Study on Three-Phase Reclosing Strategy Applicable to Tie Line of Photovoltaic Power Station

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ABSTRACT When a fault occurring in the tie line of photovoltaic power station is cleared by the protection three-phase trip, photovoltaic power source (PVS) will form an unplanned island with the local load. However, since the voltage regulation and frequency control capability of PVS is generally poor, it is very difficult to satisfy the synchronous reclosing conditions, eventually resulting in an automatic reclosing failure. According to the islanding control strategy of PVS and the principle of phase-locked loop (PLL), a vector relationship model of PVS port actual voltage, port calculation voltage, grid-connected point voltage and so on before and after reclosing is established. Based on this, the influences of reclosing phase difference, amplitude difference and frequency difference on reclosing impulse voltage and current are analyzed, and a synchronous check reclosing strategy applicable to the tie line of PVS is proposed, which can effectively improve the success rate of the three-phase reclosing in tie line. Digital simulation results verify the correctness of the proposed reclosing strategy.

INDEX TERMS Photovoltaic power, three-phase reclosing, reclosing impulse, analysis of influencing factors, synchronous check reclosing strategy.

I. INTRODUCTION

In recent years, photovoltaic power has become an important field for global energy transformation with rapidly increased installed capacity, which is mainly attributed to its technology advancement and cost reduction [1]. Large-capacity photovoltaic power source (PVS) is mainly connected to the power grid through the high-voltage overhead tie line [2]. And over 80\% of faults occurring in the high-voltage overhead lines are transient faults [3]. When a transmission line encounters a transient fault and is disconnected by the protection, it can recover normal power supply by performing one reclosing. Therefore, auto-reclosing devices are widely used in transmission lines to improve power supply reliability. When a fault occurring in the tie line of the photovoltaic power station is cleared by the protection three-phase trip, PVS will form an unplanned island with the local load [4], [5]. However, compared with the traditional synchronous motor, PVS does not have strong voltage regulation capability and physical inertia for frequency maintenance, which leads to that the voltage amplitude and frequency during the island operation are easily changed and it is hard to satisfy quasi-synchronization reclosing conditions [6]–[8], eventually resulting in reclosing failure. To solve this problem, the general practice adopted at present is to intertrip PVS or lock three-phase reclosing when a fault occurs in the tie line, but this practice will result in that plenty of PVS exit operation or the local load power supply is interrupted, affecting the safe and stable operation of the power grid and the efficient use of renewable energy. Consequently, to ensure the power supply reliability of system and improve the utilization ratio of renewable energy, it is of practical significance to propose a three-phase reclosing strategy applicable to the tie line of renewable power station.
To date, various researches have been carried out to study the impact of renewable energy power access on the reclosing technology and to develop relevant strategies. Rizo et al. [9] focused on the microgrid including distributed power source, and proposed a synchronous control strategy under the circumstance of islanding operation to satisfy the requirements of quasi-synchronous reclosing. However, this method is not applicable to large-capacity renewable energy stations which have centralized access to the power grid. And Yuan et al. [10] and Li et al. [11] proposed the reclosing configuration suggestions applicable to the tie line of wind farm, considering the weakness of frequency instability of wind farm in islanding operation. But for the three-phase reclosing, it is still necessary to intertrip the renewable energy source, leading to plenty of units break away from power grid. Xie et al. [12], Zhang et al. [13] and Martínez-Lucas et al. [14] aimed at the islanding operation state of wind farm, and proposed different island control strategies such as replacement load input, high-frequency generator trip and combined pumped-storage hydroelectric farm, in order to improve the success rate of three-phase reclosing. However, these methods are costly and limited in application. Therefore, to ensure the power supply reliability and the efficient use of renewable energy, it is necessary to analyze and evaluate the impact of PVS access on the three-phase reclosing in depth and propose a three-phase reclosing strategy applicable to PVS tie line.

In this paper, a vector relationship model of PVS port actual voltage, port calculation voltage, grid-connected point voltage and so on before and after reclosing is established, according to the islanding control strategy of PVS and the principle of phase-locked loop (PLL). Based on this, the influences of reclosing phase difference, amplitude difference and frequency difference on reclosing impulse voltage and current are analyzed, and a synchronous check reclosing strategy applicable to the tie line of PVS is proposed. Digital simulation results verify the correctness of analysis conclusions and proposed reclosing strategy.

II. ISLANDING CONTROL STRATEGY AND PLL PRINCIPLE OF PVS

Before and after reclosing, the amplitude and phase relationships between PVS port actual voltage, port calculation voltage, grid-connected point voltage and so on are closely related to the islanding control strategy and PLL of PVS. The following is an analysis of the islanding control strategy and common PLL principle of PVS.

A. ISLANDING CONTROL STRATEGY OF PVS

PVS is a kind of renewable energy source which is directly connected to the grid via an inverter. Generally, when the PV array output power is constant, the output characteristics of PVS mainly depend on the inverter control strategy, which is closely related to the port voltage level. When PVS is in the islanding operation, if the output power of PVS is greater than the local load power, the island voltage will be close to or greater than the rated voltage, and PVS will still maintain the same unit power factor control strategy as normal operation [15], [16]. However, if the PVS output power is small (such as weak light and low temperature) or local load power is large, the island voltage may be lower than the rated voltage, and PVS will be converted to the low voltage ride-through (LVRT) control strategy [17].

The output power control of PVS usually adopts the vector decoupling control method [18], [19], and the positive sequence voltage of the grid is generally oriented to the d-axis. In this condition, the output power and output current equation of PVS in the island operation is shown in (1). It should be noted that since the island system still maintains three-phase symmetry after the three-phase trip of tie line breaker, the system voltage and current almost only contain positive sequence components. And the voltages and currents in (1) all represent positive sequence components.

\[
\begin{align*}
P_g &= u_{gd}i_{gd} + u_{gq}i_{gq} = u_{gd}i_{gd} \\
Q_g &= u_{gq}i_{gd} - u_{gd}i_{gq} = u_{gq}i_{gq}
\end{align*}
\]

\[
i_{gd} = \min \left( \frac{P_g}{u_g}, \sqrt{l_{max}^2 - i_{gq}^2} \right)
\]

\[
i_{gq} = \begin{cases} 
0 & u_g > 0.9 \\
1.5(0.9 - u_g) & 0.2 \leq u_g \leq 0.9 \\
I_{gmax} & u_g < 0.2
\end{cases}
\]

where: \(P_g\) and \(Q_g\) represent the output active power and reactive power of PVS; \(u_g\) represents the PVS port voltage; \(u_{gd}\) and \(u_{gq}\) represent the \(d\)-axis and \(q\)-axis component of PVS port voltage; \(i_{gd}\) and \(i_{gq}\) represent the \(d\)-axis and \(q\)-axis component of PVS output current; \(P_{g0}\) represents the output active power of PVS before the fault occurs; \(I_{gmax}\) represents the maximum current allowed for the inverter working.

B. PLL PRINCIPLE OF PVS

At present, PLL technology commonly used in PVS inverter is synchronous reference frame PLL (SRF-PLL) method [20], [21], and to accurately lock the positive sequence voltage phase under the circumstance of grid imbalance, the positive and negative sequence component of fundamental frequency voltage are usually separated in two-phase stationary (αβ) coordinate system. Among them, the voltage-source converter generally adopts a method of “\(T_1/4\) delay” (where \(T_1\) is the period of fundamental frequency voltage) [22], trying to limit the decomposition delay to within \(T_1/4\), and in actual application, a certain amount of buffer space is required to store the voltage adoption value during \(1/4\) period for calculation. In two-phase stationary coordinate system, the positive and negative sequence components of the instantaneous grid voltage can be expressed as

\[
\begin{bmatrix}
    u_{gα+} \\
    u_{gβ+}
\end{bmatrix}
= \frac{1}{2} \begin{bmatrix}
    1 & e^{-j\pi/2} \\
    e^{-j\pi/2} & 1
\end{bmatrix}
\begin{bmatrix}
    u_{gα} \\
    u_{gβ}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    u_{gα−} \\
    u_{gβ−}
\end{bmatrix}
= \frac{1}{2} \begin{bmatrix}
    1 & e^{-j\pi/2} \\
    e^{-j\pi/2} & 1
\end{bmatrix}
\begin{bmatrix}
    u_{gα} \\
    u_{gβ}
\end{bmatrix}
\]

where: subscripts “+” and “−” represent the positive and negative sequence component respectively; \(u_{gα}\) and \(u_{gβ}\)
represent the $\alpha$-axis and $\beta$-axis voltage component in the two-phase stationary coordinate system; $e^{-j\pi/2}$ represents the time-domain phase shift operator of $T_{1/4}$ delay.

The phase-locked principle block diagram of SRF-PLL is shown in Fig. 1.

As shown in Fig. 1, for SRF-PLL which directs the positive-sequence voltage to the $d$-axis, the phase-locked deviation of grid voltage can be reflected by the $q$-axis component of the positive-sequence calculation voltage ($u_{gq+}$), which means that the positive-negative sign and absolute value of $u_{gq+}$ can reflect the phase lead-lag relationship and phase difference between the actual voltage and the PLL calculation voltage. And under the circumstance of the ideal grid voltage, since both $u_{gd+}$ and $u_{gq+}$ are DC variables, the calculated voltage vector can accurately track the actual voltage vector by using PI regulator, which can achieve the zero static error adjustment for $u_{gq+}$. At the moment of reclosing, if the reclosing phase difference is not zero, the phase of the port voltage originally oriented to the $d$-axis will mutate. And the calculated phase of PLL will gradually approach the actual phase by accelerating or decelerating deflection according to the positive-negative sign of the phase-locked error.

### III. STUDY ON THE INFLUENCING FACTORS OF RECLOSING IMPULSE VOLTAGE AND CURRENT

When the circuit breaker on the PVS side of tie line reclose, since the capacity of power grid is generally much larger than the capacity of PVS, the grid-connected point voltage of PVS will be quickly pulled to synchronize by the grid voltage, and the voltage mutation degree is related to the reclosing phase difference, amplitude difference and frequency difference. Taking the grid equivalent circuit shown in Fig. 2 as an example, the following analyzes the effect of the reclosing phase difference, amplitude difference and frequency difference on the reclosing impulse voltage and current respectively, according to the vector relationship diagram before and after the reclosing.

#### A. INFLUENCE ANALYSIS OF RECLOSING PHASE DIFFERENCE

When the voltage on the line end of the PVS side breaker leads the busbar end voltage, the reclosing phase difference is defined as positive, and on the contrary it is negative. The following analysis takes the cases where the reclosing phase differences are $90^\circ$ and $150^\circ$ as examples.

When the reclosing phase difference is $-90^\circ$, for the convenience of analysis, it is assumed that the island operating voltage before reclosing is greater than 0.9 p.u. According to the equivalent circuit shown in Fig. 2, the vector relationship diagrams of the PVS port actual voltage, port calculation voltage and grid-connected point voltage before the reclosing, at the reclosing moment, at the intermediate state after reclosing and the steady state are shown in Fig. 3. And in Fig. 3: subscripts “0” represents the initial state before reclosing; $U_g$ represents the port voltage vector of PVS; $I_g$ represents the output current vector of PVS; $\Delta I_g$ represents the output current vector difference before and after reclosing; $Z_g$ represents the total impedance of collecting wire, box transformer and main transformer in Fig. 2. $\dot{U}_{pcc}$ represents the bus terminal voltage (grid-connected point voltage) vector of the PVS side breaker in Fig. 2; $\dot{U}_{pcc}$ represents the line terminal voltage vector of the PVS side breaker in Fig. 2.

As shown in Fig. 3(a), when the reclosing angle is $-90^\circ$, the line terminal voltage of the PVS side breaker ($\dot{U}_{pcc}$) lags behind the bus terminal voltage ($\dot{U}_{pcc}$) by $90^\circ$ before reclosing. And when the voltage amplitude of PVS island is greater than 0.9 p.u., PVS will only output the active power according to the island control strategy as shown in (1). In this condition, the port voltage and output current of PVS are in phase, and both are oriented to $d$-axis. Since the total impedance of the collecting line, box transformer, and main transformer...
(\(Z_g\)) is almost purely inductive, it can be approximated that the voltage drop from PVS port to main transformer outlet (\(\hat{I}_g Z_g\)) lead the output current by 90°. As shown in Fig. 3(b), \(\hat{U}_{pec}\) is quickly pulled to synchronize with \(\hat{U}_{pcc}'\) (namely the grid voltage), and its phase lags behind the phase before reclosing by 90°. Due to the weak control capacity of PVS on its port voltage (\(\hat{U}_g\)), \(\hat{U}_g\) will also mutate when \(\hat{U}_{pec}\) mutates. It can be seen from the analysis of PLL principle in section II(B), the phase-locked \(d\)-axis is always deflected following \(\hat{U}_g\) to achieve phase-locking. Therefore the phase of the phase-locked \(d\)-axis will change slightly during the mutation process. And the sudden change of \(\hat{U}_g\) will lead to a reduction of the amplitude of PLL calculation port voltage (namely the projection value of \(\hat{U}_g\) on the phase-locked \(d\)-axis, as shown by the dotted line in Fig. 3(b)), resulting in the change of \(d\)-axis and \(q\)-axis components of output current according to (1). Among them, since PVS needs to generate reactive power, its output \(q\)-axis current is negative, which indicates that \(\hat{I}_g\) will lag behind the phase-locked \(d\)-axis. And the phase difference between them is determined by the magnitude of PLL calculation port voltage. The vector sum of the grid-connected point voltage vector and the voltage drop vector is the port voltage vector of PVS, as shown in (3).

\[
\hat{U}_g = \hat{U}_{pcc} + \hat{I}_g \hat{Z}_g
\]  

Since PLL still does not lock the accurate phase of \(\hat{U}_g\), the phase-locked \(d\)-axis continues to deflect toward \(\hat{U}_g\). And before reaching the steady state, the phase-locked phase will produce a certain overshoot due to PI regulation control, as shown in Fig. 3(c). The phase-locked \(d\)-axis lags \(\hat{U}_g\) slightly, and if PI adjustment parameter is set properly, this lagging phase angle will be small. In this condition, \(\hat{U}_g\) is projected on the phase-locked \(d\)-axis by more than 0.9 times the rated voltage, and \(\hat{I}_g\) is in phase with the phase-locked \(d\)-axis vector according to (1). Finally, it undergoes a certain transient adjustment process to achieve the steady state as shown in Fig. 3(d).

When the reclosing phase difference is 90°, the vector relationship diagrams of the PVS port actual voltage, port calculation voltage and grid-connected point voltage before the reclosing, the reclosing moment, the intermediate state after reclosing and the steady state are shown in Fig. 4.

As shown in Fig. 4(a), when the reclosing angle is \(-90°\), the line terminal voltage of the PVS side breaker (\(\hat{U}_{pcc0}'\)) leads the bus terminal voltage (\(\hat{U}_{pcc0}\)) by 90° before reclosing. And as shown in Fig. 4(b), the amplitude of PLL calculation port voltage (as shown by the dotted line in Fig. 4(b)) is also small. However, compared to that \(\hat{I}_g\) and the phase-locked \(d\)-axis are deflected in the same direction in Fig. 3(b), the deflection directions of the two are opposite in Fig. 4(b), because when the amplitude of PLL calculation port voltage is less than 0.9 p.u., the output \(q\)-axis current vector is always on the negative \(q\)-axis, which indicates that \(\hat{I}_g\) is always deflected clockwise. And the phase-locked \(d\)-axis is deflected counterclockwise with \(\hat{U}_g\) when the reclosing angle is 90°. Therefore, as shown in Fig. 3(b) and Fig. 4(b), when the reclosing angle is \(-90°\), the output current vector difference before and after the reclosing (\(\Delta \hat{I}_g\)) will be greater than that in the case where the reclosing angle is 90°, which indicates that the high-frequency impulse component of former’s output current will be larger. And since both of the reclosing fundamental frequency currents are controlled by the limited amplitude link, the maximum reclosing current peak (namely the superposition of the fundamental frequency component and the high-frequency component) when the reclosing angle is \(-90°\) will be greater than that in the case where the reclosing angle is 90°.

In addition, comparing Fig. 4(b) with Fig. 3(b), it can be seen that when the reclosing angle is 90°, the effective value of \(\hat{U}_g\) will be significantly larger than that in the case of reclosing angle is \(-90°\), since their phase difference between \(\hat{U}_{pcc}\) and \(\hat{I}_g \hat{Z}_g\) is different. And when the reclosing angle is 90°, the active power generated by PVS is smaller than that in the case of reclosing angle of \(-90°\) at the moment of reclosing due to the larger phase difference of \(\hat{I}_g\) and \(\hat{U}_g\), which indicates that the unbalanced active power stored in the inverter DC bus capacitor is larger, resulting in that the output current controlled by the bus voltage outer loop will remain longer in the limit value during the subsequent transient process.

It should be noted that the above vector analysis method is also applicable to the case where the island operating voltage is lower than 0.9 p.u.. The research indicates when the island operating voltage is lower than 0.9 p.u., the effect of reclosing phase angle on the fundamental frequency voltage and PVS output power is the same as the previous analysis, because the impedance of \(Z_g\) is generally much smaller than the load impedance, resulting in that the phase differences between \(\hat{U}_{g0}\) (namely phase-locked \(d\)-axis) and \(\hat{U}_{pcc0}'\) before reclosing are all small in the cases of different islanding voltage amplitudes, which indicates that as long as the reclosing phase difference is the same, the phase difference between \(\hat{U}_{pcc}\) and the phase-locked \(d\)-axis is almost the same. In this condition, the magnitude and phase relationships of \(\hat{U}_g\) and

![FIGURE 4. Voltage and current vector diagram when the reclosing phase difference is 90°.](image-url)
\( \dot{I}_g \) obtained from (1) and (3) are also the same. In other words, the vector magnitude and phase relationships at the moment of reclosing are only related to the reclosing phase difference, but not to the island voltage amplitude before reclosing. And since the reclosing fundamental frequency voltage and the reclosing output power of PVS depend only on the vector relationship at the moment of reclosing (see Fig. 3(b) and Fig 4(b)), both of them are not affected by the island voltage amplitude before reclosing.

The maximum reclosing impulse current is related to the fundamental frequency current vector difference before and after reclosing, and the relationship between the fundamental frequency current before reclosing and the island voltage amplitude before closing is as shown in (1). Consequently, as the island voltage amplitude decreases, the maximum reclosing impulse current when the reclosing angle is \(-90^\circ\) will gradually be changed from greater than that in the case where the reclosing angle is \(90^\circ\), to less than that in the case where the reclosing angle is \(-90^\circ\). Then comparing Fig. 3(b), Fig. 4(b), Fig. 5(b) and Fig. 6(b), it can been seen that as the absolute value of reclosing phase difference increases, the vector difference of \(\dot{I}_g\) and \(\dot{U}_g\) become larger, which indicates that the high-frequency impulse components of reclosing current and voltage also become larger.

From the above analysis based on the voltage-current vector relationship diagram, the following conclusions can be drawn:

1) The reclosing impulse performance when the reclosing phase difference is \(\varphi (0^\circ < \varphi < 180^\circ)\) is different from that in the case where the reclosing phase difference is \(-\varphi\), which is embodied in: (1) Since their lead-lag relationship between the port voltage vector and the grid-connected voltage vector is different at the moment of reclosing, the maximum port fundamental frequency voltage of the former is larger than that

\[ FIGURE 5. \text{Voltage and current vector diagram when the reclosing phase difference is } -150^\circ. \]

\[ FIGURE 6. \text{Voltage and current vector diagram when the reclosing phase difference is } 150^\circ. \]
of the latter. And due to the limiting control of the reclosing fundamental frequency current of PVS, the maximum reclosing fundamental frequency voltage has a greater threat to the closing safety. Therefore, the reclosing performance when the reclosing phase difference is $\phi$ is more disadvantageous than that in the case where the reclosing phase difference is $-\phi$; (2) At the moment of reclosing, due to the larger phase difference between the port voltage and the output current, the PVS output active power of the former is smaller than that of the latter; (3) The high-frequency impulse component of reclosing current is related to the positive-negative sign of $\phi$, the island voltage amplitude and so on. When the island voltage before closing is greater than 0.9 p.u., due to the influence of the PLL phase-locked $d$-axis deflection direction, the high-frequency impulse component of reclosing current of the former is smaller, and the peak value of the maximum reclosing current is also smaller;

2) The larger the absolute value of the reclosing angle, since the larger the vector difference of the port voltage and current before and after reclosing, the larger the high-frequency impulse components of the reclosing voltage and current;

3) In the case of the most severe three-phase reclosing impulse, the maximum reclosing fundamental frequency voltage appears at the moment when the grid-connected voltage vector is in phase with the voltage drop vector from PVS port to main transformer outlet. If the PVS output current limit is assumed to be a typical value of 1.2 p.u., and the inductive reactance of the box transformer and the main transformer are assumed to be typical values of 0.06 p.u. and 0.1 p.u. respectively, and the collecting line impedance is ignored, the theoretical value of the maximum reclosing fundamental frequency voltage obtained from (2) is 1.19 p.u.. However, since there is still a reclosing transient high-frequency voltage, the transient over-voltage problem still occurs at the reclosing moment. It should be noted that when the amplitude of the island voltage is greater than this theoretical value, the maximum reclosing fundamental frequency voltage will appear at the moment of reclosing, and its value is the island voltage before reclosing.

**B. INFLUENCE ANALYSIS OF RECLOSING AMPLITUDE DIFFERENCE**

When the island voltage amplitude is different, the vector relationship diagrams between the PVS port voltage, the grid-connected point voltage and the output current before and after reclosing are shown in Fig. 7. And in Fig. 7, $\phi$ represents the reclosing phase difference.

As shown in Fig. 7(a) and Fig. 7(b), When the PVS port voltage in the islanding operation is greater than 0.9 p.u., the output current vector is in phase with the port voltage vector. And when the PVS port voltage in the islanding operation is less than 0.9 p.u., since PVS needs to generate reactive power according to LVRT requirement, there is a phase difference between the output current vector and the port voltage vector. In the cases of different island voltage amplitudes, the phase difference between the PVS port voltage and grid-connected point voltage is as shown in (4).

$$
\begin{align*}
\theta &= \arctan \frac{P_{0g}}{U_{g0}^2} \quad U_{g0} > 0.9 \\
\theta &= \arctan \frac{I_{g\max}Z_g \sin \theta_1}{U_{g0} - I_{g\max}Z_g \cos \theta_1} \quad 0.9 \geq U_{g0} \geq 0.2 \\
\theta &= 0 \quad U_{g0} < 0.2 \\
\theta_1 &= \arctan \sqrt{\frac{I_{g\max}^2 - [1.5(0.9 - U_{g0})]^2}{1.5(0.9 - U_{g0})}} \\
\end{align*}
$$

where: $\theta$ represents the phase difference between the PVS port voltage and grid-connected point voltage.

It can be seen from (4) that when the island voltage amplitude is greater than or equal to 0.9 p.u., as the voltage amplitude increases, the output current amplitude decreases due to the constant output active power of PVS, resulting in that the phase difference between the port voltage vector and the grid-connected point voltage also decreases. And when the island voltage amplitude is less than 0.9 p.u. is greater than 0.2 p.u., as the voltage amplitude decreases, the phase difference between the port voltage and the grid-connected point voltage increases first and then decreases. When the island voltage amplitude is less than 0.2 p.u., PVS only generate the reactive power, and the port voltage and the grid-connected point voltage are almost in phase. However, as $Z_g$ is generally much smaller than the load impedance, the phase difference between the port voltage and the grid-connected point voltage is not large under different island voltage amplitudes.
When the reclosing angle is large, such as greater than 90°, the phase difference between the PVS port voltage and the grid-connected point voltage before reclosing can be approximately ignored. And it can be seen from the analysis in section III(A) that the vector magnitude and phase relationships at the moment of reclosing are only related to the reclosing phase difference, but not to the island voltage amplitude before reclosing. Consequently, the port voltage vectors before and after reclosing in the cases of different island voltage amplitudes are shown in Fig. 7(c). In this condition, as the amplitude of the island voltage increases from 0.2 p.u. to 1.3 p.u., the larger the vector difference between the port voltage vectors before and after the reclosing ($\Delta U_g$), which indicates that the high-frequency impulse voltage at the moment of reclosing will become larger. And when the reclosing phase difference is small, such as less than 90°, the port voltage vectors before and after reclosing are shown in Fig. 7(d). In this condition, it is necessary to consider the influence of the phase difference between the PVS port voltage and the grid-connected point voltage before reclosing on $\Delta U_g$, and the reclosing impulse voltage no longer increases monotonously as the island amplitude increases.

C. INFLUENCE ANALYSIS OF RECLOSING FREQUENCY DIFFERENCE

Since PVS belongs to the renewable energy source of direct grid-connected type through inverter, it has no physical inertia in maintaining frequency compared with traditional synchronous motor and double-fed fun, and both of the frequency measurement speed of its PLL and switch tube control speed of IGBT are very fast. Moreover, according to the relevant standard [17], the allowable operational frequency range of PVS is 48 Hz~50.5 Hz, which indicates that the reclosing frequency difference will be within $-0.5$ Hz~2 Hz. In this condition, the transient response of the impedance components such as lines and transformers in power station to this reclosing frequency difference can be ignored. Therefore, the frequency of PVS, whose capacity is much smaller than the grid system, will be quickly pulled to the fundamental frequency of grid, and the reclosing transient impulse process is mainly related to the reclosing phase difference and amplitude difference, and is less affected by the frequency difference.

In summary, since PVS has fast frequency tracking capability and the frequency difference between PVS and the power grid is within 2 Hz at the moment of reclosing, the influence of frequency difference on tie line reclosing can be ignored.

IV. SIMULATION VERIFICATION OF FACTORS AFFECTING RECLOSING IMPULSE

In this section, a power system simulation model including PVS is built based on PSCAD/EMTDC software, as shown in Fig. 8. In this model, the rated power of PVS is 20 MW, the rated voltage of the DC bus is 1000 V, and the DC bus capacitance is 8 mF. The capacity of box transformer is 22 MVA, its transformation ratio is 0.48 kV/36.75 kV, and its leakage reactance is 6%. The length of the collecting line is 200 m, and its positive sequence and zero sequence impedance parameters per unit length are: $r_{c1} = 0.17 \Omega/km$, $x_{c1} = 0.39 \Omega/km$, $r_{c0} = 0.49 \Omega/km$, $x_{c0} = 1.17 \Omega/km$. The capacity of main transformer is 25 MVA, its transformation ratio is 36.75 kV/121 kV, and its leakage reactance is 10%.

The voltage level and length of the tie line are 110 kV and 100 km, and its positive sequence and zero sequence impedance parameters per unit length are: $r_1 = 0.08 \Omega/km$, $x_1 = 0.39 \Omega/km$, $r_0 = 0.23\Omega/km$, $x_0 = 1.17 \Omega/km$. The positive sequence equivalent resistance and reactance of power grid are 0.622 $\Omega$ and 7.216 $\Omega$ respectively, and the zero sequence equivalent resistance and reactance are 2.66 $\Omega$ and 12.26 $\Omega$ respectively.

In subsequent simulation analysis, all electrical quantities are converted to per-unit values in order to facilitate understanding. And corresponding relationships between the nominal values and per-unit values of each electrical quantity are shown in Table 1.

In the simulation experiments, protections on both sides of the tie line clear the fault after 100ms delay, and the protection on the grid side of tie line recloses with no-voltage checking after 0.5 s delay. To achieve the synchronous check reclosing of the protection on the PVS side of tie line, PVS must remain in the island operation state before reclosing, but not exit operation due to the action of overvoltage/undervoltage or overfrequency/underfrequency protection. According to the grid-connected standards of PVS [17], only when the frequency of PVS is in the range of 48 Hz-50.5 Hz and

![FIGURE 8. Simulation model of power grid including PVS.](image-url)

**TABLE 1. Corresponding relationships between the nominal values and per-unit values of electrical quantities.**

| Electrical quantity                  | Nominal value | Per-unit value | Electrical quantity                  | Nominal value | Per-unit value |
|-------------------------------------|---------------|---------------|-------------------------------------|---------------|---------------|
| Tie line phase voltage amplitude    | 89.8 kV       | 1 p.u.        | PVS port phase voltage amplitude    | 391.9 V       | 1 p.u.        |
| Tie line phase voltage RMS          | 63.5 kV       | 1 p.u.        | PVS port phase voltage RMS          | 277.1 V       | 1 p.u.        |
| Tie line phase current amplitude    | 185.5 A       | 1 p.u.        | PVS port phase current amplitude    | 34 kA         | 1 p.u.        |
| Tie line phase current RMS          | 131.2A        | 1 p.u.        | PVS port phase current RMS          | 24.1 kA       | 1 p.u.        |
the voltage amplitude is in the range of 0.4 p.u.-1.3 p.u., its allowable operational time is more than 0.5 s, which means that PVS can at least maintain operation until the reclosing with zero voltage checking of the grid side protection. The following is the simulation analysis of the cases of different reclosing phase difference, amplitude difference and frequency difference, in order to verify the correctness of the reclosing impact analysis in Section III.

A. SIMULATION OF DIFFERENT RECLOSING PHASE DIFFERENCES

In this section, the changes of reclosing impulse voltage and current under the circumstances of different reclosing angle is analyzed according to the simulation results, in order to verify the correctness of the relevant analysis conclusions in Section III(A). Due to the limitation of article length, only the simulation waveforms of the two kinds of closing phase angle differences (−90° and 90°) are given below, and the influences of other reclosing phase differences are shown in Table 1. During the simulation, the magnitude and frequency of the grid voltage are 1 p.u. and 50 Hz respectively. PVS is in a full capacity operation before the fault and its output current is 1 p.u.. And a single-phase grounding fault occurs at the midpoint of the tie line at 1.5 s. The protections on both sides of the tie line clear the fault at 1.6 s. The fault duration is 0.1 s. And then the protection on the grid side of tie line reclose with zero voltage checking at 2.1 s. The magnitude and frequency of the island voltage are 1 p.u and 48 Hz before reclosing.

1) RECLOSING PHASE DIFFERENCES ARE −90° AND 90°

When the reclosing phase difference are −90° and 90° the voltage amplitude waveforms of the two ends (the line end and the busbar end) of the circuit breaker on the PVS side of tie line and reclosing instantaneous voltage waveform are shown in Fig. 9. And in Fig. 9(a) and (c), the solid line and the broken line represent the voltage amplitude waveforms of the busbar end and the line end of the circuit breaker respectively.

It can be seen from Fig. 9(a) and (c) that when the fault is cleared by the protection of tie line at 1.6 s, the voltage amplitude of the PVS island operation (namely the voltage amplitude of the busbar end) is still 1 p.u., and the voltage amplitude of the line end is zero before the protection on the grid side of tie line recloses with zero voltage checking at 2.1 s. As shown in Fig. 9(b) and (d), when the reclosing phase difference is −90° and 90°, the voltage on the PVS side of tie line is instantaneously pulled to the synchronization by the grid voltage at the moment of reclosing, and its transient process is almost negligible.

The waveforms of the three-phase voltage and the fundamental frequency three-phase voltage RMS at PVS port are shown in Fig. 10.

As shown in Fig. 10(a)(c) that when the reclosing angles are −90° and 90°, there are serious impulses of both the port voltage at the moment of reclosing, and the peak value of the reclosing voltage are 2.23 p.u. and 2.54 p.u. respectively.

It can be seen from Fig. 10(b)(d), in the cases where the reclosing angles are −90° and 90°, the maximum effective values, which are measured by the measuring component composed of FFT algorithm, of fundamental frequency voltage are 1.03 p.u. and 1.15 p.u. respectively, and the latter’s reclosing voltage peak value and maximum fundamental frequency voltage effective value both are greater than those of the former.

The waveforms of the three-phase current at PVS port are shown in Fig. 11.
It can be seen from Fig. 11 that when the reclosing angles are $-90^\circ$ and $90^\circ$, the peak values of their reclosing current are 1.34 p.u. and 1.29 p.u. respectively, and the former’s peak value is greater. The durations during their current RMS are the limit value of 1.2 p.u. are 0.03 s and 0.06 s respectively, and the latter’s duration is longer.

The $d$-axis and $q$-axis component waveforms of the PLL calculation voltage at PVS port are shown in Fig. 12.

And in Fig. 12, the solid line and the broken line represent the $d$-axis component and the $q$-axis component respectively. As shown in Fig. 12, in the cases of two reclosing angles, the $d$-axis components of PLL calculation voltage both drop rapidly after reclosing. And when the reclosing angle is $-90^\circ$, the $q$-axis component value of PLL calculation voltage is
TABLE 2. Simulation results of the reclosing impulse current and voltage in the cases of different reclosing phase differences.

| Reclosing phase difference | Peak value of reclosing current (p.u.) | Maximum fundamental frequency RMS of reclosing current (p.u.) | Peak value of reclosing voltage (p.u.) | Maximum fundamental frequency RMS of reclosing voltage (p.u.) | Duration of reclosing voltage greater than 1.35 p.u. (ms) |
|---------------------------|----------------------------------------|---------------------------------------------------------------|---------------------------------------|---------------------------------------------------------------|-------------------------------------------------------|
| 0°                        | 1                                      | 1                                                             | 1                                     | 1                                                             | /                                                     |
| -30°                      | 1.1                                    | 1.1                                                           | 1.14                                  | 1.02                                                          | /                                                     |
| 30°                       | 1.05                                   | 1                                                             | 1.53                                  | 1.05                                                          | 0.5                                                   |
| -90°                      | 1.34                                   | 1.2                                                           | 2.23                                  | 1.03                                                          | 0.8                                                   |
| 90°                       | 1.29                                   | 1.2                                                           | 2.54                                  | 1.15                                                          | 1.5                                                   |
| -150°                     | 1.73                                   | 1.2                                                           | 3.1                                   | 1.05                                                          | 17.9                                                  |
| 150°                      | 1.5                                    | 1.2                                                           | 3.36                                  | 1.15                                                          | 21.1                                                  |
| 180°                      | 1.65                                   | 1.2                                                           | 3.26                                  | 1.15                                                          | 58.8                                                  |

negative due to the phase-locked \( d \)-axis leading the actual port voltage vector at the moment of reclosing, and then the phase-locked \( d \)-axis will decelerate in order to track the actual port voltage vector again. In this process, it can be seen from Fig. 12(a) that the \( q \)-axis component value of PLL calculation voltage will continuously increase to a positive value, and then gradually return to 0. And only when the phase-locked \( d \)-axis lags the actual port voltage (as shown in Fig. 3(c)), the circumstance where the \( q \)-axis component of the calculated voltage is positive will appear. Consequently, simulation waveforms in Fig. 12 verified the overshoot phenomenon in Fig. 3. And when the reclosing angle is 90°, the \( q \)-axis component value of the calculation voltage is positive since the phase-locked \( d \)-axis lags the port voltage at the moment of reclosing, and there is also a phase-locked overshoot phenomenon. In addition, since PLL adopts the positive and negative sequence separation method of \( T_1/4 \) delay, the value of \( d \)-axis and \( q \)-axis component will change at the time of \( T_1/4 \) after reclosing.

2) SIMULATION RESULT ANALYSIS OF DIFFERENT RECLOSING PHASE DIFFERENCES

The simulation results of the reclosing impulse current and voltage in the cases of different reclosing phase differences are shown in Table 2. And in Table 2, peak values of reclosing current and voltage are the superimposed values of high-frequency components and power frequency components at the moment of reclosing. The peak value of the closing voltage affected by the high-frequency impulse component can reach several times the rated voltage, but the closing power frequency voltage does not exceed 1.15 p.u..

It can be seen from Table 2 that comparing the reclosing case where the reclosing angle is \( \phi \) (0° < \( \phi \) < 180°) with the reclosing case where the reclosing angle is \(-\phi\), the reclosing voltage peak value and the fundamental frequency voltage effective value of the former are larger, but its reclosing current peak value is smaller. And when the reclosing angles are all negative or positive, as the absolute value of the reclosing angle increases, the peak values of the reclosing voltage and reclosing current also increase. When \(|\phi| \geq 90°\), the maximum effective values of the reclosing fundamental frequency current are all the limit value of 1.2 p.u. since the output fundamental frequency current of PVS is controlled by the inverter limiting link, and the maximum effective values of the reclosing fundamental frequency voltage are all 1.15 p.u., which is close to the theoretical calculation value of 1.19 p.u. in Section III(A). And in this condition, the grid-connected point voltage vector and the vector of voltage drop from PVS port to main transformer outlet are in phase. The above simulation results verify the correctness of the analysis conclusions concerning the influence of the reclosing phase difference on reclosing impulse in Section III(A).

B. SIMULATION OF DIFFERENT RECLOSING AMPLITUDE DIFFERENCES

In this section, the changes of reclosing impulse voltage and current under the circumstances of different reclosing amplitude differences are analyzed according to the simulation results, in order to verify the correctness of the relevant analysis conclusions in Section III(B). When the grid voltage amplitude is greater than the island voltage amplitude, the reclosing amplitude difference is defined as positive, and on the contrary it is negative. Due to the limitation of article length, only the simulation waveforms of the two kinds of reclosing amplitude differences (0.4 p.u. and \(-0.3 \) p.u.) and the reclosing angle of 90° are given below, and the influences of other reclosing amplitude differences are shown in Table 2. The remaining simulation conditions are the same as in Section IV(A).

1) RECLOSING AMPLITUDE DIFFERENCES ARE 0.4 p.u. AND \(-0.3 \) p.u.

When the reclosing amplitude differences are 0.4 p.u. and \(-0.3 \) p.u., the waveforms of the three-phase voltage and the fundamental frequency three-phase voltage RMS at PVS port are shown in Fig. 13.

It can be seen from Fig. 13(a)(c) that when the reclosing amplitude differences are 0.4 p.u. and \(-0.3 \) p.u., the peak value of the reclosing voltage are 1.63 p.u. and 2.85 p.u. respectively. As the reclosing amplitude difference decreases, the reclosing voltage peak value increases. And as shown in Fig. 13(b)(d), in the cases where the reclosing amplitude are 0.4 p.u. and \(-0.3 \) p.u., both the maximum effective value, which are measured by the measuring component composed
of FFT algorithm, of fundamental frequency voltage are 1.15 p.u.

The waveforms of the three-phase current at PVS port are shown in Fig. 14.

As shown in Fig. 14, when the reclosing amplitude differences are 0.4 p.u. and −0.3 p.u., the peak values of reclosing current are almost the same, and their values are 1.3 p.u. and 1.29 p.u. respectively.

2) SIMULATION RESULT ANALYSIS OF DIFFERENT RECLOSING AMPLITUDE DIFFERENCES

The simulation results of the reclosing impulse current and voltage in the cases of different reclosing amplitude differences are shown in Table 3.

It can be seen from Table 3 that when the closing phase difference is 90°, in the cases of different reclosing amplitude differences, the reclosing current peak values, the maximum effective values of reclosing fundamental frequency current and the maximum effective values of reclosing fundamental frequency voltage are almost the same, whose values are 1.3 p.u., 1.2 p.u. and 1.15 p.u. respectively, and the reclosing voltage peak value increases as the reclosing amplitude difference decreases. When the reclosing phase difference is 45°, since the reclosing angle is small, PLL calculation voltage will be close to the rated voltage of grid. Therefore, when the effective value of the island voltage is greater than or equal to 1 p.u. (namely the reclosing amplitude difference is less than or equal to zero), the maximum effective value of reclosing fundamental frequency current does not reach the limit value of 1.2 p.u., and when the island voltage is less than or equal to 0.8 p.u., since the output current of PVS in island operation state will reach the limit value, the maximum effective value of reclosing fundamental frequency current is 1.2 p.u., and the effective value of PVS output current return to 1 p.u. quickly after reclosing. Moreover, when the reclosing phase difference is 45°, as the reclosing amplitude difference decreases, the maximum closing voltage peak first decreases and then increases. The above simulation results verify the correctness of the analysis conclusions concerning
TABLE 3. Simulation results of the reclosing impulse current and voltage in the cases of different reclosing amplitude differences.

| Reclosing phase difference | Reclosing amplitude difference (p.u.) | Peak value of reclosing current (p.u.) | Maximum fundamental frequency RMS of reclosing current (p.u.) | Peak value of reclosing voltage (p.u.) | Maximum fundamental frequency RMS of reclosing voltage (p.u.) | Duration of reclosing voltage greater than 1.35 p.u. (ms) |
|---------------------------|---------------------------------------|----------------------------------------|-------------------------------------------------------------|---------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| 90°                       | 0.6                                   | 1.3                                    | 1.2                                                         | 1.59                                  | 1.15                                                         | 0.3                                                           |
|                           | 0.4                                   | 1.3                                    | 1.2                                                         | 1.63                                  | 1.15                                                         | 1.2                                                           |
|                           | 0.2                                   | 1.3                                    | 1.2                                                         | 2.13                                  | 1.15                                                         | 1.3                                                           |
|                           | 0                                     | 1.0                                    | 1.2                                                         | 2.54                                  | 1.15                                                         | 1.5                                                           |
|                           | -0.3                                  | 1.29                                   | 1.2                                                         | 2.85                                  | 1.3                                                          | 3.2                                                           |
| 45°                       | 0.6                                   | 1.23                                   | 1.2                                                         | 1.37                                  | 1.08                                                         | 0.1                                                           |
|                           | 0.4                                   | 1.23                                   | 1.2                                                         | 1.32                                  | 1.08                                                         | ／                                                           |
|                           | 0.2                                   | 1.22                                   | 1.2                                                         | 1.62                                  | 1.08                                                         | 0.3                                                           |
|                           | 0                                     | 1.13                                   | 1.1                                                         | 1.85                                  | 1.08                                                         | 1.4                                                           |
|                           | -0.3                                  | 1.12                                   | 1.09                                                        | 1.91                                  | 1.3                                                          | 2.2                                                           |

the influence of the reclosing amplitude difference on reclosing impulse in Section III(B).

**C. SIMULATION OF DIFFERENT RECLOSELING FREQUENCY DIFFERENCES**

In this section, the changes of reclosing impulse voltage and current under the circumstances of different reclosing frequency difference is analyzed accordingly to the simulation results, in order to verify the correctness of the relevant analysis conclusions in Section III(C). When the grid frequency is greater than the island frequency, the reclosing frequency difference is defined as positive, and on the contrary it is negative. Due to the limitation of article length, only the simulation waveform of the two kinds of reclosing frequency differences (1 Hz and -0.5 Hz) and the island voltage amplitude of 1 p.u. are given below, and the influences of other reclosing frequency differences are shown in Table 3. The remaining simulation conditions are the same as in Section IV(A).

1) RECLOSING FREQUENCY DIFFERENCES ARE 1 Hz AND -0.5 Hz

When the reclosing frequency differences are 1 Hz and -0.5 Hz, the frequency waveforms of the voltage at both ends of the circuit breaker on the PVS side of tie line are shown in Fig. 15.

It can be seen from Fig. 15 that in the cases of two kinds of reclosing frequency differences, the voltage frequencies of PVS island operation (namely the voltage frequencies of the busbar end) become 49 Hz and 50.5 Hz respectively when the fault is cleared by the protection of tie line. And at the moment of reclosing, both the voltage frequency of the busbar end quickly return to 50 Hz. It should be noted that since the voltage amplitude of the line end is 0 during the period of fault cleared and protection reclosing with zero voltage checking, the voltage frequency measurement of the line end in this period is invalid.

The waveforms of the three-phase voltage and the fundamental frequency three-phase voltage RMS at PVS port are shown in Fig. 16.

As shown in Fig. 16, when the reclosing frequency differences are 1 Hz and -0.5 Hz, the peak values of the reclosing voltage are almost equal, which are 2.55 p.u. and 2.54 p.u. respectively. And the difference between them may be caused by a small deviation between the reclosing phase difference and the amplitude difference in the two simulation cases. And both the maximum effective value of the reclosing fundamental frequency voltage are 1.15 p.u..

The waveforms of the three-phase current at PVS port are shown in Fig. 17.

It can be seen from Fig. 17 that when the reclosing frequency differences are 1 Hz and -0.5 Hz, the peak values of the reclosing current are equal, both being 1.28 p.u.
FIGURE 16. Waveforms of reclosing three-phase voltage at PVS port and its fundamental frequency RMS when the reclosing frequency differences are 1 Hz and –0.5 Hz.

2) SIMULATION RESULT ANALYSIS OF DIFFERENT RECLOSING FREQUENCY DIFFERENCES

The simulation results of the reclosing impulse current and voltage in the cases of different reclosing frequency differences are shown in Table 4.

It can be seen from Table 4 that when the reclosing amplitude difference is the same, the peak values of reclosing current, the maximum effective values of reclosing fundamental frequency current, the peak values of reclosing voltage and the maximum effective values of reclosing fundamental frequency voltage are all almost the same, which verify the correctness of the analysis conclusions concerning that the reclosing frequency difference within the allowable operating range of PVS has almost no influence on the reclosing impulse voltage and current in Section III(C).

V. SYNCHRONOUS CHECK RECLOSING STRATEGY

From the above influence analysis and simulation experiments, it can be seen that the main influencing factors of the reclosing impulse current and voltage are the reclosing phase difference and amplitude difference, and the reclosing frequency difference has no almost effect on it. The current capacity of IGBT in the PVS inverter is generally 3 times the rated current, and its overcurrent protection setting is generally 2 p.u.-3 p.u. [23]. Moreover, to prevent the overvoltage breakdown of IGBT tube and the overmodulation of PVS inverter, the overvoltage quick-break protection setting of PVS inverter is generally 1.35 p.u..

Based on this, combining the relevant operation standard of PVS [17], this section proposes a synchronous check reclosing strategy applicable to the tie line protection of PVS, and its main goal is to control the reclosing impulse voltage and current to be within 1.35 p.u. and 2 p.u. respectively.

The synchronous check reclosing conditions are:

a. The reclosing voltage amplitude difference is in the range of –0.3 p.u. ~ –0.6 p.u. (island operating standard);

b. The reclosing voltage phase difference is in the range of –30° ~ 10°;
TABLE 4. Simulation results of the reclosing impulse current and voltage in the cases of different reclosing frequency differences.

| Reclosing amplitude difference (p.u.) | Reclosing frequency difference (Hz) | Peak value of reclosing current (p.u.) | Maximum fundamental frequency RMS of reclosing current (p.u.) | Peak value of reclosing voltage (p.u.) | Maximum fundamental frequency RMS of reclosing voltage (p.u.) | Duration of reclosing voltage greater than 1.35 p.u. (ms) |
|--------------------------------------|-----------------------------------|---------------------------------------|------------------------------------------------|--------------------------------------|------------------------------------------------|------------------------------------------------------|
|                                      | 2                                 | 1.3                                   | 1.2                                           | 1.63                                 | 1.15                                           | 1.2                                                  |
|                                      | 1                                 | 1.29                                  | 1.2                                           | 1.61                                 | 1.15                                           | 1.2                                                  |
|                                      | -0.5                              | 1.27                                  | 1.2                                           | 1.62                                 | 1.15                                           | 1.2                                                  |
| 0                                    | 2                                 | 1.29                                  | 1.2                                           | 2.54                                 | 1.15                                           | 1.5                                                  |
|                                      | 1                                 | 1.28                                  | 1.2                                           | 2.55                                 | 1.15                                           | 1.5                                                  |
|                                      | -0.5                              | 1.28                                  | 1.2                                           | 2.54                                 | 1.15                                           | 1.5                                                  |
| -0.3                                 | 2                                 | 1.29                                  | 1.2                                           | 2.85                                 | 1.3                                            | 3.2                                                  |
|                                      | 1                                 | 1.28                                  | 1.2                                           | 2.88                                 | 1.3                                            | 3.3                                                  |
|                                      | -0.5                              | 1.27                                  | 1.2                                           | 2.84                                 | 1.3                                            | 3.2                                                  |

c. The reclosing frequency difference is in the range of −2Hz~0.5 Hz (island operating standard, the allowable operational frequency range of PVS is 48 Hz~50.5 Hz).

To verify the effectiveness of the proposed reclosing strategy, the corresponding simulation experiments were carried out in this paper, and the results are shown in Table 5, and two sets of the simulation waveform of PVS port voltage in the boundary conditions of the proposed synchronous check reclosing strategy are shown in Fig. 18.

The simulation results show that when the proposed synchronous check reclosing conditions are satisfied, both the reclosing impulse voltage and current are within the allowable range, and the protection on the PVS side of tie line can successfully achieve the three-phase reclosing. When the three-phase reclosing is used, if some phases fail to reclose due to breaker reasons, the three-phase reclosing will quickly open the connected phases and no longer reclose. And during the reclosing process, if some phases are not connected, the reclosing impulse voltage and current are different from those when the three phases are reclosing simultaneously. The following uses the cases of phase-A reclosing and phase-AB reclosing when the closing angle is −90° as examples for illustration, as shown in Fig. 19.

It can be seen from Fig. 19 that when only phase-A recloses or phase-AB reclose, the peak values of the reclosing voltage at PVS port are 1.3 p.u. and 1.7 p.u. respectively. Compared with the three-phase voltage waveform shown in Fig. 10 (a), both the peak values of the reclosing voltage in two cases of phase-A reclosing and phase-AB reclosing are smaller. And the research shows that the impulse voltage and current generated by non-full-phase reclosing are generally lower than those generated by full-phase reclosing.
TABLE 5. Simulation results of the synchronous check reclosing strategy.

| Reclosing amplitude difference (p.u.) | Reclosing phase difference | Peak value of reclosing current (p.u.) | Maximum fundamental frequency RMS of reclosing current (p.u.) | Peak value of reclosing voltage (p.u.) | Maximum fundamental frequency RMS of reclosing voltage (p.u.) | Duration of reclosing voltage greater than 1.35 p.u. (ms) |
|--------------------------------------|---------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------------------------|
|                                      | -60°                      | 1.23                                   | 1.2                                                         | 1.15                                   | 1.03                                                         | /                                                        |
|                                      | -50°                      | 1.23                                   | 1.2                                                         | 1.1                                      | 1.02                                                         | /                                                        |
|                                      | -40°                      | 1.24                                   | 1.2                                                         | 1.07                                   | 1.02                                                         | /                                                        |
|                                      | -30°                      | 1.24                                   | 1.2                                                         | 1.12                                   | 1.01                                                         | /                                                        |
|                                      | -20°                      | 1.23                                   | 1.2                                                         | 1.16                                   | 1.01                                                         | /                                                        |
|                                      | -10°                      | 1.23                                   | 1.2                                                         | 1.16                                   | 1.01                                                         | /                                                        |
|                                      | 0°                        | 1.22                                   | 1.2                                                         | 1.18                                   | 1.01                                                         | /                                                        |
|                                      | 1°                        | 1.23                                   | 1.2                                                         | 1.23                                   | 1.02                                                         | /                                                        |
|                                      | 20°                       | 1.23                                   | 1.2                                                         | 1.33                                   | 1.03                                                         | /                                                        |
|                                      | 30°                       | 1.24                                   | 1.2                                                         | 1.42                                   | 1.04                                                         | 0.2                                                      |
| 0.6                                  | -60°                      | 1.23                                   | 1.2                                                         | 1.1                                      | 1.04                                                         | /                                                        |
|                                      | -50°                      | 1.23                                   | 1.2                                                         | 1.08                                   | 1.03                                                         | /                                                        |
|                                      | -40°                      | 1.23                                   | 1.2                                                         | 1.07                                   | 1.02                                                         | /                                                        |
|                                      | -30°                      | 1.23                                   | 1.2                                                         | 1.06                                   | 1.02                                                         | /                                                        |
|                                      | -20°                      | 1.23                                   | 1.2                                                         | 1.09                                   | 1.01                                                         | /                                                        |
|                                      | -10°                      | 1.22                                   | 1.2                                                         | 1.1                                      | 1.01                                                         | /                                                        |
|                                      | 0°                        | 1.22                                   | 1.2                                                         | 1.11                                   | 1.01                                                         | /                                                        |
|                                      | 10°                       | 1.22                                   | 1.2                                                         | 1.15                                   | 1.02                                                         | /                                                        |
|                                      | 20°                       | 1.24                                   | 1.2                                                         | 1.28                                   | 1.04                                                         | /                                                        |
|                                      | 30°                       | 1.24                                   | 1.2                                                         | 1.36                                   | 1.06                                                         | 0.1                                                      |
| 0.4                                  | -60°                      | 1.3                                    | 1.2                                                         | 1.32                                   | 1.03                                                         | /                                                        |
|                                      | -50°                      | 1.24                                   | 1.2                                                         | 1.3                                      | 1.02                                                         | /                                                        |
|                                      | -40°                      | 1.22                                   | 1.2                                                         | 1.15                                   | 1.02                                                         | /                                                        |
|                                      | -30°                      | 1.22                                   | 1.2                                                         | 1.11                                   | 1.02                                                         | /                                                        |
|                                      | -20°                      | 1.2                                    | 1.2                                                         | 1.09                                   | 1.01                                                         | /                                                        |
|                                      | -10°                      | 1.2                                    | 1.2                                                         | 1.05                                   | 1.01                                                         | /                                                        |
|                                      | 0°                        | 1.2                                    | 1.2                                                         | 1.03                                   | 1                                                            | /                                                        |
|                                      | 10°                       | 1.2                                    | 1.2                                                         | 1.18                                   | 1.02                                                         | /                                                        |
|                                      | 20°                       | 1.2                                    | 1.2                                                         | 1.26                                   | 1.03                                                         | /                                                        |
|                                      | 30°                       | 1.2                                    | 1.2                                                         | 1.52                                   | 1.05                                                         | 0.3                                                      |
| 0.2                                  | -60°                      | 1.23                                   | 1.18                                                        | 1.55                                   | 1.03                                                         | 0.7                                                      |
|                                      | -50°                      | 1.18                                   | 1.17                                                        | 1.38                                   | 1.02                                                         | 0.1                                                      |
|                                      | -40°                      | 1.16                                   | 1.14                                                        | 1.18                                   | 1.02                                                         | /                                                        |
|                                      | -30°                      | 1.1                                    | 1.08                                                        | 1.14                                   | 1.02                                                         | /                                                        |
|                                      | -20°                      | 1.06                                   | 1.04                                                        | 1.07                                   | 1.01                                                         | /                                                        |
|                                      | -10°                      | 1                                    | 1                                                            | 1.02                                   | 1.01                                                         | /                                                        |
|                                      | 0°                        | 1                                    | 1                                                            | 1                                       | 1                                                            | /                                                        |
|                                      | 10°                       | 1                                    | 1                                                            | 1.14                                   | 1.02                                                         | /                                                        |
|                                      | 20°                       | 1                                    | 1                                                            | 1.31                                   | 1.03                                                         | /                                                        |
|                                      | 30°                       | 1.05                                   | 1.53                                                        | 1.05                                    | 0.5                                                          | /                                                        |
| 0                                    | -60°                      | 1.17                                   | 1.16                                                        | 1.45                                   | 1.3                                                          | 0.2                                                      |
|                                      | -50°                      | 1.14                                   | 1.13                                                        | 1.38                                   | 1.3                                                          | /                                                        |
|                                      | -40°                      | 1.06                                   | 1.06                                                        | 1.3                                     | 1.3                                                          | /                                                        |
|                                      | -30°                      | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | -20°                      | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | -10°                      | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | 0°                        | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | 10°                       | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | 20°                       | 1                                    | 1                                                            | 1.3                                      | 1.3                                                         | /                                                        |
|                                      | 30°                       | 1                                    | 1                                                            | 1.41                                    | 1.3                                                          | 0.1                                                      |

Therefore, employing the synchronous check reclosing strategy proposed in this paper can also ensure the safe operation of PVS and power grid during non-full-phase reclosing.

It should be pointed out that in the proposed reclosing conditions, conditions (a) and (c) are mainly based on the relevant regulations given by the operational standard of PVS, and no other constraints are attached. In other words, as long as PVS can maintain the island operation state at the moment of reclosing, i.e., the protection on the PVS side of tie line can detect the non-zero voltage at the bus terminal, and the reclosing phase difference is within the range of the synchronous check reclosing conditions, the circuit breaker on the PVS side of the tie line can perform fast three-phase reclosing, which can greatly improve the success rate of three-phase
reclosing and prevent PVS from being in the unplanned islanding operation for a long time due to the transient fault in tie line, eventually improving the power supply reliability and PVS utilization significantly. Consequently, the proposed reclosing strategy has good engineering application value.

VI. CONCLUSION
Aiming at the adverse effects of PVS access on the three-phase reclosing of tie line, this paper establishes a vector relationship model of PVS port voltage, grid-connected point voltage and so on before and after reclosing, analyzes the influencing factors of the reclosing impulse voltage and current, and proposes a synchronous check reclosing strategy applicable to the tie line of PVS. The correctness of the impact analysis and the effectiveness of the proposed strategy are verified by digital simulation. The main obtained results are as follows:

1) For the three-phase reclosing, the reclosing phase difference and amplitude difference have a great influence on the reclosing impulse, while the reclosing frequency difference which satisfies the operational standard (48 Hz-50.5 Hz) has almost no effect on it;

2) In terms of the influence of the reclosing phase difference, the reclosing impulse performance when the reclosing angle is $\varphi (0^\circ < \varphi < 180^\circ)$ is more disadvantageous than that in the case where the closing angle is $-\varphi$, because the peak value of former’s reclosing fundamental frequency voltage is greater. And the larger the absolute value of the reclosing angle, the greater the peak value of reclosing impulse voltage and current;

3) In terms of the influence of the reclosing amplitude difference, when the reclosing angle is large, such as greater than 90°, the peak value of the reclosing impulse voltage increases as the amplitude of the island voltage increases from 0.2 p.u. to 1.3 p.u.. And when the reclosing phase difference is small, such as less than 90°, it is necessary to consider the influence of the phase difference between the PVS port voltage and the grid-connected point voltage, and the reclosing impulse voltage no longer increases monotonously as the island amplitude increases;

4) The research indicates that by adopting the synchronous check reclosing strategy proposed in this paper, the success rate of the three-phase reclosing on PVS tie line can be effectively improved under the premise of ensuring the safety of renewable energy source and power grid, which could not only prevent the large-scale off-grid of renewable energy source when the transient fault occurs, but also significantly improve the utilization of renewable energy.

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