MA Filter-based Modeling and Control of Smoothing Photovoltaic Power Fluctuations by Inverter Air Conditioners

Lizhong Xu¹, Kang Xie²*, Chunliang Lu¹, Taoyi Qi², Xiang Ma¹, Leiyan Lv¹ and Yu Yao²
¹State Grid Zhejiang Electric Power Co., Ltd
²College of Electrical Engineering, Zhejiang University
* xiekang@zju.edu.cn

Abstract: Renewable energies (RES) will receive higher attention in the future, and continuously increase the penetration rate in the power system to achieve low carbon goal. However, the volatility and intermittent nature of RES generation caused by the uncertainty of the weather have brought huge challenges to the safe and stable operation of the power system. IACs have become a substitute for traditional power plants to accommodate RES by changing their operating power. This paper proposes a control method based on the MA filter to smooth photovoltaic generation power fluctuations utilizing inverter air conditioners (IACs). The photovoltaic power data is filtered by the MA filter in real time firstly. An output power with little fluctuations and one power deviation with high frequency fluctuations are obtained. The power deviation with high frequency fluctuations will be smoothed by IACs, while the remaining power deviation will be smoothed by ESSs. The case studies show a smooth power output is obtained for the power system after filtering.

Key word: MA filter-based modeling and control; Smoothing photovoltaic power fluctuations; Inverter air conditioners (IACs).

1. Introduction
Since the signing of the Paris Agreement, major countries in the world have established action plans to achieve the ambitious goals of the carbon peaking and the carbon neutrality [1]. For example, China has promised that carbon dioxide emissions will reach the highest level by 2030 and will gradually decrease thereafter, i.e. realizing the carbon peaking. Before 2060, China's carbon dioxide emissions will be completely offset through a series of energy saving and emission reduction measures [2]. Therefore, more RES facilities will be installed to replace fossil energy generating units, e.g. China's RES generation installed capacity accounting for more than half before 2025, according to China National Energy Administration [3]. However, due to the uncertainty of the weather, renewable energies (RES) have huge volatility and intermittent, which is difficult to predict and control. It is great challenge for the power system to provide enough operating reserve to balance electricity generation and consumption. Urbanization has also brought about a leap in urban power consumption, especially the air conditioner. For example, at peak period of the summer electricity consumption, air-conditionings (ACs) can account for 40% or even higher [4]. Due to the thermal inertia of the room, temporarily reducing the cooling capacity of ACs will not have much impact on the user. With the improvement of communication technology, flexible resources can provide regulation capacity for the power system by remote control. Meanwhile, inverter air conditioners (IACs) account for a huge share of ACs, which is the mainstream...
type of ACs. Therefore, IACs have become a substitute for traditional power plants to accommodate RES by changing their operating power. Many researches have focused on modeling and control of IACs to participate in demand response (DR) [5].

Besides, a lot of research has paid attention to smoothing photovoltaic power fluctuations or accommodating photovoltaic power. Reference [6] proposes a model predictive control (MPC) based on power/voltage smoothing strategy. The predictive control method are also used to avoid photovoltaic output power by the ESS and the EV. The user's comfort and willingness to participate are not considered in references. The frequency regulation method utilizing flexible resources is proposed to directly participate in the regulation of the power system in References [10-12]. However, this method of directly participating in the power system regulation has uncertainties. Therefore, it is essential to reduce the photovoltaic power fluctuations in real time.

To issue these challenges, the moving average (MA) filter-based strategy is proposed in this paper to smooth photovoltaic power fluctuations by IACs. The remaining of this paper is organized as follows. Section 2 establishes the MA filter-based IACs regulation model and control frame. The MA filter-based control strategy is developed to smooth photovoltaic fluctuations in Section 3. Case study is carried out in Section 4, and finally Section 5 concludes this paper.

2. Modeling of IACs smoothing photovoltaic power fluctuations

2.1. Modeling of the IAC

The first-order ETP model is widely used to describe room temperature [13], which can be expressed by

\[ C' \frac{dT(t)}{dt} = Q'_{\text{ac}}(t) + Q'_{\text{a}}(t) + Q'_{\text{o}}(t) \]

where \( C' \) is the equivalent thermal capacity of the room; \( Q'_{\text{a}} \) is the thermal power generated indoors, from people, electric appliances and other disturbance factors; \( Q'_{\text{ac}} \) and \( Q'_{\text{o}} \) are the cooling power of the IAC and heat transfer of the outdoor air, respectively. \( Q_{\text{a}} \) can be described as

\[ Q'_{\text{a}}(t) = \frac{T_{\text{a}}(t) - T_{\text{r}}(t)}{R'_{\text{a}}} \]

where \( R'_{\text{a}} \) is the equivalent thermal resistance of the room.

Compared with fixed frequency air conditioners, inverter air conditioners can be flexibly adjusted between zero power and maximum power. The cooling power of the AC can be obtained based on the proportional-integral (PI) controller, which can be expressed by

\[ Q'_{\text{ac}}(t) = K_p \left( T_{\text{r}}(t) - T_{\text{r}m} \right) + K_i \int \left( T_{\text{r}}(t) - T_{\text{r}m} \right) dt \]

where \( K_p \) and \( K_i \) are the proportion coefficient and the integral time constant of the IAC; \( T_{\text{r}m} \) is the reference value of the room temperature.

Besides, the relationship of the cooling power \( Q_{\text{ac}} \) and the electric power \( P_{\text{ac}} \) can be described as

\[ Q'_{\text{ac}}(t) = \kappa_{\text{ac}} P_{\text{ac}}(t) \]

where \( \kappa_{\text{ac}} \) is the energy efficiency ratio (EER) of the AC. Due to the thermal inertia of the room, the IAC can change the operating power to provide regulation capacity for the power system, without affecting user comfort. Multiple IACs can be aggregated and equivalent to one IAC by the equivalence of parameters [14], which will be used in this paper to simplify the regulation process.
2.2. Modeling of the MA filter

The Moving average (MA) filtering is a widely used filtering method that can filter out high-frequency components to obtain useful low-frequency data. The MA filter treats consecutive N sample values as a queue and calculates their average value. Then the newly sampled data is placed at the end of the queue, and the original data at the head of the queue is discarded. By repeating this process in this way, new filtering results can be obtained.

The MA filter in this paper is designed to achieve real-time control, which can be described as

$$H_{ma}(z) = \frac{1 - z^{-N}}{N(1 - z^{-1})}$$  \hspace{1cm} (5)

The magnitude-frequency curve of which is shown in the Fig. 1, when N is 2000 and 3600.

2.3. Control framework of IACs smoothing fluctuations

As shown in the Fig. 2, photovoltaic real-time data will be first input into the MA filter to obtain high-frequency components, where low-frequency components will be directly transmitted to the power system. IACs can absorb high-frequency power components by adjusting their operating power, which will be studied in the Section 3. However, IACs may not be able to smooth all high-frequency fluctuations, and these remaining deviations that cannot be smoothed will be accommodated by energy storage systems (ESSs). Therefore, the fluctuations of photovoltaic output power can be effectively smoothed.

3. MA filter-based control strategy for smoothing fluctuations

As shown in Fig. 3, before starting a new round of the control strategy, the operating parameters of IACs and photovoltaic operating data will be input, and at the same time, the parameters of the MA filter will be set.
Then, $t_{pv}$ will first be judged whether it exceeds the control cycle duration $\tau_s$ to determine whether it is necessary to reselect IACs participating in demand response (DR). When $t_{pv} \geq \tau_s$, the system operation operator (ISO) will reselect IACs that can provide regulation capacity in the DR according to the power system demand and set $t_{pv} = 0$.

Next, the filtering control process will begin. The photovoltaic generation power with large fluctuations is filtered by the MA filter in real time.

Calculate the output power after filtering and will be delivered to the power system.

Calculate the power deviation after filtering, which is smoothed by the IACs.

User comfort?

No

Yes

The IAC quits smoothing process.

Calculate the remaining power deviation after smoothing, which is smoothed by the ESSs.

Photovoltaics end?

No

Yes

Control strategy stops operating.

**Figure 3.** MA filter-based control strategy for smoothing photovoltaic fluctuations.

Next, the filtering control process will begin. The photovoltaic generation power with large fluctuations is filtered by the MA filter in real time. After filtering, a relatively stable output power $P_{pv}^{st}$ and a power deviation $P_{pv}^{de}$ will be obtained, where the former i.e. $P_{pv}^{st}$ will be directly transmitted to the power system. The power deviation $P_{pv}^{de}$ can be smoothed by the IAC by changing its operating power $P_{iac}^{s}$. During the control cycle, the indoor temperature $T_r$ of the IAC will be monitored to ensure user comfort. If $T_r$ exceeds comfort range $[T_r - \Delta T, T_r + \Delta T]$, the IAC will quit participating in smoothing photovoltaic power fluctuations.

However, there still is a remaining power deviation $P_{pv}^{de}$ after smoothing, which can be described as

$$P_{pv}^{de} = P_{pv}^{de} - P_{ic}^{s}$$  \hspace{1cm} (6)

where $P_{pv}^{de}$ will be smoothed by the ESS, which is not considered in this paper.

Finally, $t_{pv}$ will increase by one second to enter the next control cycle, when the photovoltaic is still running. Otherwise, this control process will end.
4. Case study

4.1. Test system

The test system consists of photovoltaics and IACs. The photovoltaic power data comes from real generation data every second for ten hours in a certain area of eastern China, as shown in Fig. 4. It is considered that the initial parameters of the equivalent model of IACs selected at each period \( \tau \) are the same. The initial parameters of the equivalent IAC are shown in Table 1. The feedforward link order \( N \) of the MA filter is set to 1500. The ambient temperature is selected from the real data of a certain day in summer in a certain area of eastern China, which changes every hour, which is 27.5°C, 29°C, 30.5°C, 32°C, 33.5°C, 35°C, 33.5°C, 32°C, 30.5°C, 29°C, respectively. Besides, the time duration \( \tau \) and the acceptable temperature range \( \Delta T \) is set 300 seconds and 1 °C.

### Table 1. The parameters of the equivalent IAC.

| Parameter name                  | Parameter symbol | Parameter value | Parameter unit |
|---------------------------------|------------------|-----------------|----------------|
| Equivalent thermal capacity    | \( C_a \)        | 4.44E-06        | kJ/°C          |
| Equivalent thermal resistance  | \( R_{ao} \)     | 1.82E+10        | kW/°C          |
| Room set temperature           | \( T_{set} \)    | 25              | °C             |
| Initial room temperature       | \( T_{in} \)     | 25              | °C             |
| Proportion coefficient         | \( K_p \)        | 100000          | kW/°C          |
| Integral time constant         | \( K_{in} \)     | 4000            | kW/(°C·s)      |
| Maximum cooling capacity       | \( Q_{ac \max} \) | 8E+04           | kW             |
| Minimum cooling capacity       | \( Q_{ac \min} \) | 0               | kW             |
| Maximum power change rate      | \( R_{ac \max} \) | 4E+04           | kW/s           |
| Minimum power change rate      | \( R_{ac \min} \) | -4E+04          | kW/s           |
| Energy efficiency ratio        | \( \kappa_{ac} \) | 3               | N/A            |

4.2. The performance analysis of the control strategy

Based on the proposed control strategy in section 3, photovoltaic power fluctuations are smoothed by the IAC. Fig. 4 shows the original photovoltaic power and the output power after filtering. As we have seen, the huge fluctuations of the photovoltaic output power are filtered out by the MA filter, and the stable output power can be easily accommodated by the power system.

In addition, the filtered power deviation is shown in Fig. 5, which has huge high-frequency fluctuations. In order to accommodate this component, the IAC of the demand side is used in the proposed control strategy, which can continuously adjust the operating power. As shown in Fig. 5, the
operating power change of the IAC can track the high-frequency power deviation. However, there is still a remaining power deviation due to the limitation of the change rate of the IAC power and the limitation of the room comfort. This part of the power deviation $P_{pv}^d$ is much smaller than the initial power deviation $P_{pv}^i$ and can be easily smoothed by the ESS.

![Figure 5. The power deviation is smoothed by the IAC.](image)

Besides, the proposed control strategy takes into account the comfort of the IAC users, i.e. the room temperature. As shown in Fig. 5, the room temperature change is limited in the acceptable range. As we have seen, when the deviation power is too large, the indoor temperature will fluctuate sharply, causing the IAC to withdraw from participating in smoothing photovoltaic power fluctuations. Therefore, it is crucial to choose more IACs to participate at this moment.

5. Summary
The global carbon peaking and carbon neutrality targets determine the increase in the penetration rate of RES. Therefore, more traditional thermal power units are needed to provide enough regulation capacity for dealing with the uncertainty of RES, which is not a low-carbon measure. Besides, urbanization has been bringing about a gradual increase of the urban load, even accounting for about 40% of the peak load in summer, especially IACs.

The control strategy is proposed in this paper to smooth photovoltaic fluctuations by IACs. The photovoltaic power data is filtered by the MA filter in real time firstly. An output power with little fluctuations and one power deviation with high-frequency fluctuations are obtained. The power deviation with high-frequency fluctuations will be smoothed by IACs, while the remaining power deviation will be smoothed by ESSs. The case studies show a smooth power output is obtained for the power system after filtering.

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