Power Limit Control Strategy for Household Photovoltaic and Energy Storage Inverter

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Abstract: The increased installation capacity of grid-connected household photovoltaic (PV) systems has been witnessed worldwide, and the power grid is facing the challenges of overvoltage during peak power generation and limited frequency regulation performance. With the dual purpose of enhancing the power grid safety and improving the PV utilization rate, the maximum feed-in active power can be regulated by modifying the maximum power point tracking (MPPT) algorithm and battery energy storage (BES) accessibility as control instructions. However, the existing methods not only waste installed PV capacity, but it becomes no longer accessible when the state of charge (SOC) of the BES approaches its upper limit. In response to the above problem, this paper proposes a power limit control strategy to coordinate the MPPT algorithm and the BES accessibility. The proposed strategy directly controls the inverter output current according to the power limit instructions from the electric operation control centers, leading to a bus voltage difference. The difference serves as a control signal for BES and PV. Under a power-limiting scenario, priority is given to power regulation through energy storage to absorb the limited active power. When the SOC of the BES reaches the upper limit of charging, modification of the PV MPPT algorithm facilitates the inverter output power to meet the power limit requirements. To further verify the effectiveness of the proposed power limit control strategy, both simulation and experimental studies are conducted, which consistently indicated a synchronized inverter current with grid voltage and a rapid power response of the power-limiting instruction within 0.2 s. The power limit control strategy not only improves the PV energy utilization but also supports the safe and reliable operation of the power grid in the context of soaring renewable energy penetration.

Keywords: power limit control; photovoltaic energy storage system; maximum power point tracking; active power control; bus voltage

1. Introduction

In the context of global warming and excessive carbon emissions, vigorously developing renewable energy has become the consensus worldwide. As a representative of renewable energy power generation, the integration of household PV into the grid has witnessed a soaring increase [1–3]. However, the ever-increasing PV systems have brought huge challenges to the grid. When a large number of PV systems are connected to the grid, considerable active power is injected into the grid at noon (that is, when the PV power generation capacity is highest). As a result, severe overvoltage occurs if the grid capacity remains unchanged [4–7]. In addition, due to the low inertia and the high intermittency of the PV system, the frequency regulation ability is consequently limited. When the power grid fluctuates, serious power accidents may occur under extreme conditions. Therefore, the PV system needs to regulate the output power to certain levels (specified by
grid regulations) to maintain the normal operation of the grid to avoid frequency deviation [8]. Some countries have revised and updated various active power control schemes for grid-connected PV systems. An absolute power constraint is used in Denmark to limit active power from a PV system to a set-point-defined maximum power limit in the point of connection, which is mainly used to protect the public electricity supply grid against overload in critical situations [9]. Germany has adopted this requirement through the grid regulations [10], in which newly installed PV systems must be able to limit 70% of their maximum feed-in power. In addition, similar requirements are defined in Japan’s grid regulation [11]. Therefore, large-scale distributed photovoltaic systems with voltage levels above some 10 kV need to have fault ride-through capability [12]. In the event of a grid failure, the photovoltaic system will continue to operate without leaving the grid to support the restoration of normal operation of the grid. However, the household photovoltaic power generation system with voltage level of 220/380 V needs to change its maximum output power according to the power command requirements of the electric operation control center. This kind of method assists with fault ride-through, maintains the stability of the grid voltage and frequency, and then ensures the safe operation of the grid [13].

At present, for household photovoltaic systems, the methods of demand-side management [14–16], modified MPPT algorithm [17–25], and energy storage system access [26–29] are commonly used to restrict the output power of the inverter to meet the grid requirements and improve the friendliness of PV power generation. The method of installing a load on the demand side is adopted to consume the excess power generated by PV during peak periods, which is simply implemented by a resistor circuit with an appropriate control algorithm but will lead to the energy waste in the resistor as heat generation [14]. The household load is used to consume excess power during the surplus period of PV power generation, where intelligent but complicated communication systems and coordination between different appliances are required [15]. In addition, another strategy by continuously cutting in and out the PV generation units according to the demands can be adopted to achieve the power regulation [16], which, however, shares the same drawbacks as the demand-side management strategy (using dump loads) and, more importantly, may cause instability in the PV system. There are three alternatives of the control variables for the modified MPPT algorithm: photovoltaic output power, photovoltaic output current, and photovoltaic output voltage. In [17,18], photovoltaic output power was used as a control variable. The deviation between the inverter’s power-limiting value and the photovoltaic output power under the action of the proportional–integral (PI) controller can change the duty cycle of the boost converter, which can reduce the photovoltaic output power within 1 s. The principle of this method is simple, but the response speed is relatively slow. In [18,19], photovoltaic output current was used as the control variable. The photovoltaic output voltage was divided by the inverter’s power-limiting value to obtain the photovoltaic reference output current. The deviation between the photovoltaic reference output current and the photovoltaic current was used as the photovoltaic control signal. The output current of the photovoltaic can be reduced within 0.2 s, thereby reducing the output power of the photovoltaic. This method is faster than directly controlling the photovoltaic output power. However, because the slope of the power and current curve on the right side of the maximum power point of the photovoltaic module is very large, the operating point of the photovoltaic system may go into the short-circuit condition under a sudden decrease in the irradiance condition. In [20–25], photovoltaic output voltage was used as the control variable. A modified algorithm adjusted the maximum power point to the right side to constrain photovoltaic output power within 0.1 s in [20]. An extra amount of $\Delta v_{\text{pv}}$ was added to the calculated voltage reference from the MPPT algorithm, during the power limit operation mode [21,22]. Accordingly, $\Delta v_{\text{pv}}$ was computed on the basis of the error between the DC link energy $(v_{\text{dc}})^2$ and its reference value $(v_{\text{dc}}^*)^2$ in [21]. The algorithm in [22] considered the power-limiting reference in the calculation of $\Delta v_{\text{pv}}$. The method is an iteration-based method, which requires a number of iterations in order to
reach the corresponding power limit point; thus, the principle is more complicated. It also faces the problem of poor algorithm robustness under a sudden decrease in the irradiance condition. In [23,24], PV was forced to operate on the left side of the maximum power point when PV worked in power-limiting mode, which improved the robustness of the limited power-limiting algorithm when a rapid decline in irradiance was experienced. This operation region (left side of maximum power point) resulted in slower dynamics. A general algorithm for flexible power tracking was introduced in [25]. One general voltage reference calculation algorithm was implemented, which was able to calculate the voltage reference in both MPPT and power-limiting operation modes. Once the operation point approaches the reference, the adaptive voltage step becomes smaller, which ensures the stable operation of the PV around the reference. This method adaptively adjusts the PV power on both sides of the MPPT point according to the voltage reference calculation algorithm, which is of better flexibility and faster response time (within 0.1 s). Up to date, the existing researches on power limiting based on the modified MPPT algorithm are sensitive to the power-limiting instructions from the electric operation control centers. Since no additional energy storage unit or load with sensors are required, this kind of method is more economical than using household loads and BES. However, the use of this control strategy will result in the system being forced to operate below the maximum capacity; therefore, the installed PV system cannot operate with optimized utilization. In addition, BES is another commonly used paradigm to achieve power control [26–29]. The principle of this method is simple and generally adopts the double closed-loop control mode of power outer loop and current inner loop. The reference power of the power outer loop is obtained according to the inverter power-limiting command. The reference power of the power outer loop is obtained according to the inverter power-limiting command. The reference current is further determined by the difference of reference power and the actual power. When the power is limited, the battery current decreases, leading to a limited battery power. This method not only suppresses the fluctuation of photovoltaic output power, but the curtailed PV power can also be minimized by optimally coordinating the charging/discharging among the BES [29]. Furthermore, it has a fast response speed within 0.2–0.5 s. The additional cost of BES and related controllers made the solution cost-intensive to implement in the initial stage. As the cost of the BES drops, policy supports integrating BES into a PV system (i.e., storing energy during the day and releasing energy at night), which is economical for both individual users and grid management administrators [6,30]. When the BES reaches the SOC threshold, it no longer participates in power regulation [28]. A feasible solution is to increase the capacity of the BES for larger power regulation capability, which is undoubtedly noneconomical. Therefore, separately modifying the MPPT algorithm and applying BES to perform power regulation has its own limitations.

This paper proposes a power limit control strategy that integrates the modification of the MPPT algorithm and the accessibility of the BES. The BES adjusts the power by reducing the battery output current preferentially, when the output power of the inverter is limited. When the SOC of the BES reaches the limit, the PV output power is limited by reducing the photovoltaic output current to follow the power-limiting instruction. This paper begins with a detailed description of the household PV and BES system. Then, a power limit control strategy for household PV and BES inverters is introduced. Lastly, the proposed power limit control strategy is simulated and experimentally verified under different power-limiting scenarios, consistently indicating a synchronized inverter current with grid voltage and a rapid power response of the power-limiting instruction within 0.2 s. This control strategy not only effectively reduces energy waste, but also improves the safety and reliability of the grid operation, and it has great guiding significance for the access of PV and BES system with sustainability in the future.

2. Description of Household Photovoltaic and Energy Storage System

The household photovoltaic energy storage system is shown in Figure 1. The system consists of a topological structure layer, a control layer, and an energy management layer.
The topological structure layer includes a boost converter connected to the PV arrays, a bidirectional DC–DC converter connected to the BES, a grid-connected inverter, a filter circuit, and household loads. The PV is connected to the bus through a non-isolated boost converter [31]. The PV is composed of identical photovoltaic modules to provide active power for the system. The output voltage and current of the PV are sensitive to external factors (temperature, illuminance), and the output characteristic curve is nonlinear. Therefore, this article uses the disturbance observation method [32] to achieve the maximum power point tracking of the PV. The BES is connected to the bus through a bidirectional non-isolated DC–DC converter [33], which increases the flexibility of power control. The parameters of BES and bidirectional non-isolated DC–DC converter are designed according to the recommendations of the literature [34]. The inverter adopts a single-phase full-bridge inverter [35]. LC filters are used to remove high-frequency harmonics of household inverters [36]. In order to track the phase of the grid voltage and synchronize the inverter current and grid voltage, a second-order generalized integral phase-locked loop (SOGI-PLL) [37] is used.

In the energy management layer, the system operates at full load or at power limit according to the power instruction from the electric operation control center, and the control targets of PV and BES are determined in each operating state.
The control layer is responsible for implementing control targets determined by the energy management layer. In the control layer, in order to achieve the safe and long-term operation of the BES, the BES can participate in power adjustment only when the SOC of BES is between 20% and 80% [38]. The system includes three operation states derived from the SOC of the BES and the power-limiting instruction, including ‘inverter full-load operation’ stage, ‘inverter power limit and battery access operation’ stage, and ‘inverter power limit and battery disconnection operation’ stage.

Inverter full-load operation is when the inverter output power is lower than the inverter output power limit value \( P_{\text{inv}} \leq P_{\text{inv \_lim \_it}} \). In this state, the bus voltage is controlled at the level A. The PV works in MPPT mode, while the boost converter changes the duty cycle according to the reference voltage given by the MPPT algorithm and, consequently, changes the output voltage of the PV to maximum output power. The BES works in normal mode, and it works in the charging/discharging state according to the difference between the PV and the household load. When the PV output power is lower than the power consumed by the household load, the battery works in a discharged state to make up for the energy that the photovoltaic system should have provided. Likewise, when the output power of the PV is higher than the power consumed by the household load, the BES works in the charging state to store the energy spared by the load.

Inverter power limit and battery access operation is when the inverter output power is higher than inverter output power limit value and the battery has power regulation capability \( P_{\text{inv}} > P_{\text{inv \_lim \_it}}, 20\% \leq \text{SOC} \leq 80\% \). In this state, the bus voltage is controlled at the level B. The PV still works in MPPT mode for maximum power output. The BES works in power adjust mode, and the BES reduces its discharge power or even works in a charging mode. This reduces the waste of photovoltaic energy and restricts the output power of the inverter to the power limit requirements.

Inverter power limit and battery disconnection operation is when the output power is higher than the inverter output power limit value and the battery does not have power regulation capability \( P_{\text{inv}} > P_{\text{inv \_lim \_it}}, \text{SOC} > 80\% \). In this state, the bus voltage is controlled at the level C. The PV works in power limit mode, and the output current of the PV is reduced by controlling the boost converter. According to the photovoltaic I–V characteristic curve, the output voltage of the PV increases as a result and moves further away from the maximum power point. The purpose is to reduce the output power of PV and meet the requirements of inverter output power restrictions.

3. Power Limit Control Strategy

The power limit control strategy for the household PV and BES system is shown in Figure 2. In each operating state of the inverter, unique control loop functions are activated on the PV, BES, and inverter. The switching of the control loop is implemented by taking a ‘minimum’ operation. The reason for the ‘minimum’ operation is to reduce the output current of the PV, BES, and inverter according to the requirements of the power limit command. Table 1 displays the corresponding relationship between each operating state and the bus voltage level, the control loops of PV, the BES, and the inverter.
Figure 2. Power limit control strategy of household photovoltaic energy storage system.

Table 1. The relationship between the operating status and the control loop of the household photovoltaic energy storage system.

| Operation States          | Bus Voltage Level | PV Control               | BES Control              | Inverter Control              |
|---------------------------|-------------------|--------------------------|--------------------------|-------------------------------|
| Full load                 | A                 | MPPT mode Control loop   | Normal mode Control loop | Full-load Operation Control loop |
| Power limit and battery access | B                | MPPT mode Control loop   | Power Limit Mode Control loop | Power limit Operation Control loop |
| Power limit and battery disconnection | C              | Power limit mode Control loop | -                        | Power limit Operation Control loop |

When the inverter is under full-load operation, the inverter-side full-load operation control loop, the battery-side normal mode control loop, and the PV-side MPPT mode control loop participate in the control, while the bus voltage is controlled at bus voltage level A by the grid-connected inverter part.

When the inverter is under power limit and battery access operation, the inverter-side power limit operation control loop, the battery-side power adjusts mode control loop, and the PV-side MPPT mode control loop participate in the control, while the bus voltage is controlled by the energy storage part at bus voltage level B.

When the inverter is under power limit and battery disconnection operation, the inverter-side power limit operation control loop and the PV-side power limit mode control loop participate in the control, while the bus voltage is controlled at bus voltage level C by the PV part. The control strategy under the three operating states of the system is described below.
3.1. Full-Load Operation of the Inverter

When the inverter is running at full load, the bus voltage is controlled by the grid-connected inverter part on the bus voltage reference $V_{\text{bus,ref}}$, i.e., the bus voltage level A. $i_{\text{inv,ref}2}$ is obtained by $V_{\text{bus,ref}}$ through the control of the voltage loop proportional–integral (PI) controller, as the current reference of the inverter-side current loop proportional–resonant (PR) controller, $i_{\text{inv,ref}2}$, controls the inverter output current. The corresponding control scheme is shown in Equation (1).

\[
\begin{align*}
& (V_{\text{bus,ref}} - V_{\text{bus}}) \times (K_{p,pv} + \frac{1}{s}) \times \frac{\alpha_{0}}{s^{2} + \omega_{0}^{2}} = i_{\text{inv,ref}2}^{} \\
& (i_{\text{inv,ref}2} - i_{\text{inv}}) \times (K_{p,pv}) = D_{\text{inv}2}
\end{align*}
\]

where $V_{\text{bus}}$ is the bus voltage, $K_{p,pv}$ is the proportional coefficient of the PI controller for the inverter voltage control loop, $K_{L,pv}$ is the integral coefficient of the PI controller for the inverter voltage control loop, $i_{\text{inv}}$ is the inverter output current, $K_{p,pv}$ is the proportional coefficient of the inverter PR controller, $K_{r,inv}$ is the resonance coefficient of the inverter PR controller, $\omega_{0}$ is the fundamental frequency of the inverter output current, $\omega_{c}$ is the cutoff frequency of the inverter output current, and $D_{\text{inv}2}$ is the duty cycle of the gate driver for the inverter.

The BES works in the normal mode. The power reference $P_{\text{bat,ref}}$ is equal to the difference between the photovoltaic power $P_{\text{pv}}$ and the load power $P_{\text{load}}$, i.e., $P_{\text{bat,ref}} = P_{\text{load}} - P_{\text{pv}}$. $i_{\text{bat,ref}1}$ is obtained by $P_{\text{bat,ref}}$ through the control of the power loop PI controller, as the current reference of the battery-side current loop PI controller, $i_{\text{bat,ref}1}$, controls the current of the energy storage. The corresponding control scheme is shown in Equation (2).

\[
\begin{align*}
& (P_{\text{bat,ref}} - P_{\text{bat}}) \times (K_{p,\text{bat}} + \frac{1}{s}) = i_{\text{bat,ref}1}^{} \\
& (i_{\text{bat,ref}1} - i_{\text{bat}}) \times (K_{p,\text{bat}} + \frac{1}{s}) = D_{\text{bat}1}
\end{align*}
\]

where $P_{\text{bat}}$ is the battery power, $K_{p,\text{bat}}$ is the proportional coefficient of the PI controller for the battery power control loop, $K_{L,\text{bat}}$ is the integral coefficient of the PI controller for the battery power control loop, $i_{\text{bat}}$ is the battery current, $K_{p,\text{bat}}$ is the proportional coefficient of the PI controller for the battery current control loop, $K_{\text{r,inv}}$ is the integral coefficient of the PI controller for the battery current control loop, and $D_{\text{bat}1}$ is the duty cycle of the gate driver for the bidirectional DC–DC converter on the battery side.

The PV works in the MPPT mode, and the PV voltage reference $V_{\text{pv,ref}}$ is given by the disturbance observation method. $i_{\text{pv,ref}1}$ is obtained by $v_{\text{pv,ref}}$ through the control of the voltage loop PI controller, as the current reference of the PV side current loop PI controller, $i_{\text{pv,ref}1}$, controls the output current of the PV. The corresponding control scheme is shown in Equation (3).

\[
\begin{align*}
& (V_{\text{pv,ref}} - V_{\text{pv}}) \times (K_{p,\text{pv}} + \frac{1}{s}) = i_{\text{pv,ref}1}^{} \\
& (i_{\text{pv,ref}1} - i_{\text{pv}}) \times (K_{p,\text{pv}} + \frac{1}{s}) = D_{\text{pv}1}
\end{align*}
\]

where $V_{\text{pv}}$ is the PV voltage, $K_{p,\text{pv}}$ is the proportional coefficient of the PI controller for the PV voltage control loop, $K_{L,\text{pv}}$ is the integral coefficient of the PI controller for the PV voltage control loop, $i_{\text{pv}}$ is the PV current, $K_{p,\text{pv}}$ is the proportional coefficient of the PI controller for the PV current control loop, $K_{\text{r,inv}}$ is the integral coefficient of the PI controller for the PV current control loop, and $D_{\text{pv}1}$ is the duty cycle of the gate driver for the boost converter on the PV side.

3.2. Power Limit and Battery Access Operation of the Inverter

When the inverter is in power limit and battery access operation, the deviation between the inverter output power limit value $P_{\text{inv,limit}}$ and the inverter output power $P_{\text{inv}}$ is
negative; hence, the inverter-side power loop PI controller will reduce $i_{\text{inv}_1}$, after the comparison of $i_{\text{inv}_1}$ and $i_{\text{inv}_2}$, by taking the smaller operation, $i_{\text{inv}_1}$, as the reference current $i_{\text{inv}}$ of the inverter-side current loop PR controller, whereby the inverter output current will decrease with the decrease in $i_{\text{inv}_1}$. The corresponding control scheme is shown in Equation (4).

$$
\begin{align*}
(P_{\text{inv}} - P_{\text{inv}}) &\times (K_{p,\text{inv}} + \frac{K_{i,\text{inv}}}{s}) \times \frac{s}{s^2 + \omega_0^2} = i_{\text{inv}_1} \\
(i_{\text{inv}_1} - i_{\text{inv}}) &\times (K_{p,\text{inv}} + \frac{2K_{i,\text{inv}}}{s^2 + 2\omega_0s + \omega_0^2}) = D_{\text{inv}_1}
\end{align*}
$$

(4)

where $P_{\text{inv}}$ is the inverter output power, $K_{p,\text{inv}}$ is the proportional coefficient of the PI controller for the inverter power control loop, $K_{i,\text{inv}}$ is the integral coefficient of the PI controller for the inverter power control loop, and $D_{\text{inv}_1}$ is the duty cycle of the gate driver for the inverter.

The bus voltage will rise rapidly due to the decrease in inverter current, exceeding the bus voltage reference $V_{\text{bus}_1} + V_{\text{bus}_2}$, i.e., the bus voltage will exceed the bus voltage level B; hence, the battery side voltage loop PI controller will reduce $i_{\text{bat}_2}$, after the comparison of $i_{\text{bat}_2}$ and $i_{\text{bat}_1}$, by taking the smaller operation, $i_{\text{bat}_2}$, as the reference current $i_{\text{bat}_1}$ of the battery-side current loop PI controller, whereby the output current of the energy storage battery will decrease with the decrease in $i_{\text{bat}_2}$. When $i_{\text{bat}_2}$ decreases to a negative value, the battery becomes charged, absorbing excess power. The corresponding control scheme is shown in Equation (5).

$$
\begin{align*}
(V_{\text{bus}_1} + V_{\text{bus}_2} - V_{\text{bus}}) &\times (K_{p,\text{bat}} + \frac{K_{i,\text{bat}}}{s}) = i_{\text{bat}_2} \\
(i_{\text{bat}_1} - i_{\text{bat}_2}) &\times (K_{p,\text{bat}} + \frac{K_{i,\text{bat}}}{s}) = D_{\text{bat}_2}
\end{align*}
$$

(5)

where $K_{p,\text{bat}}$ is the proportional coefficient of the PI controller for the bus voltage control loop, $K_{i,\text{bat}}$ is the integral coefficient of the PI controller for the bus voltage control loop, and $D_{\text{bat}_2}$ is the duty cycle of the gate driver for the bidirectional DC–DC converter on the battery side.

PV still works in the MPPT mode.

3.3. Power Limit and Battery Disconnection Operation of the Inverter

When the inverter is in inverter power limit and battery disconnection operation, the BES is no longer involved in power regulation, and the bus voltage will also rise rapidly because the inverter current follows the decrease in the inverter current reference $i_{\text{inv}_1}$, exceeding the bus voltage reference $V_{\text{bus}_1} + V_{\text{bus}_2}$, i.e., the bus voltage will exceed the bus voltage level C; hence, the photovoltaic side voltage loop PI controller will reduce $i_{\text{PV}_2}$, after the comparison of $i_{\text{PV}_2}$ and $i_{\text{PV}_1}$, by taking the smaller operation, $i_{\text{PV}_2}$, as the reference current $i_{\text{PV}_1}$ of the PV side current loop PI controller, whereby the output current of the PV will decrease with the decrease in $i_{\text{PV}_2}$. As a result, the PV output voltage will rise, far away from the maximum power point, and work in power limit mode. The corresponding control scheme is shown in Equation (6).

$$
\begin{align*}
(V_{\text{bus}_1} + V_{\text{bus}_2} - V_{\text{bus}}) &\times (K_{p,\text{PV}} + \frac{K_{i,\text{PV}}}{s}) = i_{\text{PV}_2} \\
(i_{\text{PV}_2} - i_{\text{PV}_1}) &\times (K_{p,\text{PV}} + \frac{K_{i,\text{PV}}}{s}) = D_{\text{PV}_2}
\end{align*}
$$

(6)

where $K_{p,\text{PV}}$ is the proportional coefficient of the PI controller for the bus voltage control loop, $K_{i,\text{PV}}$ is the integral coefficient of the PI controller for the bus voltage control loop, and $D_{\text{PV}_2}$ is the duty cycle of the gate driver for the boost converter on the PV side.
4. Simulation Results and Discussion

In order to verify the proposed control strategy, the system simulation model shown in Figure 1 was established in MATLAB/SIMULINK. The photovoltaic module in the household photovoltaic energy storage system was adopted from the Simscape Electrical Specialized Power Systems Renewable Energy Block Library in Matlab/SIMULINK. The photovoltaic module’s ambient temperature was set to 25 °C, and the illuminance was set to 1000 W/m². Each photovoltaic module had an open circuit voltage of 37.5 V and a short-circuit current of 11.1 A. The maximum power point voltage and current were 30 V and 10 A, respectively. The number of PV series-connected modules per string was 10, and the number of parallel strings was 1. The battery was adopted from the Simscape Electrical Specialized Power Systems Electric Drives Library in Matlab/SIMULINK. The system parameters are shown in Table 2.

Table 2. Main parameters of the household photovoltaic energy storage system.

| PV Arrays and Boost Converter       |                  |
|------------------------------------|------------------|
| PV open-circuit voltage            | $V_{oc}$         |
| PV short-circuit current           | $I_{sc}$         |
| PV maximum power point voltage     | $V_{mp}$         |
| PV maximum power point current     | $I_{mp}$         |
| PV maximum power                   | $P_{mp}$         |
| Filter capacitor                   | $C_{pv}$         |
| Filter inductor                    | $L_{pv}$         |
| Battery and Bidirectional DC-DC Converter |                  |
| Battery nominal voltage            | $V_{bat}$        |
| Battery maximum charge current     | $I_{charge\_limit}$ |
| Battery maximum discharge current  | $I_{discharge\_limit}$ |
| Battery internal resistance        | $r$              |
| Filter capacitor                   | $C_{bat}$        |
| Filter inductor                    | $L_{bat}$        |
| Grid and Inverter                  |                  |
| Grid voltage (RMS)                 | $V_{grid}$       |
| Grid frequency                     | $\omega$         |
| Filter capacitor                   | $C_{f}$          |
| Filter inductor                    | $L_{f}$          |
| DC Bus                             |                  |
| Bus voltage                        | $V_{bus}$        |
| Bus capacitor                      | $C_{bus}$        |
| Common Parameters for All converters|                 |
| Sampling frequency                 | $f_s$            |
| Switching frequency                | $f_{sw}$         |

At the initial moment, PV works in maximum power point tracking mode, its output power $P_{pv}$ is 3000 W, the battery output power $P_{bat}$ is 1600 W, the inverter output power $P_{inv}$ is 4600 W, and the inverter output power limit value $P_{inv\_limit}$ is 5000 W. The bus voltage reference $V_{bus\_ref}$ is 360 V, the bus voltage reference $V_{bus\_ref} + V_{bus\_bat}$ is 370 V, and the bus voltage reference $V_{bus\_ref} + V_{bus\_pv}$ is 385 V.

Figure 3 describes the relationship among the inverter output power limit value $P_{inv\_limit}$, the inverter output power $P_{inv}$, the battery energy storage output power $P_{bat}$, and the PV output power $P_{pv}$. Figure 3 is subdivided into four regions ($R_1, \ldots, R_4$). In each region, the
The dynamic change processes of bus voltage $V_{bus}$, PV voltage $V_{pv}$, inverter output current $I_{inv}$, battery output current $I_{bat}$, and PV output current $I_{pv}$ are shown in Figure 3a–d.

In region $R_1$, the inverter output power limit $P_{inv\_limit}$ is reduced from 5000 W to 3500 W. The inverter current decreases with the decrease in $P_{inv\_limit}$, whereas the bus voltage increases rapidly from 360 V and stabilizes at 370 V when the power limit command ends. The increase in bus voltage is used as a control signal of the battery current to reduce the battery output current, thereby reducing the battery output power from 1600 W to 500 W. PV is the same as the initial moment, still carrying out the maximum power output, and its power is 3000 W. The inverter output power is reduced from the initial 4600 W to the inverter power limit value of 3500 W.

![Figure 3. The relationship among the power, voltage, and current of a household photovoltaic energy storage inverter. Dynamic changes of voltage and current in (a) region $R_1$ (b) region $R_2$ (c) region $R_3$ (d) region $R_4$.](image)

In region $R_2$, the inverter output power limit $P_{inv\_limit}$ continues to decrease from 3500 W to 1500 W. The inverter current continues to decrease following the decrease in $P_{inv\_limit}$. The increase of the bus voltage is still used as a control signal for the battery current, and the battery output current continues to decrease, such that the battery output power changes from discharging 500 W to charging 1500 W. PV still works in the maximum power point tracking state, and its output power remains at 3000 W. The inverter output power is reduced from 3500 W to the inverter power limit value of 1500 W.
In region $R_3$, the battery is disconnected and no longer participates in power regulation; thus, its output power is zero. The bus voltage rises rapidly before finally stabilizing at 385 V. The increase in bus voltage is used as the control signal of the PV output current to reduce the photovoltaic output current, such that the PV output power is reduced from 3000 W to the inverter power limit value of 1500 W, which meets the requirements of the inverter output power limit.

In region $R_4$, the inverter output power limit $P_{\text{inv\_limit}}$ is increased from 1500 W to 4000 W, and the inverter output current increases with the increase in $P_{\text{inv\_limit}}$. The bus voltage is restored to 360 V, the PV power limit is released, and the maximum power point tracking is continued to achieve the maximum power output, whereby its output power is 3000 W.

In the above process of limiting the output power of the inverter, when the battery is connected to the bus through a bidirectional DC–DC converter, the power regulation by the battery is implemented preferentially. When the battery does not have power regulation capability, the PV output power can also be effectively limited to the inverter output power limit value.

5. Experimental Verification

In order to further verify the effectiveness of the proposed household photovoltaic and energy storage inverter power limit control strategy, we built an experimental platform, as shown in Figure 4. The experimental platform consisted of a photovoltaic and energy storage inverter, PV simulator, lithium battery, power grid interface, oscilloscope, and power analyzer. The parameters of the photovoltaic energy storage inverter and the grid parameters were the same as the simulation parameters given in Table 2. The voltage range of the lithium battery was 100–500 V, the working voltage during the test was 425 V, the maximum charge/discharge current was 25 A, and the maximum charging power was 2000 W. The model of the PV simulator was Chroma-62150H-600S, with an open-circuit voltage of 360 V, short-circuit current of 11 A, maximum power point voltage of 300 V, and maximum power point current of 10 A. The power–voltage curve and current–voltage curve of the PV simulator are shown in Figure 5. The oscilloscope model was YOKOGAWA-DLM2024, which was responsible for measuring the inverter output voltage and the inverter output current. The power analyzer model was YOKOGAWA-WT1806E, and the sampling period was set to 100 ms. The power analyzer was responsible for measuring the effective value of bus voltage, inverter output voltage, inverter output current, photovoltaic output voltage, photovoltaic output current, battery output voltage, and battery output current. In addition, the power analyzer was responsible for measuring the active power output by the photovoltaic device, battery, and inverter.

At the initial moment (i.e., no power-limiting instruction sent), the battery output power $P_{\text{bat}}$ was 2000 W, the photovoltaic output power $P_{\text{pv}}$ was 3000 W, the inverter output power $P_{\text{inv}}$ was 5000 W, and the inverter output power limit value $P_{\text{inv\_limit}}$ was 5000 W. The voltage of bus voltage level A was 470 V, the voltage of bus voltage level B was 480 V, and the voltage of bus voltage level C was 495 V.
The experiment consisted of four stages, corresponding to the four stages \((R_1, \ldots, R_4)\) in Figure 6, as described in detail below. At each stage, the bus voltage, and the voltage, current, and active power of the photovoltaic device, battery, and inverter are shown in Figure 6a–d, respectively.
In region $R_1$, the inverter output power limit value $P_{\text{inv\_limit}}$ was reduced from 5000 W to 2000 W. The inverter current decreased with the decrease in $P_{\text{inv\_limit}}$. The bus voltage increased rapidly from 470 V to 480 V and consequentially stabilized. The increase in bus voltage was used as a control signal to reduce the battery output current, such that the battery output power changed from 2000 W (discharging) to 1000 W (charging). The photovoltaic device was in the same working state as the initial moment, still carrying out
the maximum power output, and its power was 3000 W. The inverter output power was reduced from the initial power (5000 W) to the limit value of 2000 W.

In region $R_2$, the inverter output power limit $P_{inv\_lim}$ continued to be reduced from 2000 W to 1000 W. The inverter current followed the decrease in $P_{inv\_lim}$. The increase in bus voltage was still used as the control signal of the battery, whereby the battery output current continued to decrease, such that the battery charging power was changed from 1000 W to 2000 W. The photovoltaic device still worked in the maximum power point tracking state, and its output power remained at 3000 W. The inverter output power was reduced from 2000 W to the inverter power limit value of 1000 W.

In region $R_3$, the inverter output power limit $P_{inv\_lim}$ was reduced from 2000 W to 0 W. Because the battery in the $R_2$ region reached the maximum charging power of 2000 W, it did not have the power adjustment capability at this stage and no longer participated in the power adjustment. Consequently, the bus voltage rose rapidly, before finally stabilizing at 495 V. The increase in bus voltage was used as the control signal of the photovoltaic to reduce the photovoltaic output current, thereby reducing the photovoltaic output power from 3000 W to 2000 W. The inverter output power was reduced from 2000 W to the inverter power limit value of 0 W.

In region $R_4$, the inverter output power limit $P_{inv\_lim}$ was increased from 0 W to 5000 W, the inverter output current followed the increase in $P_{inv\_lim}$, and the bus voltage returned to 470 V. The battery and photovoltaic device were released from the power limit state. Under this state, the battery output power was 2000 W, and the photovoltaic device continued to track the maximum power point to achieve the maximum power output (3000 W).

The experimental results show that, in the process of limiting the output power of the inverter, the output power of the inverter could respond quickly within 200 ms according to the power instructions. The inverter output current was in the same frequency and phase as the grid voltage, ensuring the quality of the inverter output power. The change in bus voltage was used as a control signal for photovoltaic and energy storage. When the battery had the power adjustment capability, the power adjustment was performed by reducing the battery output current preferentially. When the battery did not have power regulation capability, the photovoltaic output power could also be effectively limited to the inverter output power limit value by reducing the photovoltaic output current. Table 3 shows the comparison between the experimental results of this research and the demand-side management method, modified MPPT algorithm, and energy storage battery access method.

| Categories                  | Method                  | Response | Advantage                                      | Disadvantage                           |
|-----------------------------|-------------------------|----------|-----------------------------------------------|----------------------------------------|
| Demand-side management      | Resistance Consumption [14] | -        | Easy implementation                            | Energy is lost in heat generation      |
|                             | Household load consumption [15] | -        | Reusable energy                               | Complex implementation and instability |
|                             | PV switching [16]        | -        |                                               |                                        |
| Modified MPPT algorithm     | Power-based [17,18]      | 1 s      | Once for all investments                      | Nonoptimal utilization of installed PV |
|                             | Current-based [18,19]    | 0.2 s    |                                               |                                        |
|                             | Voltage-based (right side) [20–22] | 0.1 s   |                                               |                                        |
|                             | Voltage-based (left side) [23,24] | -        |                                               |                                        |
|                             | Voltage-based (both sides) [25] | 0.1 s   |                                               |                                        |
| Energy storage access       | Current control [26–29]  | 0.2–0.5 s| Reusable energy and power regulation          | SOC limitation                         |
| This work                  | Coordinated control      | 0.2 s    | Simple, fast, and coordinated                 | Irradiance fluctuation-sensitive      |

Table 3. Comparison of power-limiting control methods.
The comparison results show that the realization of the power-limiting control strategy in this study was relatively simple. The limited power command response time was relatively short, i.e., between that of the modified MPPT algorithm and the energy storage access method. The coordination of the modified MPPT algorithm and the energy storage access method was realized in this paper. Moreover, whether using the modified MPPT algorithm or the accessing energy storage to limit the output power of the inverter, the bus voltage was stabilized due to the reduction in photovoltaic and battery output power. In this case, the stabilization of the bus voltage was passive. In this paper, the bus voltage was used as a control signal, and it was quickly stabilized by photovoltaic devices or batteries. This involved a process of actively stabilizing the bus voltage, not only effectively reducing the waste of energy, but also ensuring the safe and stable operation of the power grid. When the battery no longer had the power regulation capability, the method of reducing the photovoltaic output current was adopted to make the inverter output power meet the power command requirements. This method was less robust under a sudden decrease in irradiance, which deserves further attention in future studies.

6. Conclusions

Aiming at the limitation of the method of modifying the MPPT algorithm and battery access when the household photovoltaic inverter limits the active power output, a coordinated power limit control strategy was proposed. This strategy uses the bus voltage as the control signal. When limiting the output power of the inverter, the energy storage battery participates in power regulation preferentially. When the SOC of the BES reaches the limit, the PV output power is limited to change the working point of the PV on the MPPT curve, such that the active power feed into the grid is maintained within the set limit. The simulation and experimental results consistently indicate a synchronized inverter current with grid voltage and a rapid power response of the power limiting instruction within 0.2 s. The power limit control strategy can effectively improve the utilization of PV and ensure the safe and stable operation of the power grid.

Author Contributions: Conceptualization, Z.X. and Y.S.; methodology, Z.X., H.F., and Y.S.; software, Z.X. and S.T.; validation, Z.X. and J.S.; writing—original draft preparation, Z.X. and S.T.; review and editing, Z.X., H.F., J.S., and Y.S.; supervision, Y.S.; project administration, Z.X. and Y.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (Grant No. 2018YFB1500904 and No. 2019YFB2103200), the Key Scientific Research Program of Shanghai (Grant No.18DZ1203305), and the Shanghai Engineering Research Center for Artificial Intelligence and Integrated Energy Systems (Grand No. 19DZ2252000).

Acknowledgments: This work was supported by the AISWEI Renewable Energy Technology (Jiangsu, China) Co., Ltd. for engineering verification.

Conflicts of Interest: The authors declare no conflict of interest.

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