Phase-Locked Strategy of Photovoltaic Connected to Distribution Network With High Proportion Electric Arc Furnace

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ABSTRACT With the rapid development of industrialization, the proportion of electric arc furnaces (EAF) in distribution networks is getting higher and higher. Aiming at the problem that grid voltage is distorted by a large number of arc furnace nonlinear loads accessing to distribution networks, it is crucial to make dynamic analysis of distribution network voltage and adopt a control strategy of grid-connected converter based on the new phase-locked loop (PLL) technology. As a result, the harmonic distortion rate is reduced and the quality of grid-connected current and voltage is improved. In this paper, photovoltaic (PV) system model and the typical dynamic model of the EAF are established. By analyzing the influence of the EAF model on the PV grid-connected converter with the traditional phase-locked loop while connected to distribution network, a control strategy of the PV grid-connected converter with the self-adjusting double SOGI (MAF-SASOGI) phase-locked loop with the ideal low-pass filter is proposed. Through the simulation analysis, it is verified that precise phase locked can be realized and harmonic content of the system can be reduced by the PLL strategy proposed in this paper. Therefore, the quality of PV grid-connected voltage and current is improved.

INDEX TERMS Distribution network, electric arc furnaces (EAF), voltage distortion, photovoltaic (PV) grid-connected, phase-locked strategy.

I. INTRODUCTION

With the depletion of fossil fuel reserves, renewable energy (RES) will become an increasingly important part of power generation. Among the existing RES technologies, solar energy has become the most promising choice because it is ubiquitous and environmentally friendly [1], [2]. It is the advantages of solar energy that make PV system more and more widely applied in developed and developing countries [3]–[5]. However, with the rapid economic development in various countries, electric load is simultaneously growing rapidly. Especially, the wide application of the impact load of the AC arc steelmaking furnace [6]–[8] has caused voltage distortion of distribution network, which seriously affects the effective grid connection of the PV system, and brings great challenges to the application of the PV system. The International Electrotechnical Organization’s IEEE std.1547 and China’s national standard GB/T 14549-93 and other grid specifications allow a certain proportion of harmonics applied in industrial grid [9], [10]. However, under grid voltage distortion conditions, the phase-locked loop in PV grid-connected converters designed with the ideal grid voltage as a constraint will no longer be phase-locked accurately. It may cause the harmonic content of grid-connected current to exceed IEEE Std.1547-2 and IEEE Std.1547-4 allowable range [11], [12], and further pollutes the power grid and disrupts its stability.

A series of research on the PLL control strategy of the PV grid-connected converter has been done worldwide. It is demonstrated in [13], [14] that one of the most commonly used synchronous reference frame phase locked loop (SRF-PLL) technologies in PV grid-connected. Yet, the PLL is
only suitable for the ideal grid voltage. When the distribution network voltage is distorted, the voltage components of d-axis and q-axis obtained after Park change are no longer constant, which will lead to a large phase-locked error. A phase-locked strategy for zero crossing control of power grid voltage is proposed in reference [15]. Although this strategy has a good effect when the power grid voltage is stable, it will not be accurate when the distribution network voltage is distorted. In [16], the strategy of delay is used to separate the positive and negative sequence voltage, but the delay time is a fixed value. When the distribution network voltage is distorted, the grid frequency will no longer be constant, and there will be a large error in phase locked. In order to make PLL still applicable to distribution network voltage distortion, some scholars have proposed PLL strategy based on multiple filters [17], PLL strategy based on complex coefficient filter [18], [19], and PLL strategy based on cross decoupling in αβ coordinate system [20]. Although these several phase-locked techniques have certain effects when the voltage of the distribution network is slightly distorted, when the voltage of the distribution network is severely distorted, these methods require multiple filter units to achieve effective phase-locked. Therefore, when the voltage distortion of distribution network is serious, using the above lock-in techniques not only increases the calculation burden, but also consumes a lot of resources. Various control strategy such as a phase-locked strategy based on second-order generalized integral [21], [22], a high-resolution SOGI-PLL phase-locked strategy [23], an improved control strategy based on negative sequence component compensation [24] etc. have been recently proposed for the control of PLL. Although these PLL control strategies are feasible to some extent, there are still large errors in PLL due to the disadvantages of poor dynamic performance and a small amount of harmonics in the positive sequence voltage component. In [25], a control strategy of SOGI-PLL based on self-regulation technology is proposed. Although this technology can filter out a large number of harmonics in the system, there are still some higher harmonics, which will reduce the accuracy of the PLL. 

Therefore, in order to effectively connect the PV system to the grid even when the distribution network voltage is seriously distorted, this paper proposes a self-adjusting dual SOGI phase-locked strategy based on the ideal low-pass filter. EAF load, a mathematical model of EAF load grid-connected is constructed. According to the characteristics of EAF, the simulation model of EAF is established by solving the nonlinear differential equation in harmonic domain. The energy equation of EAF is [26]:

\[
C_1 r^n + C_2 \frac{dr}{dt} = \frac{C_3}{r^{m+2}} \dot{r}^2
\]

where \(i\) is the arc current, the unit is kA, \(r\) is the arc radius, the unit is m, \(C_1\) is the correction coefficient of the high-order term, \(C_2\) is the correction coefficient of the low-order term, \(C_3\) is the correction coefficient of the constant term, and \(n, m\) are variable parameters.

According to Ohm’s law, the EAF voltage in the EAF model is:

\[
u = \frac{i}{g}
\]

where \(g\) is the conductance of arc, and the relationship between the arc radius and the constant term correction coefficient can be defined as:

\[
g = \frac{r^{m+2}}{C_3}
\]

In this paper, if \(n = 2\) and \(m = 1\) are taken, equation (1) is:

\[
C_1 r^4 + C_2 r^2 \frac{dr}{dt} = C_3 \dot{r}^2
\]

By solving equation (4), the EAF radius is obtained as follows:

\[
r(t) = \left\{ \left[ \frac{\frac{5C_3}{C_2} \frac{2C_1}{C_2} \dot{r}^2 dt}{e^{\frac{C_1}{C_2}} - e^{-\frac{C_1}{C_2}}} \right]^\frac{1}{2} + C_m \right\}
\]

where \(C_m\) is the initial value of arc radius. Take the current as:

\[
i = I_m \sin(2\pi ft)
\]

The expression of arc radius in one cycle can be obtained:

\[
r(t) = \left\{ \frac{C_3 I_m^2}{2C_1} - r_1(t) r_2(t) + C_m e^{\frac{2C_1}{C_2} t} \right\}^\frac{1}{3}
\]

In equation (7):

\[
r_1(t) = \frac{C_3 I_m^2}{2C_1^2 + \left( \frac{4\pi fC_2}{5} \right)^2}
\]

\[
r_2(t) = \left\{ C_1 \cos4\pi ft + \frac{4\pi fC_2}{5} \sin4\pi ft \right\}
\]

A random function is added to arc radius to simulate the randomness of arc starting and material collapse in the EAF, so as to ensure that the model is closer to the actual operation. The expression of random arc radius is:

\[
r = r(t) \times R_x(t)
\]

where \(R_x(t)\) is a random function.

II. MODELS AND METHODS

A. MODELING OF EAF GRID-CONNECTED

Compared with other loads in power grid, EAF load has its obvious characteristics, non-linearity, impact and time-varying. When the EAF is connected to distribution network, grid connected voltage contains not only odd harmonic components, but also a large number of even harmonic components. When the grid-connected capacity of the EAF reaches a certain proportion, the impact of the grid-connected point voltage cannot be ignored. According to the characteristics of
It can be seen from the Figure 3, the distortion rate of distribution network voltage is different when the different proportion EAF is connected. When the EAF is not connected into the distribution network, the total harmonic distortion (THD) rate at the bus is almost negligible. When the EAF is connected to the distribution network at a proportion of 25%, the THD rate of the bus is 10.31%, and the voltage distortion of the distribution network is not obvious due to the weak non-linearity and time-varying of the EAF. When the proportion of EAF increases to 50%, the EAF not only shows strong non-linearity and time-varying, but also presents the significant impact. Due to the full appearance of various characteristics of the EAF, the THD rate of the bus is 23.98%, and the voltage distortion of the distribution network is very obvious.

B. MODELING OF PV GRID-CONNECTED

1) MODELING OF PV ARRAY

The mathematical model of PV array is described in reference [27] by the author. At any temperature, the \( U-I \) equation of PV array is:

\[
I_{pv} = N_p I_{sc} \cdot \left(1 - C_1 [\exp(\frac{U_{pv} - dU}{C_2 N_p U_{oc}}) - 1] + dI \right) \quad (11)
\]

where \( C_1, C_2, dI \) and \( dU \) in (11) can be respectively written as shown in (12):

\[
\begin{align*}
C_1 &= (1 - I_m/I_{sc}) \cdot \exp(-U_m/C_2 U_{oc}) \\
C_2 &= (U_m/U_{oc} - 1) / \ln(1 - I_m/I_{sc}) \\
dI &= -\alpha \cdot G/G_{ref} \cdot (T_c - T_{ref}) + (G/G_{ref} - 1) \cdot N_p I_{sc} \\
dU &= \beta \cdot dT - R_s \cdot dI
\end{align*}
\]

where \( U_{oc} \) and \( I_{sc} \) are the open circuit voltage and short circuit current respectively, which are provided by the component manufacturer, \( U_m \) and \( I_m \) are the maximum power point voltage and current respectively, \( \alpha \) and \( \beta \) are the current and voltage temperature variation coefficients under the reference radiation intensity, \( R_s \) is the series resistance of the PV module, \( N_p \) and \( N_S \) are the number of PV modules in parallel and in series.

The output power of PV array at any solar radiation intensity and ambient temperature is:

\[
P_{pv} = U_{pv} I_{pv} (1 - K_{loss}) \quad \text{(13)}
\]

where \( K_{loss} \) is the series-parallel loss coefficient of PV modules in a PV array.

Maximum power point tracking (MPPT) algorithm has been described in detail in reference [28] by the author, and will not be described here.

\( U-I, U-P \) curves and MPPT processes of PV arrays under different solar radiation intensities are shown in Figure 4.
curve is highly nonlinear near the maximum power point. If the output voltage of the PV array is constant, the output current $I_{PV}$ increases in proportion to the irradiance. It can be seen from Figure 4 (b) that when the light intensity is constant, the output power $P_{PV}$ of PV array presents a non-monotonic trend with the change of its output voltage $U_{PV}$. When the output voltage $U_{PV}$ is low, the output power $P_{PV}$ of the PV array increases with the increase of the output voltage $U_{PV}$. When the output voltage $U_{PV}$ is high, the output power $P_{PV}$ of PV array decreases with the increase of the output voltage $U_{PV}$. The $U$-$P$ characteristic curve reflects the strong correlation between the output power of PV array and irradiation, and indicates that the smaller voltage interference near the maximum power point can lead to a greater power adjustment.

2) MODELING OF PV GRID-CONNECTED CONVERTER
In this paper, DC / DC and DC / AC cascaded PV grid-connected structure is adopted, and its specific structure and control are shown in Figure 5.

In Figure 5, $L$ is the inductance in the Boost module, $C_1$ is the DC-side capacitance, $V_D$ is diode, $L_L$ in LCL is inductance of filter at converter side, $C$ is filter capacitance, $u_a$, $u_b$ and $u_c$ are three-phase output voltage respectively, $u_{ga}$, $u_{gb}$ and $u_{gc}$ are three-phase output voltage of inverse respectively, $u_{dc}$ is the DC bus voltage, $i_{L_a}$, $i_{L_b}$ and $i_{L_c}$ are three-phase inductance current of filter at converter side respectively, $i_{L_a}$, $i_{L_b}$ and $i_{L_c}$ are grid-connected current respectively.

In the PV grid-connected control model, the PV side first lists its control equation (as shown in Equation 14) based on the $U$-$I$, $U$-$P$ characteristics and MPPT characteristics of the PV array, and controls the Boost circuit through this equation to obtain the DC-side voltage $u_{dc}$.

$$m_{pv} = (k_{ppv} + \frac{k_{ipv}}{s})(U_{mppt} - U_{pv})$$  \hspace{1cm} (14)  

The grid-connected voltage and current are turned into $I_{dpv}$, $I_{qpv}$ and $U_{dpv}$ through Park transformation. The grid-connected voltage obtained by voltage transformer is sent to MAF-SASOGI PLL to obtain the phase-locked angle $\theta$.

The errors of $u_{dpvref}$ and $u_{dc}$ are adjusted by PI controller to generate $i_{dpvref}$, then $i_{dpvref}$ and $i_{dpv}$ are adjusted by PI controller to calculate the gating signal $m_{dl}$. $i_{dpvref}$ is obtained by dividing $Q_{ref}$ by $u_{dpv}$, and then the error between $i_{dpvref}$ and $i_{qpv}$ is adjusted by PI controller to calculate the gating
signal $m_q$. The equation can be expressed as follows:

$$
\begin{align*}
    m_d &= \frac{u_{dc} - I_{dpv} \omega_0 L (k_{pd} + \frac{k_{id}}{s}) (I_{dpvref} - I_{dpv})}{u_{dc}} \\
    m_q &= \frac{I_{dpv} \omega_0 L + (k_{pq} + \frac{k_{iq}}{s}) (I_{dpvref} - I_{dpv})}{u_{dc}} \\
\end{align*}
$$

(15)

The phase-locked angle $\theta$ and the gate control signals ($m_d$ and $m_q$) are sent to the SPWM. The grid-connected converter of PV is controlled by the signals ($m_{ra}$, $m_{rb}$, and $m_{rc}$) obtained from following formula:

$$
\begin{align*}
    m_{ra} &= [m_d \cos(\theta - \pi/2) - m_q \sin(\theta - \pi/2)] \\
    m_{rb} &= [m_d \cos(\theta - \pi/2 - 2\pi/3) - m_q \sin(\theta - \pi/2 - 2\pi/3)] \\
    m_{rc} &= [m_d \cos(\theta - \pi/2 + 2\pi/3) - m_q \sin(\theta - \pi/2 + 2\pi/3)] \\
\end{align*}
$$

(16)

III. PHASE-LOCKED STRATEGY OF PV GRID-CONNECTED

According to the load characteristics of EAF, combined with the existing phase-locked method, a phase locked strategy based on MAF-SASOGI is proposed in this paper. The control block diagram is shown in Figure 6.

![FIGURE 6. Control model of grid-connected converter.](image)

The phase-locked strategy proposed in this paper overcomes the serious distortion of grid current caused by the inaccuracy of the traditional PLL, when the distribution network voltage is distorted. The phase-locked strategy based on SOGI and the secondary pollution of the grid voltage trigger serious distortion of the distribution network voltage (including a large number of odd and even harmonics). There are still large harmonic components in the separated positive sequence voltage, which affect the PV grid connection and other disadvantages.

The PLL strategy of MAF-SASOGI is established based on the fundamental principles of the traditional PLL shown in Figure 7 and the fundamental principles of the SOGI-PLL shown in Figure 8.

The ideal grid voltage only contains the positive sequence voltage related to the control part of PV grid-connected converter. However, when grid voltage is distorted, a large number of negative sequence voltage will be generated, which seriously affects the accuracy of PLL and the effectiveness of grid-connected PV system. By applying the SOGI-based PLL control strategy, separation of positive and negative sequence voltage can be realized and negative sequence voltage generated by voltage distortion can be separated. The quality of grid connected current is improved.

In Figure 8, there are two outputs, $Y(S)$ and $H(S)$. Expressions of band-pass filter and low-pass filter can be obtained from the schematic diagram as follows:

$$
\begin{align*}
    D(S) &= \frac{Y(S)}{F(S)} = \frac{K \omega_0 S}{S^2 + K \omega_0 S + \omega_0^2} \\
    Q(S) &= \frac{H(S)}{F(S)} = \frac{K \omega_0^2}{S^2 + K \omega_0 S + \omega_0^2} \\
\end{align*}
$$

(17)

(18)

where $F(S)$ is the input voltage, $\omega_0$ is the undamped natural angular frequency, $K$ is the damping coefficient.

The Bode diagrams of band-pass filter and low-pass filter with different damping coefficient $K$ are shown in Figure 9 and Figure 10 respectively.
According to Figures 9 and 10, the smaller the $K$ is, the narrower the pass-band is and the stronger the filtering ability is. In the phase frequency diagram, the smaller the $K$ is, the slower the curve declines and the longer the response time is. By comparison, when $K = 1.414$, the system has good stability and dynamic performance. Therefore, the damping coefficient in this paper is 1.414.

The waveform of positive and negative sequence voltage on $\alpha$ axis based on SOGI is shown in Figure 11. When the input signal distortion is very significant, the harmonic suppression capacity decreases near the resonant. As a result, the separated positive sequence voltage still has a large harmonic component. PV system is not effectively connected to the grid.

The MAF-SASOGI phase-locked strategy is proposed in this paper. The DC components and high-order harmonics of filter is solved when the distribution network voltage is distorted.

The PLL control strategy of adding self-regulation module and differential node with ideal low-pass filter (MAF) is shown in Figure 12. The detail description of the above module of phase-locked strategy is as follows.

The MAF transfer function of complex frequency domain is:

$$G_{MAF}(S) = \frac{1 - e^{-T_o S}}{T_o S}$$  \hspace{1cm} (19)

It can be simplified as follows:

$$G_{MAF}(S) = \frac{1}{1 + 0.5T_o S}$$  \hspace{1cm} (20)

where $T_o$ is the window width of MAF. $T_o = 0.01$ s, in this paper.

Mathematical expression equation of the improved SOGI included band-pass filter and low-pass filter are follows:

$$D'(S) = \frac{F''(S)}{F(S)} = \frac{k_S \cdot K\omega_0 S}{S^3 + K\omega_0 S^2 + (\omega_0 + k_S \cdot K\omega_0) S + K\omega_0^2 S}$$  \hspace{1cm} (21)
where \( k_s \) is self-adjusting coefficient and \( K \) is damping coefficient.

When the self-adjusting coefficient \( k_s \) is taken on different value, the bode diagrams of band-pass filter and low-pass filter are given in Figure 13 and Figure 14 respectively.

According to the amplitude frequency analysis of Figure 13 and Figure 14, when \( k_s \) is smaller in the amplitude frequency graph, the pass-band is narrower and filtering ability is stronger. When \( k_s \) is smaller in the phase frequency graph (as seen in Figure 13 and Figure 14), the curve declines slower and the response time is longer. When the self-regulation coefficient is 10, the system has better stability and dynamic performance through comparison and analysis.

It can be seen from Figure 12 and equation 19, output voltage \( F'(S) \) is obtained through the self-regulation coefficient \( k_s \). \( F'(S) \) is the same amplitude and phase as the input voltage \( F(S) \), but \( F'(S) \) has less harmonic content than \( F(S) \). \( F'(S) \) is sent to the SOGI module with the difference node containing MAF.

MAF can make the \( H''(S) \) severely damp at high-frequency band and prevent the high-order harmonics. The difference node can restrain the DC component and the low harmonic, and obtain \( F_\alpha(S) \), \( H_\alpha(S) \), \( F_\beta(S) \) and \( H_\beta(S) \) voltage components in the \( \alpha, \beta \) coordinate system.

The above voltage component is substituted into formulas (23) and (24). The positive sequence components \( (u^+_\alpha \) and \( u^+_\beta) \) and the negative sequence components \( (u^-_\alpha \) and \( u^-_\beta) \) of \( \alpha \) and \( \beta \) axis can be obtained.

\[
\begin{align*}
  u^+_\alpha &= \frac{1}{2}(F_\alpha''(S) - H_\beta''(S)) \\
  u^+_\beta &= \frac{1}{2}(H_\alpha''(S) + F_\beta''(S)) \\
  u^-_\alpha &= \frac{1}{2}(H_\beta''(S) + F_\alpha''(S)) \\
  u^-_\beta &= \frac{1}{2}(F_\beta''(S) - H_\alpha''(S))
\end{align*}
\] (24)

The positive and negative sequence voltage waveform on \( \alpha \) axis is shown in Figure 15. The positive and negative sequence voltage is separated based on the MAF-SASOGI.

It can be seen from the Figure 15, MAF-SASOGI control strategy can filtering out the DC component, low-order harmonic and high-order harmonic of distribution network voltage. Therefore, a sine voltage component with a very low THD is separated.

Grid-connected voltage of PV system is only related to the positive sequence voltage. The three-phase voltage \( u_{g1}, u_{gb1} \) and \( u_{gc1} \) that control the grid connected of PLL can be obtained through the Clark inverse transformation of the positive sequence voltage. The accurate phase-locked angle \( \theta \) can be obtained by sending the three-phase voltage \( (u_{g1}, u_{gb1} \) and \( u_{gc1}) \) to the basic PLL.

IV. EXAMPLE SIMULATION

In order to better verify the effectiveness of the PLL control strategy in the PV grid-connected converter in the distribution network of high proportion EAF, this paper constructs the system model based on the actual grid system, as shown in Figure 16. The power grid is mainly reduced from 220kv to 66kv bus by T2 transformer, and then reduced to 10kv BUS3 and BUS4 through transformer T3 and T4 respectively. High proportion EAF load is connected into Bus3 through industrial transformer T5. General commercial load and residential building are connected into Bus4 through common transformer T6. PV system is connected through transformer T7.

In this paper, traditional d-q PLL, PLL based on SOGI and PLL based on MAF-SASOGI are used to grid-connected PV system, respectively. The BUS4 voltage and harmonic content are compared and analyzed based on above three control strategies. Analysis scenarios include:

- PV is not connected to the distribution network.
PV grid-connected based on traditional d-q phase-locked strategy.
- PV grid-connected based on SOGI phase-locked strategy.
- PV grid-connected based on MAF-SASOGI phase-locked strategy.

In order to avoid the influence of transformer in the substation on the simulation results, the transformer adopts ideal transformer with Yyn wiring in each substation. The system simulation parameter and set value are shown in Table 1.
PV grid-connected based on this phase-locked strategy is seriously inconsistent with the IEEE Std. in recent years.

When using a PLL control strategy based on SOGI for grid-connected, THD of BUS4 is reduced to 11.83% (odd harmonic distortion is 10.70%, even harmonic distortion is 5.04%). The accuracy of the PLL is improved by SOGI. BUS4 voltage has been improved compared to traditional d-q PLL scenario. But, there are still a large number of low-order harmonics, high-order harmonics and DC components when the positive and negative sequence voltage is separated. Therefore the grid-connected PV is far from the desired result.

When the PV adopts the MAF-SASOGI phase-locked strategy proposed in this paper, because the MAF in the PLL can filter out the high-order harmonics, and the difference node can filter out the DC component and the low-order harmonics, the accuracy of the phase-locked strategy is significantly improved compared with the previous two scenarios. At this time, the THD of Bus4 is reduced to 2.88% (odd harmonic distortion of 2.72% and even harmonic distortion of 0.95%). The PV system can not only complete the effective grid-connected, but also improve the voltage distortion of Bus4.

![Voltage waveform separated into positive and negative sequence.](image1)

**FIGURE 15.** Voltage waveform separated into positive and negative sequence.

**FIGURE 16.** System diagram of example simulation.

| TABLE 1. Parameter settings of the simulation model. |
|-----------------------------------------------------|
| **Table 1.** Parameter settings of the simulation model. |
| Parameter | Value |
| --- | --- |
| $C_1$ | Higher-order correction factor | 5000 |
| $C_2$ | Low-order correction factor | 1 |
| $C_3$ | Constant term correction factor | 2.75 |
| $n$ | Variable parameter | 2 |
| $m$ | Variable parameter | 1 |
| $G_{ref}$ | Reference solar irradiance | 1000 W/m² |
| $T_{ref}$ | Reference cell temperature | 25 °C |
| $U_{oc}$ | Open circuit voltage | 45 V |
| $I_s$ | Short circuit current | 5.5 A |
| $U_{max}$ | Maximum power voltage | 36 V |
| $I_{max}$ | Maximum power current | 5 A |
| $\alpha$ | Temperature coefficients of current | 0.0003 A/°C |
| $\beta$ | Temperature coefficients of voltage | 0.0005 V/°C |
| $N_p$ | Number of series modules | 20 |
| $N_q$ | Number of series modules | 12 |
| $K_{loss}$ | Loss factor | 0.2 |

PV grid-connected based on this phase-locked strategy is seriously inconsistent with the IEEE Std. in recent years.
The 2∼13th harmonic and total harmonic distortion based on different phase-locked strategies are shown in Table 2. The change curve of phase-locked angle based on basic d-q phase-locked strategy, SOGI phase-locked strategy and MAF-SASOGI phase-locked strategy is shown in Figure 19. It can be seen from Figure 19, when the distribution network voltage is seriously distorted, there will be a lot of odd and even harmonics in the distribution network voltage. The basic d-q PLL will produce serious errors because it does not contain the filtering function. The SOGI PLL can filter out some order harmonics by separating the positive and negative sequence of the voltage. When the distribution network voltage is seriously distorted, due to the conduction limitation of band-pass filter bandwidth, the harmonic suppression ability near the resonance frequency will be poor. The DC component and higher harmonic produced from SOGI PLL affect the accuracy of the PLL. The MAF-SASOGI phase-locked strategy can make up for the shortcomings of the two strategies mentioned above. It can not only filter the low-order harmonics, but also filter the DC component and high-order harmonics through the self-adjusting coefficient and the difference node with MAF, so the phase-locked angle is almost error free.

The A phase current at grid connection point based on the three phase-locked strategies of basic d-q, SOGI and MAF-SASOGI is shown in Figure 20. It can be seen from Figure 20 when the distribution network contains high proportion of arc furnace load and the voltage is seriously distorted. When the grid-connected converter with basic d-q PLL is used for PV grid-connected, grid-connected current is seriously distorted. The 2-7 harmonic content of grid-connected current is very high (2.40%, 18.41%, 1.31%, 10.40%, 2.41%, 9.20%, respectively). The grid-connected current does not meet the IEEE Standard. When using the converter with SOGI PLL for PV grid-connected, although the 2-7 harmonic content slightly decreased (0.67%, 7.40%, 0.79%, 4.90%, 0.43%, 4.91%, respectively), the grid-connected current still has some degree of distortion. However, when the grid connected converter with MAF-SASOGI PLL is used for PV grid-connected, due to the effective filtering and precise phase-locked, the 2-7 harmonic content is reduced to a very low level (0.48%, 1.92%, 0.39%, 1.21%, 0.32%, 1.24%). The grid-connected current is close to the sine, and the grid-connected current fully meets the grid-connected standard of IEEE Std. in recent years.

V. CONCLUSION
In order to solve the problem that the grid voltage is seriously distorted when the distribution network contains a high proportion of arc furnace load and the voltage is seriously distorted, the phase-locked strategy of PV connected to distribution network with high proportion EAF is proposed. The phase-locked strategy is based on d-q, SOGI and MAF-SASOGI. The simulation results show that the MAF-SASOGI phase-locked strategy can effectively suppress the harmonic content and the grid-connected current fully meets the grid-connected standard of IEEE Std. in recent years.

TABLE 2. Harmonic content of each order in different scenarios: (a) PV is non-grid; (b) Grid-connected based on basic d-q phase-locked strategy; (c) Grid-connected based on SOGI phase-locked strategy; (d) Grid-connected based on MAF-SASOGI phase-locked strategy.

| Order | A (%) | B (%) | C (%) | D (%) |
|-------|-------|-------|-------|-------|
| 2nd   | 1.57  | 2.40  | 0.67  | 0.48  |
| 3rd   | 17.20 | 18.41 | 7.40  | 1.92  |
| 4th   | 0.90  | 1.31  | 0.79  | 0.39  |
| 5th   | 0.38  | 10.40 | 4.90  | 1.21  |
| 6th   | 0.74  | 2.41  | 0.43  | 0.32  |
| 7th   | 5.85  | 9.20  | 4.91  | 1.24  |
| 8th   | 0.85  | 1.42  | 0.57  | 0.38  |
| 9th   | 5.51  | 7.25  | 2.62  | 0.48  |
| 10th  | 0.76  | 1.21  | 0.67  | 0.37  |
| 11th  | 4.11  | 5.60  | 1.67  | 0.49  |
| 12th  | 0.61  | 1.28  | 0.44  | 0.30  |
| 13th  | 2.23  | 5.61  | 1.62  | 0.25  |

FIGURE 18. Harmonic content of each order in different scenarios: (a) PV is non-grid; (b) Grid-connected based on basic d-q phase-locked strategy; (c) Grid-connected based on SOGI phase-locked strategy; (d) Grid-connected based on MAF-SASOGI phase-locked strategy.
portion of EAF load, and the PV grid-connected converter can still be safely and effectively connected to the grid, this paper proposes a self-adjusting double SOGI phase-locked strategy with an ideal low-pass filter, which is effectively applied to the PV grid with high harmonic content. Through theoretical derivation and simulation analysis, the conclusion is as follows:

Through the analysis of voltage characteristics in distribution network with high proportion of EAF, it is known that a lot of negative sequence voltage is generated a series of measures such as adding self-adjusting filter, double second-order generalized integrator and difference node with MAF are used to separate the positive and negative sequence of grid voltage. The positive sequence voltage component that not include harmonic and DC can be obtained in $\alpha$, $\beta$ two-phase static coordinate system. Then the positive sequence voltage is sent to the control part of the PLL, which can make the PLL realize precise phase-locked and obtain the phase-locked angle little or without error.

The results of simulation analysis show that the proposed method in this paper can not only make the PLL complete the precise phase-locked, but also optimize the grid current by reducing the harmonic content of each order in the system, and improve the voltage quality of the grid.

**COMPETING INTERESTS**

The authors declare that they have no competing interests.

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