calculated results revealed that the average energy utilization efficiency of refrigerator $\eta_r$ was 81.81%. Moreover, the operating frequency $f$ and rotational speed $r$ of the refrigerator were investigated and then monitored. The results showed that frequency $f$ and rotational speed $r$ remained about 45 Hz and 2500 r min$^{-1}$, and solar irradiance ranged between 200 Wm$^{-2}$ and 400 Wm$^{-2}$. This moment, refrigerator rotational speed $r$ could reach 83.33% of the maximum speed.

Above investigations revealed that refrigerator frequently shutdown in cloudy day. As a result, refrigeration characteristics fluctuated greatly, which not only reduced the coefficient of performance of refrigerator, but also greatly shortened the compressor service life. So, the controller was optimized by turning down the lower solar irradiance limit of system control program. The operating characteristics of PV refrigeration system under condition 1 were tested by experiment, and the data were also shown in Table 7 and Figure 12. Results revealed that refrigerator operated stably and continuously in cloudy day. The cumulative solar irradiation was 10.91 MJm$^{-2}$, and the minimum solar irradiance used to continuously drive compressor was 80 Wm$^{-2}$. The lower solar irradiance limit was optimized from 150 to 80 Wm$^{-2}$, refrigerator operated stably and continuously in any weather conditions. The
ice production and the \( \text{COP}_r \), were improved by 40.91% and 12.36%, respectively.

In Figure 12, it was observed that compressor operated stably without shutdown during the experiment. Minimum operating frequency and rotational speed were, respectively, 17 Hz and 841.4 rmin\(^{-1}\) at the lowest solar irradiance of 80 Wm\(^{-2}\). The running frequency and rotational speed increased along with the increase of solar irradiance. When solar irradiance increased to 320 Wm\(^{-2}\), frequency and rotational speed reached the maximum value of 60 Hz and 2852.31 rmin\(^{-1}\), respectively. After optimization, the ice production increased about 40.91% from 65 kg to 110 kg and the refrigeration coefficient of performance \((\text{COP}_r)\) was improved by 12.36% from 1.855 to 1.651. Comparing the results of condition 1 of Table 2 and intermittent operation of Table 6, it was obvious that low irradiance had a certain influence on the energy efficiency \((\eta_r)\) and \((\text{COP}_r)\) of refrigerator. When the accumulated irradiance converted by PV arrays was 9.14 MJ/m\(^2\) in Table 6, the \(\eta_r\) was 81.81%, which was 12.97 percentage points lower than that of the high irradiation 16.94 MJ/m\(^2\) in Table 2, but the \((\text{COP}_r)\) was 1.76% higher than that of high irradiation.

5 | CONCLUSION

In order to promote household PV air conditioning large scale and industrial utilization, the cheap and technically mature ice thermal storage, substituting for battery bank, was adopted to store solar energy in this paper. So, a 3HP household air conditioning assisted with phase change material (PCM) storage tank was established and tested in four operating conditions. Moreover, in order to efficiently solve the effects from the intermittent and instantaneous of the solar energy on the refrigerating performance of the PV refrigeration system without of auxiliary battery bank energy storage device. The software MATLAB/Simulink was employed to simulate the impact of solar irradiance fluctuation on the refrigeration performance. The directly driving technology combined the variable frequency operation of the compressor, and the maximum power point tracking of the PV arrays were introduced and analyzed in the research work.

1. Experimental results indicated that refrigerator operated stably and high efficiently directly driven by distributed photovoltaic energy system without battery bank. The \((\text{COP}_r)\) of refrigerator driven by power grid was about 6.31% higher than that of refrigerator directly driven by distributed photovoltaic energy, and the \((\text{COP}_r)\) of refrigerator operating in out-of-box mode was about 1.38 times that of operating in ice storage mode. The solar energy utilization efficiency \(\eta\) in conditions 1 and 2 was 18.23% and 27.71% in typical sunny day, respectively. \((\text{COP}_r)\) of condition 1 was almost 1.38 times that of condition 2. \((\text{COP}_r)\) of refrigerator was not affected by driven power. However, the cooling capacity and stability of refrigeration performance were affected by the instantaneous fluctuation of solar irradiance.

2. The inevitable motor fluctuation was mainly caused by the MPPT response time of PV arrays. So, the optimization of calculation step \(K\) in MPPT control strategy of incremental conductance method was beneficial to improve the response time and reduce fluctuation amplitude. When \(K\) was assigned value 0.002, the comprehensive output performance of PV array was better. Compressor motor fluctuation time caused by the increase and decrease of solar irradiance in typical sunny, rainy, and cloudy days was about 65.22 s, 197.05 s, and 270.48 s, respectively. Moreover, the response time of motor frequency conversion operation caused by the instantaneous variation of solar irradiance was longer than the MPPT response time of photovoltaic energy system.

3. The optimization on refrigerator continuously and stably operating at low irradiance has been carried out. The lower solar irradiance limit was lowered from 150 Wm\(^{-2}\) to 80 Wm\(^{-2}\), and the compressor operated stably without shutdown in 10.91 MJ/m\(^2\). The refrigeration coefficient of performance was improved by 12.36%, and the utilized solar energy also increased about 0.45 MJ m\(^{-2}\).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by National Natural Science Foundation of China (51966019) and Major Science and Technology Special Project of Yunnan (Grant No. 202002AF080002). The research work was also supported by Jiaxing public welfare project (2020AY10019).

NOMENCLATURE

Symbol

\( \text{COP} \) | Coefficient of performance
---|---
\( C \) | Specific heat capacity of water (J kg\(^{-1}\) K\(^{-1}\))
\( f \) | Compressor operating frequency (Hz)
\( G \) | Solar irradiance (W m\(^{-2}\))
\( h \) | Enthalpy (kJ/kg)
\( I \) | Current (A)
\( m \) | Weight (kg)
\( \dot{m} \) | Mass flow (kg s\(^{-1}\))
\( \text{MPPT} \) | Maximum power point tracking
\( p \) | Pressure (Pa)
\( P \) | Electric power (kW)
\( q \) | Accumulated solar irradiance received by PV arrays (MJ m\(^{-2}\))
CONFLICT OF INTEREST
We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

ORCID
Yongfeng Xu https://orcid.org/0000-0001-7642-0771

REFERENCES
1. Sharma M, Vaish R, Chauhan VS. Energy and exergy analyses of a pyroelectric-based solar energy harvesting system. Energy Technol. 2015;3(12):1271-1278.
2. Allouhi A, Kousksou T, Jamil A, Bruel P, Mourad Y, Zeraouli Y. Solar driven cooling systems: an updated review. Renew Sustain Energy Rev. 2015;44:159-181.
3. Ghafoor A, Munir A. Worldwide overview of solar thermal cooling technologies. Renew Sustain Energy Rev. 2015;43:763-774.
4. Ferreira CI, Kim DS. Techno-economic review of solar cooling technologies based on location-specific data. Int J Refrig. 2014;39:23-37.
5. Miskat MI, Rashedi A. Exergy efficiency and enviroeconomic analysis of solar photovoltaic power in Nepal. Energy Technol. 2021;9(8):2100093.
6. Carlos M, Yusuf B. Comparison of the influence of solid and phase change materials as a thermal storage medium on the performance of a solar chimney. Energy Sci Eng. 2021;9(8):1274-1288.
7. Enibe SO. Solar refrigeration for rural application. Renew Energy. 1997;12(2):157-167.
8. Kattakayam TA, Srinivasan K. Photovoltaic panel generator based autonomous power source for small refrigeration units. Sol Energy. 1996;56(6):543-552.
9. Victor TT, Klaus M, Philip T, Santiago MB, Joachim M. Design and performance of a small-scale solar ice-maker based on a DC-freezer and adaptive control unit. Sol Energy. 2016;139:433-443.
10. Xu YF, Ma X, Hassanien RHE, Luo X, Li GL, Li M. Performance analysis of static ice refrigeration air conditioning system driven by household distributed photovoltaic energy system. Sol Energy. 2017;158:147-160.
11. Toure S, Fassinou WF. Cold storage and autonomy in a three compartments photovoltaic solar refrigerator: experimental and thermodynamic study. Renew Energy. 1999;17:587-602.
12. Kaplanis S, Papmmstasiou N. The study and performance of a modified conventional refrigerator to serve as a PV powered one. Renew Energy. 2006;31(6):771-780.
13. Sukamongkol Y, Chungpaibulpatana S, Ongsakul W. A simulation model for predicting the performance of a solar photovoltaic system with alternation current loads. Renew Energy. 2002;27:237-258.
14. Aktacir MA. Experimental study of a multi-purpose PV-refrigerator system. Int J Phys Sci. 2011;6(14):746-757.
15. Tina GM, Grasso AD. Remote monitoring system for stand-alone photovoltaic power plants: the case study of a PV-powered outdoor refrigerator. Energy Convers Manage. 2014;2(78):862-871.
16. Parker DS, Dunlop JP. Solar photovoltaic air conditioning of residential buildings. In: ACEEE Summer Study on Energy Efficiency in Building, California. 1994.
17. Liu ZB, Li A, Wang QH, Chi YY, Zhang LF. Performance study of a Quasi grid-connected photovoltaic powered DC air conditioner in a hot summer zone. *Appl Therm Eng.* 2017;121:1102-1110.
18. Huang BJ, Hou TF, Hsu PC, et al. Design of direct solar PV driven air conditioner. *Renew Energy.* 2016;88:95-101.
19. Naser BM, Shaltout A. Analysis and design of photovoltaic powered air conditions using slip-frequency control scheme. *Elect Power Comp Syst.* 2007;35(1):81-95.
20. Balaji N, Kumar PSM, Velraj R, Kulasekharan N. Experimental investigations on the improvement of an air conditioning system with a nanofluid-based intercooler. *Arab J Sci Eng.* 2015;40:1681-1693.
21. Francisco J, Aguilar VP, et al. Operation and energy efficiency of a hybrid air conditioner simultaneously connected to the grid and to photovoltaic panels. *Energy Proc.* 2014;48:768-777.
22. Lemis A, Cardenas DM, Haro M, et al. Lead sulfide nanocubes for solar energy storage. *Energy Technol.* 2020;8(7):2000301.
23. Cherif A, Dhoubib A. Dynamic modelling and simulation of a photovoltaic refrigeration plant. *Renew Energy.* 2002;26:143-153.
24. Modi A, Chaudhuri A, Vijay B, et al. Performance analysis of a solar photovoltaic operated domestic refrigerator. *Appl Energy.* 2009;86(12):2583-2591.
25. Bi Y, Zang G, Qin L, Li H, Wang H. Study on the characteristics of charging/discharging processes in three-phase energy storage coupling in solar air conditioning system. *Energy Build.* 2019;204:109456.
26. Rahdar MH, Emamzadeh A, Ataei A. A comparative study on PCM and ice thermal energy storage tank for air-conditioning systems in office buildings. *Appl Therm Eng.* 2016;96:391-399.
27. Jannesari H, Abdollahi N. Experimental and numerical study of thin ring and annular fin effects on improving the ice formation in ice-on-coil thermal storage systems. *Appl Energy.* 2017;189:369-384.
28. Li XY, Qu DQ, Yang L, Li KD. Experimental and numerical investigation of discharging process of direct contact thermal energy storage for use in conventional air-conditioning systems. *Appl Energy.* 2017;189:211-220.
29. Mosaffa AH, Farshi LG. Exergoeconomic and environmental analyses of an air conditioning system using thermal energy storage. *Appl Energy.* 2016;162:515-526.
30. Axoaoulos PJ, Theodoridis MP. Design and experimental performance of a PV Ice-maker without battery. *Sol Energy.* 2009;83(1):1360-1369.
31. Xu YF, Li M, Luo X, et al. Experimental investigation of solar photovoltaic operated ice thermal storage air-conditioning system. *Int J Refrig.* 2018;86:258-272.
32. Han YH, Li M, Wang YF, et al. Impedance matching control strategy for a solar cooling system directly driven by distributed photovoltaics. *Energy.* 2019;168:953-965.
33. Li GL, Han YH, Li M, et al. Study on matching characteristics of photovoltaic disturbance and refrigeration compressor in solar photovoltaic direct-drive air conditioning system. *Renew Energy.* 2021;172:1145-1153.
34. Goyal P, Baredar P, Mittal A, Siddiqui AR. Adsorption refrigeration technology – an overview of theory and its solar energy applications. *Renew Sustain Energy Rev.* 2016;53:1389-1410.
35. Ji X, Li M, Fan JQ, Zhang P, Luo B, Wang LL. Structure optimization and performance experiments of a solar powered finned-tube adsorption refrigeration system. *Appl Therm Energy.* 2014;113(6):1293-1300.
36. Chen JF, Dai YJ, Wang RZ. Experimental and analytical study on an air-cooled single effect LiBr-H2O absorption chiller driven by evacuated glass tube solar collector for cooling application in residential buildings. *Sol Energy.* 2017;151:110-118.
37. Li M, Xu CM, Hassaniem RHE, Xu YF, Zhuang BW. Experimental investigation on the performance of a solar powered lithium bromide–water absorption cooling system. *Int J Refrig.* 2016;71:46-59.

**How to cite this article:** Xu Y, Li M. Impact of instantaneous solar irradiance on refrigeration characteristics of household PCM storage air conditioning directly driven by distributed photovoltaic energy. *Energy Sci Eng.* 2022;10:752–771. doi:10.1002/ese3.1050