Applicability study of single-phase reclosing in tie line of photovoltaic power plant

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Abstract
Overhead transmission line faults are mostly single-phase grounding faults, and to ensure the power supply reliability of photovoltaic power plants in the cases of tie line transient faults, a feasible solution is to employ the single-phase reclosing. However, for the single-phase reclosing of the tie line, photovoltaic power source may face the over-voltage problem during the non-full phase operation, which will seriously affect the success rate of the single-phase reclosing. This paper, according to different non-full phase operation control strategies of photovoltaic power source, establishes the corresponding sequence network analysis models, and proposes the theoretical calculation method of non-full phase operation voltage, which takes account of different neutral point grounding modes of step-up transformer and different load levels. Meanwhile, the closing impulse problem of the single-phase reclosing is discussed. The correctness of the theoretical method is verified by digital simulation results. On this basis, the applicable scope and application suggestions of the single-phase reclosing are given. The research conclusions can provide important guidance and reference for the application of single-phase reclosing technology in tie line of renewable energy power plant.

1 | INTRODUCTION
To solve the increasingly severe energy crisis and environmental problems, grid-connected photovoltaic power generation technology has developed rapidly, and photovoltaic power generation accounts for an increasing proportion of installed capacity in the power system [1]. Large-scale photovoltaic power source (PVS) is connected to the power grid via tie lines mainly composed of overhead lines [2], and the automatic reclosing methods used by tie lines can generally be divided into three-phase reclosing and single-phase reclosing. As for the three-phase reclosing method, compared with synchronous motors, PVS almost has no physical inertia and effective voltage control capability, which results in that it is very easy to disconnect from the power grid due to system frequency deviation and voltage deviation during the islanding operation [3, 4]. To ensure the high reclosing success rate of PVS in the case of tie line transient faults, and considering that most of overhead transmission line faults are single-phase grounding faults [5], a feasible solution is to employ the single-phase reclosing device on the tie line of PVS [6]. However, as for the single-phase reclosing, when a single-phase grounding fault occurring in the tie line is cleared by the single-phase trip of protection, PVS will be in the status of non-full phase operating. In this condition, affected by factors such as the control strategy of PVS, the neutral point grounding mode of transformer and so on, the disconnected phase voltage of PVS may be much larger than the setting value of over-voltage protection, leading to the disconnection of PVS from power grid and the single-phase reclosing failure. In addition, due to the limited ability of insulated gate bipolar transistor (IGBT) tubes in PVS inverter to withstand over-voltage and over-current [7], if the impulse current and voltage of the single-phase reclosing are too large, it will directly threaten the safe operation of PVS. Consequently, to ensure the success rate of reclosing and the operation safety of PVS, it is of practical significance to develop the research on non-full phase operation voltage characteristics and single-phase reclosing impulse problems of PVS.

At present, most studies on the single-phase reclosing of the renewable energy power plant are about the adaptive reclosing [8, 9], whose key point is to correctly judge whether the line fault is transient or permanent, and then decide whether to reclose. Obviously the precondition for realising adaptive reclosing is that when the single-phase of tie line is...
disconnected, the renewable energy power plant cannot exit operation due to over-voltage or over-current. However, the existing fault analysis methods for the non-full phase operation (single-phase disconnection) of the power grid are mainly based on the assumption that power sources are all traditional synchronous generators [10–12], and are not applicable for fault conditions containing renewable power sources. Guo et al. [13] and Yang et al. [14], respectively, analysed the impact of photovoltaic power and wind turbine on the automatic reclosing of the tie line. It was believed that the frequency of photovoltaic power and wind turbine in the island state is prone to shift, which is the key factor that causes the three-phase reclosing failure. But the influence of renewable energy sources on the single-phase reclosing of the tie line was not considered. For the wind farm whose tie line is equipped with the single-phase reclosing, Xiong et al. [15] mainly studied the non-full phase operating voltage on the system side of the wind farm tie line. But considering that the fault current supplied by the wind farm is much smaller than that from the power grid, the wind farm side was treated as an open circuit in the theoretical analysis. Therefore, the analysis conclusion is only applicable to the system side of the tie line, lacking the evaluation of the non-full phase operation voltage on the wind farm side. According to a simulation study of the entire process from the fault occurrence to the action of the single-phase reclosing, Yuan et al. [16] demonstrated the feasibility of employing the single-phase reclosing on the high-voltage tie line of renewable energy power plants. The influence of the neutral point grounding mode of step-up transformer on the non-full phase operating voltage is not considered, and it is limited to qualitative analysis, lacking the support of the necessary theoretical analysis. Here, it is found that in some cases, there may be an over-voltage phenomenon of the renewable energy power plant during the non-full phase operation, which will lead to the failure of single-phase reclosing.

According to different non-full phase operation control strategies of PVS and their corresponding analysis models of sequence networks, this paper proposes a theoretical calculation method of PVS non-full phase operation voltage, taking into account different neutral point grounding modes of the step-up transformer. Meanwhile, the closing impulse problem of single-phase reclosing is discussed. The correctness of the theoretical method is verified by digital simulation results. On this basis, the applicable scope and application recommendations of single-phase reclosing are further given. The research conclusions can provide important guidance and reference for the application of single-phase reclosing technology in tie line of renewable energy power plant.

2 | DIFFERENT NON-FULL PHASE OPERATION CONTROL STRATEGIES OF PVS AND THEIR SEQUENCE NETWORK ANALYSIS MODELS

PVS is a renewable energy source directly connected to the power grid through the inverter, and its output characteristics are closely related to the inverter control strategy. There are mainly two typical control strategies of PVS under the circumstance of symmetrical voltage. One is to employ the negative-sequence current suppression control method in the case of symmetrical voltage, in order to reduce the adverse impact of negative-sequence components on the power grid. The other is mainly used for the asymmetrical short circuit. Only when the positive-sequence voltage of the PVS port is lower than the threshold, such as 0.9 $V_{g*}$, the negative-sequence current suppression method of the low-voltage ride-through (LVRT) control strategy is started. According to the above two typical control strategies of PVS, their corresponding sequence network analysis models are established in the following.

2.1 | Negative-sequence current suppression control strategy is started

During the non-full phase operation of single-phase reclosing, the three-phase voltage of the PVS port will be asymmetric. When the suppressing negative-sequence current control strategy using the positive-sequence voltage measurement is started [17,18], phase-locked loop of the PVS inverter will separate the positive and negative-sequence components of port voltage, and generally directs the positive-sequence voltage of power grid to d-axis [19–21]. Meanwhile, the instruction value of the negative-sequence current is set to 0. Under the circumstance of this control strategy, the output current of PVS is shown in (1):

$$\begin{align*}
\begin{cases}
    i_{gd}^+ &= \min \left( \frac{P_0}{U_g}, \sqrt{I_{g_{\max}}^2 - i_{gq}^2} \right) & U_{g*} > 0.9 \\
    i_{gq}^+ &= 1.5(0.9 - U_{g*}) & 0.9 \geq U_{g*} \geq 0.2 \\
    i_{gd}^- &= 0 & U_{g*} < 0.2 \\
    i_{gq}^- &= 0
\end{cases}
\end{align*}$$

(1)

where $i_{gd}^+$ and $i_{gq}^+$ represent the d-axis and q-axis positive-sequence components of the output current of PVS, respectively; $i_{gd}^-$ and $i_{gq}^-$ represent the d-axis and q-axis negative-sequence components of the output current of PVS, respectively; $U_{g*}$ represents the positive-sequence voltage amplitude of power grid; $P_0$ represents the normal active power of PVS; $I_{g_{\max}}$ represents the maximum allowable current of PVS.

It can be seen from (1) that for the positive-sequence network, PVS can be equivalent to a voltage-controlled current source model whose amplitude and phase are both controlled by the positive-sequence voltage. For the negative-sequence network, since PVS does not output the negative-sequence current, the PVS side of tie line can be equivalent to an open circuit.
2.2 Negative-sequence current suppression control strategy is not started

The non-full phase operation of the single-phase reclosing is different from the asymmetric short-circuit fault because it generally does not cause a large drop in the voltage of power grid. When the amplitude of the non-full phase operation voltage is greater than 0.9 p.u., the negative-sequence current suppression control strategy, which is mainly used for asymmetrical short-circuit fault, may be not started. In this condition, the positive-sequence output current characteristics of PVS are the same as in (1), which means that the positive-sequence network analysis model of PVS is still a voltage-controlled current source. But the negative-sequence output characteristics of PVS will change. According to controller equations of the voltage outer loop and current inner loop of PVS inverter, the negative-sequence network model of PVS under the circumstance that the negative-sequence current suppression strategy is not started is established next.

When the negative-sequence current suppression strategy is not started during the non-full phase operation, the output positive-sequence current and negative-sequence voltage, or the negative-sequence current and positive-sequence voltage of PVS will generate a double-frequency power [18], and their relation is shown in (2):

\[
\begin{align*}
P_{g2} \cos(2\omega_1 t + \theta) &= P_{g2} \cos(2\omega_1 t) + P_{g2} \sin(2\omega_1 t) \\
Q_{g2} \cos(2\omega_1 t + \theta) &= Q_{g2} \cos(2\omega_1 t) + Q_{g2} \sin(2\omega_1 t) \\
\begin{bmatrix}
P_{g2} \\
Q_{g2} \\
\end{bmatrix} &=
\begin{bmatrix}
ug_1 & u_{g\theta} & u_{g\phi} & u_{g\gamma} \\
u_{g\theta} & -u_{g\theta} & -u_{g\phi} & u_{g\gamma} \\
u_{g\phi} & u_{g\phi} & -u_{g\phi} & -u_{g\gamma} \\
u_{g\gamma} & u_{g\gamma} & u_{g\gamma} & -u_{g\gamma} \\
\end{bmatrix}
\begin{bmatrix}
ig_d+ \\
ig_d- \\
ig_q+ \\
ig_q- \\
\end{bmatrix}
\end{align*}
\]

(2)

where \(P_{g2}\) and \(Q_{g2}\) represent the double-frequency active and reactive power, respectively; \(u_{g\phi}\) and \(u_{g\gamma}\) represent the \(d\)-axis and \(q\)-axis positive-sequence components of PVS port voltage, respectively, \(u_{g\theta}\) and \(u_{g\gamma}\) represent the \(d\)-axis and \(q\)-axis negative-sequence components of PVS port voltage, respectively; \(2\omega_1\) represents the fundamental frequency angular velocity.

Since PVS generally directs the positive- and negative-sequence voltage of the power grid to the positive- and negative-sequence \(d\)-axis, respectively, the parameters \(u_{g\phi}\) and \(u_{g\gamma}\) in (2) are both 0. When the positive-sequence voltage during the non-full phase operation is high and the negative-sequence current suppression strategy is not started, it can be known from (1) that the \(d\)-axis component of the PVS output current will be much larger than the \(q\)-axis component. It can be approximated that PVS works in the operating state of unit power factor, and the parameter \(i_{g\gamma+}\) in (2) is 0. In this condition, the expression of the double-frequency active power in (2) can be simplified as shown in (3):

\[
\begin{align*}
P_{g2} &= \frac{(u_{g\phi} i_{g-d} + u_{g\gamma} i_{g-q})^2}{-2u_{g\phi} i_{g-d} u_{g\gamma} (i_{g-d} - i_{g-q})} \\
n_{g+d} &= u_{g\phi} + \\
n_{g-q} &= u_{g\gamma} \\
i_{g-d} &= \sqrt{i_{g-d}^2 + i_{g-q}^2}
\end{align*}
\]

(3)

where \(n_{g+d}\) and \(n_{g-q}\) represent the positive- and negative-sequence voltages of PVS port, respectively; \(i_{g-d}\) represents the negative-sequence current of PVS.

Since the equivalent impedance of positive-sequence network is almost equal to the load impedance, it will be much greater than the equivalent impedance of zero-sequence network, which is mainly composed of the zero-sequence impedance of lines and transformers. And it is obvious that when the neutral point on the high-voltage side of step-up transformer is directly grounded, the negative-sequence voltage of the PVS port and tie line will be much smaller than the positive-sequence voltage. In this condition, the parameter \(u_{g\gamma}\) in (3) can be approximately regarded as 0. When the neutral point on the high-voltage side of step-up transformer is ungrounded, since the local load of PVS is mainly the active load, whose equivalent impedance can be considered as resistive and is much larger than the impedance of lines and transformers, the positive-sequence network equivalent impedance is almost the load impedance. The negative network equivalent impedance is nearly the parallel impedance of PVS negative-sequence equivalent impedance and load impedance. When the negative-sequence equivalent impedance of PVS is smaller than the load impedance, the parallel impedance of the two will be much smaller than the positive-sequence network equivalent impedance. In this condition, the positive-sequence current and voltage of the fault port of tie line are almost in phase, while the negative-sequence voltage and current of the fault port are in reversed phase, and the negative-sequence equivalent impedance of PVS is resistive due to the influence of external circuit characteristics. However, when the negative-sequence equivalent impedance of PVS is large, since the load impedance is resistive, the parallel impedance of the two and the equivalent impedance of the positive-sequence network are also resistive in series. And in this condition, the positive-sequence current and voltage of the fault port are also almost in phase, and the negative-sequence equivalent impedance of PVS is also resistive due to the influence of external circuit characteristics. Consequently, the value of \(i_{g-d}\) in (3) and (3) can be simplified as shown in (4):

\[
P_{g2} = n_{g+d} i_{g-d} + n_{g-q} i_{g-q+}.
\]

(4)

During the non-full phase operation of PVS, the double-frequency active power generated by PVS will result in the
double-frequency fluctuation of the DC bus voltage, which will eventually affect the PVS port voltage through the inverter control link. To clearly explain the relationship between the double-frequency active power fluctuation and the PVS port voltage, the control block diagram of the PVS inverter is given next, as shown in Figure 1. In Figure 1, the subscript “*” represents the instruction value.

It can be seen from Figure 1 that when the DC bus voltage has a double-frequency fluctuation due to the presence of the double-frequency active power, the output d-axis current instruction value will also generate a double-frequency component through the outer voltage control loop of inverter. However, the output q-axis current instruction value is not affected by the bus voltage fluctuation and has no double-frequency component. Since the actual output d-axis and q-axis currents are generally extracted through a notch filter link, their measured values are almost DC components. In this condition, according to the inner current control loop of the inverter, the PVS port d-axis voltage will also generate a double-frequency component, while the PVS port q-axis voltage has no double-frequency component. According to (4) and Figure 1, the expressions of double-frequency components of the DC bus voltage, the output d, q-axis current instruction value and the PVS port d, q-axis voltage are shown in (5):

\[
\begin{align*}
U_{d+2nd} &= \frac{u_d + i_d - u_q - i_q + u_d* - i_d* + u_q* - i_q*}{2C U_{dc} \omega_1} \\
i_{d+2nd} &= U_{d+2nd} \sqrt{k_{1d}^2 + \frac{k_{2d}^2}{4}} \\
i_{q+2nd} &= 0 \\
i_{g+2nd} &= i_{d+2nd} \\
U_{g+2nd} &= 0
\end{align*}
\]

where \(U_{d+2nd}\), \(i_{d+2nd}\), \(i_{q+2nd}\), \(i_{g+2nd}\), \(u_{g+2nd}\), \(u_{d+2nd}\) and \(u_{q+2nd}\) represent the double-frequency components of the DC bus voltage, the output d, q-axis current instruction values and the PVS port d, q-axis voltages, respectively; \(C\) represents the DC bus capacitance; \(U_{dc}\) represents the DC bus voltage instruction value; \(K_{pd}\) and \(K_{pq}\) represent the proportional and integral adjustment parameters of the inner current control loop, respectively.

When the double-frequency components of \(d, q\)-axis voltages are transformed from \(d, q\) coordinate system to \(abc\) coordinate system, the negative-sequence fundamental frequency voltage and the third harmonic voltage will be generated, and the expression of the negative-sequence fundamental frequency voltage is shown in (6):

\[
\begin{align*}
\begin{cases}
    u_n^- = \frac{k u_d + i_d}{1 - k_{1d} +} \\
    k = \sqrt{\frac{k_{1d}^2 + \frac{k_{2d}^2}{4} + \frac{k_{2d}^2}{4}}{4 C U_{dc} \omega_1}}
\end{cases}
\end{align*}
\]

According to (6), the equivalent impedance of PVS in the negative-sequence network is

\[
z_n^- = \frac{k u_d}{1 - k_{1d} +},
\]

where \(z_n^-\) is the negative-sequence equivalent impedance of PVS.

It can be seen from (7) that during the non-full phase operation, PVS, whose negative-sequence current suppression strategy is not started, can be equivalent to a non-constant impedance model in the negative-sequence network. And this impedance is related to the parameter \(k\), the PVS port positive-sequence voltage and the output positive-sequence d-axis current.

### 3 | THEORETICAL ANALYSIS METHOD AND CALCULATION MODEL OF NON-FULL PHASE OPERATING VOLTAGE

Taking phase-A grounding fault of the tie line as an example, the schematic diagram of PVS non-full phase operation is shown in Figure 2. It should be noted that the main research object of this paper is the single-phase reclosing on the tie line of photovoltaic power plant. Generally speaking, the weaker the electrical connection between the photovoltaic power plant and the grid system, the more disadvantaged it is that the voltage and
current of the photovoltaic power plant during the non-full phase operation are maintained at the rated value. Therefore, it is the most serious application scenario of the over-voltage problem that the photovoltaic power plant is interconnected with the grid system only through a tie line, and it is reasonable to focus on this scenario for analysis.

As for the single-phase reclosing, on the one hand, it is necessary to deeply study the adverse impact of the non-full phase operating status on PVS. On the other hand, it is necessary to evaluate and analyse the possible closing impulse current and voltage of the single-phase reclosing. The above studies should comprehensively consider the effects of the neutral grounding mode of step-up transformer, the control strategy of PVS under unbalanced voltage, the local load level, etc. Among them, the influence of the neutral grounding mode of the step-up transformer dominates. The detailed analysis and description are as follows.

3.1 The neutral point on the high-voltage side of step-up transformer is directly grounded

3.1.1 The negative-sequence current suppression control strategy is started

When phase A of the tie line is disconnected and the neutral point on the high-voltage side of step-up transformer is directly grounded, the positive-sequence, negative-sequence and zero-sequence networks are shown in Figure 3. Among them, since the negative-sequence current suppression control strategy is started, the PVS side of the negative-sequence network can be considered as open circuit. In Figure 3, subscripts 1, 2 and 0 represent the positive-sequence, negative-sequence and zero-sequence, respectively; \( I_{g1} \) and \( V_{f1} \) represent the equivalent current source of PVS and the positive-sequence voltage of the PVS port, and their relation is shown in (1); \( Z'_{g1} \) represents the equivalent voltage source of the power system; \( Z_{g1} \) represents the impedance of the package transformer of PVS; \( Z_{T}, Z_{LD} \) and \( Z_{L} \) represent the impedance of the step-up transformer, local load and tie line, respectively.

In Figure 3, since the load impedance is generally much larger than the impedances of lines, transformers, and power system, the positive-, negative- and zero-sequence equivalent impedances of the fault port can be approximated as shown in (8):

\[
\begin{align*}
Z_{1\Sigma} &= Z_{LD1} \\
Z_{2\Sigma} &= Z_{LD2} \\
Z_{0\Sigma} &= Z_{T0} + Z_{L0} + Z'_{g0}.
\end{align*}
\]  

(8)

When phase A of the tie line is disconnected, the boundary condition of the fault location is shown in (9):

\[
\begin{align*}
I_{f1} &= 0 \\
\Delta V_{f1} &= \Delta V'_{f1} = 0.
\end{align*}
\]  

(9)

According to (9), the composite-sequence network in the case of phase-A disconnection can be obtained as shown in Figure 4(a).

According to (8), since the negative-sequence equivalent impedance is almost the load impedance, which is generally much larger than the zero-sequence equivalent impedance, the composite-sequence network shown in Figure 4(a) can be simplified to the equivalent circuit shown in Figure 4(b). In Figure 4, \( V'_{f} \) represents the open-circuit voltage of the fault port, and its value is the difference value between the PVS equivalent voltage source \( (Z_{LD1}I_{g1}) \) and the power system equivalent potential source \( (E'_{g}) \) in Figure 3(b).

For three-sequence voltages of the tie line, it can be seen from Figure 4(b) that since \( Z_{1\Sigma} \) is approximately equal to the load impedance and much larger than \( Z_{0\Sigma} \), the positive-sequence...
The negative-sequence current suppression control strategy is not started

When the negative-sequence current suppression control strategy of PVS is not started during the non-full phase operation, it can be seen from (7) that PVS can be equivalent to a non-constant impedance model. In this condition, the negative-sequence network is shown in Figure 5, and both positive-sequence and zero-sequence networks are the same as in Figure 3.

It can be seen from Figure 5 that when the negative-sequence current suppression strategy of PVS is not started, since the load impedance is in parallel with the PVS equivalent impedance, \( Z_2 \Sigma \) is smaller than that in the circumstance of starting the negative-sequence current suppression strategy (as shown in Figure 3(c)). In this condition, the parallel equivalent impedance of the negative-sequence and zero-sequence networks (as shown in Figure 4(a)) is also smaller, which is also much smaller than \( Z_1 \Sigma \). Consequently, the fault phase voltage of the tie line is still almost equal to the rated voltage, and there is no over-voltage problem during the non-full phase operation. Meanwhile, the analysis conclusions of PVS non-full phase operation in Section 3.1.1 are also applicable to the case where the negative-sequence current suppression strategy of PVS is not started.

3.2 The neutral point on the high-voltage side of step-up transformer is ungrounded

3.2.1 The negative-sequence current suppression control strategy is started

When the neutral point on the high-voltage side of step-up transformer is ungrounded and the negative-sequence current suppression control strategy of PVS is started, compared with Figure 3, the three-sequence network diagram differs only in that the zero-sequence network is open. The equivalent impedances of the positive and negative-sequence networks are still the same as those in (5). And since the positive-sequence and negative-sequence impedances of the load are equal, the composite-sequence network and the positive-sequence simplified network of the fault phase are shown in Figure 6.

It can be seen from Figure 6(a) that the positive-sequence voltage of the fault port can be equivalent to the voltage drop on \( Z_{L(D)} \) in the positive-sequence network. Meanwhile, since the tie line impedance and the system’s equivalent impedance are much smaller than the load impedance, they can be regarded as short circuit. In this condition, the positive-sequence network shown in Figure 3(b) can be simplified as shown in Figure 6(b). According to Figure 6(b), the positive-sequence voltage of the tie line can be derived as

\[
\dot{V}_{L,1} = \frac{Z_{L(D)}I_{g1}}{2} + \frac{E'_g}{2}. \tag{10}
\]
characteristics of PVS [19], [22], it is generally believed that PVS only outputs active power when the positive-sequence voltage is greater than 0.9 p.u. Only when the positive-sequence voltage is less than 0.9 p.u., PVS needs to supply reactive power to the grid system according to the LVRT requirements, as shown in (1). And since the main research object of this paper is the over-voltage problem during the non-full phase operation, the research is only focused on the case of high-voltage amplitude of PVS. And according to (1), when the voltage of the tie line is high, PVS almost only outputs the active power, and its output of PVS. And according to (1), when the voltage of the tie line is over-voltage problem during the non-full phase operation, the grid system according to the LVRT requirements, as shown in Figure 6(b) are almost in phase, and the effective value of each feeder branch in the actual 35 kV distribution network is greater than 0.9 p.u. Only when the positive-sequence voltage of the tie line can be solved by (10), as shown in (11):

$$V_{L1} = \frac{E'_{L1} + \sqrt{E''_{L1}^2 + 8Z_{LD1}P_0}}{4}.$$  (11)

From (11) and Figure 6, the effective values of the negative-sequence and zero-sequence voltage of the fault port and the contact line can be derived as shown in (12):

$$V_{L2} = V_{L0} \approx \Delta V_{fA1} = \Delta V_{fA2} = \Delta V_{f60} = \left| -3E'_{L1} + \sqrt{E''_{L1}^2 + 8Z_{LD1}P_0} \right|.$$  (12)

Since the phases of three-sequence voltages of fault phase A are same, the effective value of phase-A voltage can be derived from (11) and (12) as shown in (13):

$$V_{fA1} = \left| -5E'_{L1} + 3\sqrt{E''_{L1}^2 + 8Z_{LD1}P_0} \right|.$$  (13)

When phase A of the tie line is disconnected and PVS is in non-full phase operation state, phase B and C voltages of the tie line are both restricted by the grid voltage, and their effective values are almost equal to the rated value. According to (13), the fault phase, whose voltage is affected by the PVS output power and local load level (characterised by the magnitude of load impedance $Z_{LD1}$), may face the over-voltage problem, resulting in the over-voltage protection action and exiting operation of PVS. If parameters in (13) are all expressed by per-unit value, $E'_{L1}$ is always 1 p.u., and $P_0$ is also constant at 1 p.u. under the circumstance of rated power operation. From the calculation of (13), it can be seen that only when the load impedance is less than 1.3 p.u. (namely the load level is greater than 77%), the effective value of the fault phase-A voltage will be less than 1.3 p.u., which can ensure the normal operation of PVS without disconnection from grid. Meanwhile, it can be seen from (11)–(13) that as the load level increases, the load impedance will gradually decrease, and the effective values of the three-sequence voltages and fault phase voltage of the tie line will also decrease. And since the negative-sequence current suppression control strategy is started, the output current contains only the positive-sequence component. As the load level rises, since the positive-sequence voltage decreases, the effective value of the output current will continue to increase until it reaches the limit value.

### 3.2.2 The negative-sequence current suppression control strategy is not started

When the neutral point on the high-voltage side of step-up transformer is ungrounded and the negative-sequence current suppression control strategy of PVS is not started, the positive and negative-sequence networks are shown in Figures 3(a) and 5, respectively. The zero-sequence network is an open circuit. When the positive-sequence voltage of non-full phase operation is high, PVS will only output active power. Since the voltage drop on the tie line, the system’s equivalent impedance, and the transformer impedance can be ignored, the equations shown in (14) can be obtained from the three-sequence networks and the boundary conditions of the fault location:

$$\begin{cases}
I_{1} = P_{0} / V_{L1} \\
I_{1} = Z_{LD1} - I_{g1} - I_{g2} \\
Z_{LD} = Z_{L1} = Z_{L2} = L_{g} = L_{g} - V_{L1} = L_{g} - V_{L1}.
\end{cases}$$  (14)

According to the analysis in Section 2.2, since the equivalent negative-sequence impedance of PVS and load impedance are almost purely resistive, and the positive-sequence voltage of the PVS port and positive-sequence output current are in phase, the phases of the voltage and current quantities in (14) are all the same. And these quantities can be regarded as scalars for calculation. In this condition, the equation about the positive-sequence voltage of the tie line, the load impedance and so on can be derived from (14), as shown in (15):

$$\begin{align}
(kE'_{g} + Z_{LD})V_{L1}^2 - (2kP_{0}Z_{LD} + Z_{LD}E'_{g})V_{L1} + kP_{0}Z_{LD}E'_{g} &= 0.
\end{align}$$  (15)
If the parameters in (15) are all expressed by the per-unit value, the three-sequence voltages and the fault phase voltage of the tie line can be derived as shown in (16):

\[
\begin{align*}
V_{1A} &= \frac{Z_{LD}(2k + 1) + \sqrt{(4k^2 + 1)Z_{LD}^2 - 4k^2Z_{LD}}}{2(k + Z_{LD})} \\
V_{1Z} &= |V_{1A} - 1| \\
V_{2} &= V_{12} \\
V_{L} &= V_{1A} + 2(V_{1A} - 1)
\end{align*}
\]

(16)

It can be seen from (16) that when the control strategy of negative-sequence current suppression is not started, the effective values of the three-sequence voltages and the fault phase voltage are related to the load level and the parameter \( k \). By the derivation of the positive-sequence voltage equation in (16), it can be seen that when the load level is lower than 200% (namely the load impedance is greater than 0.5 p.u.), as the load level rises, the effective values of three-sequence voltages and the fault phase voltage of tie line decrease. This is similar to the analysis conclusion under the circumstance of the negative-sequence current suppression strategy is started in Section 3.2.1.

3.3 Closing impulse voltage and current of single-phase reclosing

The main problem faced by the single-phase reclosing is the over-voltage phenomenon that may be caused by the non-full phase operation. And if there is no over-voltage phenomenon and PVS remain operational, since the sound phases of the tie line is still in electrical contact with the grid system and PVS maintains the grid-connected operation state, the voltage and current of PVS are always synchronised with the grid. When a transient fault occurs in the tie line, at the moment of the single-phase reclosing, since the electrical quantities on both sides of breaker are synchronised, there will be no obvious closing impulse phenomenon.

4 SIMULATION VERIFICATION OF NON-FULL PHASE OPERATING VOLTAGE CALCULATION MODEL

Based on PSCAD/EMTDC simulation platform, this paper builds a PVS simulation model as shown in Figure 7. The rated capacity of PVS is 20 MW, and the DC bus voltage and capacitance are 1000 V and 8 mF. The proportional and integral adjustment parameters of the voltage outer loop are 4 and 50, respectively. And to make the current tracking speed fast on the premise of ensuring control stability, the proportional and integral adjustment parameters of the current inner loop are designed to be 10 and 200, respectively. The rated capacity of package transformer is 21 MVA, and its leakage reactance and transformer ratio are 6% and 0.69 kV/35 kV. The rated capacity of step-up transformer is 25 MVA, and its leakage reactance and transformer ratio are 10% and 35 kV/121 kV. The tie line length is 100 km, and the positive and zero-sequence impedances per unit length of the tie line are: \( r_1 = 0.08 \Omega \) km < sp > -1 < \( /sp \) > \( x_1 = 0.4 \Omega \) km < sp > -1 < \( /sp \) > \( r_0 = 0.23 \Omega \) km < sp > -1 < \( /sp \) > \( x_0 = 1.2 \Omega \) km < sp > -1 < \( /sp \) > The positive and zero-sequence equivalent impedances of grid are: \( r_{g1} = 0.6 \Omega \), \( x_{g1} = 7.2 \Omega \), \( r_{g0} = 2.7 \Omega \), \( x_{g0} = 12.3 \Omega \). When the load power factor is 1 and 0.9, the load impedance corresponding to the load level of 100% is 61.3 \( \Omega \) and 55.2 + j66.7 \( \Omega \), respectively.

In the simulation process, a phase-A grounding fault occurs on the tie line at 1.5 s, and it is cleared by tie line protections at 1.6 s. The duration of this fault is 0.1 s. Single-phase reclosing devices on both sides of tie line are performed at 2.6 s. The following is a simulation verification of the cases where the neutral point of the step-up transformer employs different wiring methods and PVS adopts different non-full phase operation control strategies.

4.1 Simulation results in the case that the neutral point of step-up transformer is directly grounded

When the neutral point on the high-voltage side of step-up transformer is directly grounded and the load power factor is 1 and 0.9, the changes of the non-full phase current and voltage under circumstances of different PVS control strategies and load levels are analysed, in order to verify the analysis conclusions in Section 3.1. Limited by the length of this article, only simulation waveforms of the case where the negative-sequence current suppression control strategy is started and the load level is 50% are given below, and the simulation results of other control strategy and load levels are shown in Tables 1–4.

4.1.1 The negative-sequence current suppression control strategy is started and the load level is 50%

When the neutral point on the high-voltage side of step-up transformer is directly grounded and the load power factor is 1, the negative-sequence current suppression control strategy is started and the load level is 50%, the three-sequence voltage effective values and the three-phase voltage waveform of the tie line are shown in Figure 8. And in Figure 8(a), the solid, dash dot and broken lines represent positive-sequence, negative-sequence and zero-sequence voltages, respectively.
### TABLE 1  Simulation results in the case that the negative-sequence current suppression control strategy is started and the load power factor is 1

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------|----------------------------------|----------------------------------|
| 0              | 1.03                                                          | 0.98                                     | 1.02                                            | 1.02                            | 1.03                             | 1.02                             |
| 50             | 1                                                             | 1                                        | 1                                               | 1                               | 1                                | 1                                |
| 100            | 1                                                             | 1                                        | 1                                               | 1                               | 1                                | 1                                |
| 150            | 1.01                                                          | 1                                        | 1.02                                            | 1.01                            | 1.01                             | 1.02                             |
| 200            | 1.01                                                          | 0.98                                     | 1.02                                            | 1.02                            | 1.01                             | 1.02                             |

### TABLE 2  Simulation results in the case that the negative-sequence current suppression control strategy is not started and the load power factor is 1

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------|----------------------------------|----------------------------------|
| 0              | 1.08                                                          | 0.99                                     | 1                                               | 1.01                            | 1.08                             | 1.1                              |
| 50             | 1.05                                                          | 1                                        | 1.07                                            | 1                               | 1.05                             | 1.07                             |
| 100            | 1                                                             | 1                                        | 1                                               | 1                               | 1                                | 1                                |
| 150            | 1.02                                                          | 1                                        | 1.05                                            | 1                               | 1.02                             | 1.05                             |
| 200            | 1.01                                                          | 0.99                                     | 1.08                                            | 1.01                            | 1.01                             | 1.08                             |

### TABLE 3  Simulation results in the case that the negative-sequence current suppression control strategy is started and the load power factor is 0.9

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------|----------------------------------|----------------------------------|
| 0              | 1.03                                                          | 0.98                                     | 1.02                                            | 1.02                            | 1.03                             | 1.02                             |
| 50             | 1                                                             | 1                                        | 1                                               | 1                               | 1                                | 1                                |
| 100            | 1                                                             | 1                                        | 1                                               | 1                               | 1                                | 1                                |
| 150            | 1                                                             | 0.97                                     | 1.04                                            | 1.04                            | 1                                | 1.04                             |
| 200            | 1.01                                                          | 0.93                                     | 1.07                                            | 1.07                            | 1.01                             | 1.07                             |

### TABLE 4  Simulation results in the case that the negative-sequence current suppression control strategy is not started and the load power factor is 0.9

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|------------------------------------------|-------------------------------------------------|---------------------------------|----------------------------------|----------------------------------|
| 0              | 1.08                                                          | 0.99                                     | 1.1                                             | 1.01                            | 1.08                             | 1.1                              |
| 50             | 1.04                                                          | 0.98                                     | 1.06                                            | 1.02                            | 1.04                             | 1.06                             |
| 100            | 1                                                             | 0.97                                     | 1.04                                            | 1.03                            | 1                                | 1.04                             |
| 150            | 1                                                             | 0.95                                     | 1.05                                            | 1.05                            | 1                                | 1.08                             |
| 200            | 1                                                             | 0.93                                     | 1.15                                            | 1.08                            | 1                                | 1.15                             |
It can be seen from Figure 8 that in this simulation case where the neutral point of the step-up transformer is directly grounded, the effective value of the positive-sequence voltage and the peak value of three-phase voltage are both 1 p.u. during the non-full phase operation of PVS. The effective value of the negative and zero-sequence voltage of the tie line are both 0.05 p.u., which is much smaller than the positive-sequence voltage. Meanwhile, it can be seen from Figure 8(b) that when the single-phase reclosing of tie line is performed at 2.6 s, there is nearly no impulse voltage, because PVS always maintains the status of grid-connected operation, and its voltage keeps synchronised with the grid at all times.

The three-sequence current effective values and three-phase current waveform of the tie line are shown in Figure 9. And in Figure 9(a), the solid, dash dot and broken lines represent positive-sequence, negative-sequence and zero-sequence currents, respectively.

It can be seen from Figure 9 that when the negative-sequence current suppression control strategy is started, PVS only outputs the positive-sequence current, whose effective value and the peak value of three-phase current are both 1 p.u. Meanwhile, as shown in Figure 9(b), there is also no impulse current at the moment of single-phase reclosing.

4.1.2 Analysis of simulation results under the circumstances of different control strategies and load levels

When the neutral point on the high-voltage side of step-up transformer is directly grounded and the load power factor is 1, the simulation results of the non-full phase operation current and voltage in the cases of different PVS control strategies and load levels are shown in Tables 1 and 2. To indicate the influence of the load power factor on the calculation method proposed here, the simulation results when the load power factor is 0.9 are shown in Tables 3 and 4.

It can be seen from Tables 1 and 2 that when the neutral point of the step-up transformer is directly grounded, the peak values of the phase voltage and phase current during the non-full phase operation are always within the permissible operating range of the relevant standard [23]. The effective values of the positive-sequence voltage and current are both almost 1 p.u. Meanwhile, there are nearly no impulse current and voltage at the moment of single-phase reclosing, which will not threaten the safe operation of PVS. The above simulation results verify the analysis conclusions in Sections 3.1 and 3.3.

Comparing Table 1 and 2, it can be seen that when the neutral point of the step-up transformer is directly grounded, the peak values of the phase current and voltage during the non-full phase operation are nearly both larger than those in the case where the negative sequence current suppression control strategy is started. The reason is that PVS which does not start the negative sequence current suppression strategy will output a certain amount of negative-sequence current during the non-full phase operation, and the phase current generated by superimposing this negative-sequence current and the
positive-sequence current will be larger. Meanwhile, the double-frequency active power generated by this negative-sequence current and the positive-sequence voltage will cause greater fluctuations in the DC bus voltage and affect the quality of the PVS port voltage, resulting in more high-frequency voltage harmonics, which will lead to greater peak value of the phase voltage.

In addition, comparing Tables 1 and 3, Tables 2 and 4, it is obvious that when the neutral point of the step-up transformer is directly grounded, the peak value of phase voltage, current and the effective value of positive-sequence voltage and current are almost equal in the case that the load power factors are 1 and 0.9, and the maximum difference is 7%. Meanwhile, under the same load level, the positive-sequence voltage in the case of the load power factor of 0.9 will be less than or equal to that in the case of the load power factor of 1. The reason is that PVS only outputs active power when the positive-sequence voltage is greater than 0.9, and the reactive power required by local load is mainly supplied by the grid side. When the load power factor is not 1, the size of the reactive load will directly affect the value of the reactive current injected by the grid side. The voltage drop formed by this reactive current through the tie line, step-up transformer and other components will result in the decrease in the positive-sequence voltage of PVS. According to the above simulation analysis, it can be seen when the neutral point of the step-up transformer is directly grounded, the theoretical calculation model given here is always applicable when the local load factor is high.

4.2 Simulation results in the case that the neutral point of step-up transformer is ungrounded

When the neutral point on the high-voltage side of step-up transformer is ungrounded and the load power factor is 1 and 0.9, the changes of the non-full phase current and voltage in the cases of different PVS control strategies and load levels are also analysed, in order to verify the analysis conclusions in Section 3.1. Limited by the length of this article, only simulation waveforms of the case where the negative-sequence current suppression control strategy is not started and the load level is 50% are given below, and the simulation results of other control strategy and load levels are shown in Tables 5–10.

4.2.1 The negative-sequence current suppression control strategy is not started and the load level is 50%

When the neutral point of the step-up transformer is ungrounded and the load power factor is 1, the negative-sequence current suppression control strategy is not started and the load level is 50%, the effective values of fundamental frequency voltage and third harmonic voltage of fault phase are shown in Figure 10(a). The three-sequence voltage effective values and three-phase voltage waveform of the tie line are shown in Figure 10(b) and (c), respectively. And in Figure 10(a), the solid and broken lines represent the fundamental frequency and the third harmonic voltage, respectively.

It can be seen from Figure 10(b) and (c) that in this simulation case, since the double-frequency fluctuation of the DC bus voltage will lead to a third harmonic voltage (as described in Section 3.2.2), the effective value of the fundamental frequency component and the third harmonic component of phase voltage rise to 1.65 p.u. and 0.2 p.u. during the non-full phase operation. The effective value of the positive-sequence component of fundamental frequency voltage increases to 1.21 p.u., and the effective value of the negative-sequence voltage and the zero-sequence voltage are both 0.23 p.u. As shown in Figure 10(c), due to the existence of the third harmonic voltage, the three-phase voltage of the tie line during the non-full phase operation is significantly distorted, and the peak value of the fault phase voltage (phase A) increases to 1.45 p.u., while the peak values of phase B and C are still the grid rated voltage of 1 p.u.. Meanwhile, since the fault phase voltage is greater than the over-voltage protection setting value of 1.3 \( V_{nc} \) [23], after a delay of 0.5 s, the over-voltage protection operates at 2.1 s. In this condition, the three-phase breaker on the PVS side of the tie lien is tripped and PVS exits operation, and the PVS side voltage of the tie line becomes 0.

The effective values of fundamental frequency current and third harmonic current of fault phase are shown in Figure 11(a),

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|---------------|---------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------|---------------------------------|
| 50            | 1.63                                                          | 1.28                                                                          | 0.82                                                           | 0.78                                                                      | /                               | /                               |
| 70            | 1.34                                                          | 1.13                                                                          | 0.9                                                            | 0.87                                                                      | /                               | /                               |
| 80            | 1.24                                                          | 1.08                                                                          | 0.92                                                           | 0.92                                                                      | 1.24                            | 1                               |
| 100           | 1                                                             | 1                                                                             | 1                                                              | 1                                                                          | 1                               | 1                               |
| 150           | 1                                                             | 0.88                                                                          | 1.15                                                           | 1.13                                                                      | 1                               | 1.15                            |
| 200           | 1                                                             | 0.8                                                                           | 1.2                                                            | 1.2                                                                        | 1                               | 1                               |
### Table 6

Simulation results in the case that the negative-sequence current suppression control strategy is not started and the load power factor is 1

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------------------|----------------------------------|----------------------------------|
| 50             | 1.45                                                          | 1.21                                                                            | 1.03                                                           | 0.83                                                                            | /                                | /                                |
| 70             | 1.31                                                          | 1.11                                                                            | 1.02                                                           | 0.9                                                              | /                                | /                                |
| 80             | 1.18                                                          | 1.06                                                                            | 1.02                                                           | 0.94                                                                            | 1.18                             | 1.02                             |
| 100            | 1                                                             | 1                                                                                | 1                                                                | 1                                                                | 1                                | 1                                |
| 150            | 1                                                             | 0.91                                                                            | 1.2                                                             | 1.1                                                              | 1                                | 1.2                              |
| 200            | 1                                                             | 0.85                                                                            | 1.2                                                             | 1.18                                                                             | 1                                | 1.2                              |

**Figure 10**  
Tie line voltage waveforms in the case that the neutral point of step-up transformer is ungrounded and the load level is 50%: (a) effective values of fundamental frequency and third harmonic voltage of the fault phase, (b) effective values of three-sequence voltages of the tie line and (c) three-phase voltage waveform of the tie line

**Figure 11**  
PVS current waveforms in the case that the neutral point of step-up transformer is ungrounded and the load level is 50%: (a) effective values of fundamental frequency and third harmonic current of fault phase, (b) effective values of three-sequence currents of PVS and (c) three-phase current waveform of PVS
### TABLE 7  Simulation and theoretical calculation results in the case that the negative-sequence current suppression strategy is started and the load power factor is 1

| Load level (%) | Simulation results | Theoretical calculation results |
|----------------|---------------------|---------------------------------|
|                | Effective value of positive-sequence voltage of tie line (p.u.) | Effective value of negative and zero-sequence voltage of tie line (p.u.) | Effective value of fault phase voltage of tie line (p.u.) | Effective value of positive-sequence current of PVS (p.u.) | Effective value of negative and zero-sequence voltage of tie line (p.u.) | Effective value of fault phase voltage of tie line (p.u.) | Effective value of positive-sequence current of PVS (p.u.) |
| 50             | 1.28                | 0.29                            | 1.84                           | 0.78                        | 1.28                  | 0.28                            | 1.84                           | 0.78                        |
| 70             | 1.13                | 0.14                            | 1.4                            | 0.87                        | 1.13                  | 0.13                            | 1.39                           | 0.88                        |
| 80             | 1.08                | 0.08                            | 1.24                           | 0.92                        | 1.08                  | 0.08                            | 1.24                           | 0.93                        |
| 100            | 1                   | 0                               | 1                              | 1                           | 1                    | 0                               | 1                              | 1                           |
| 150            | 0.88                | 0.13                            | 0.63                           | 1.13                        | 0.88                  | 0.12                            | 0.64                           | 1.14                        |
| 200            | 0.8                 | 0.2                             | 0.42                           | 1.2                         | 0.81                  | 0.19                            | 0.43                           | 1.2                         |

### TABLE 8  Simulation and theoretical calculation results in the case that the negative-sequence current suppression strategy is not started and the load power factor is 1

| Load level (%) | Simulation results | Theoretical calculation results |
|----------------|---------------------|---------------------------------|
|                | Effective value of positive-sequence voltage of tie line (p.u.) | Effective value of negative and zero-sequence voltage of tie line (p.u.) | Effective value of fault phase voltage of tie line (p.u.) | Effective value of positive-sequence current of PVS (p.u.) | Effective value of negative and zero-sequence voltage of tie line (p.u.) | Effective value of fault phase voltage of tie line (p.u.) | Effective value of positive-sequence current of PVS (p.u.) |
| 50             | 1.21                | 0.24                            | 1.65                           | 0.83                        | 1.22                  | 0.22                            | 1.66                           | 0.82                        |
| 70             | 1.11                | 0.12                            | 1.36                           | 0.9                         | 1.13                  | 0.13                            | 1.39                           | 0.88                        |
| 80             | 1.06                | 0.07                            | 1.2                            | 0.94                        | 1.08                  | 0.08                            | 1.24                           | 0.93                        |
| 100            | 1                   | 0                               | 1                              | 1                           | 1                    | 0                               | 1                              | 1                           |
TABLE 9  Simulation results in the case that the negative-sequence current suppression control strategy is started and the load power factor is 0.9

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|----------------------------------|----------------------------------|
| 50             | 1.37                                                         | 1.21                                           | 1                                               | 0.82                                            | /                                | /                                |
| 70             | 1.28                                                         | 1.06                                           | 1.06                                            | 0.93                                            | 1.28                             | 1.06                             |
| 80             | 1.23                                                         | 1                                               | 1.1                                             | 0.99                                            | 1.23                             | 1.1                              |
| 100            | 1                                                            | 0.95                                           | 1.16                                            | 1.05                                            | 1                                | 1.16                             |
| 150            | 1                                                            | 0.85                                           | 1.2                                             | 1.17                                            | 1                                | 1.2                              |
| 200            | 1                                                            | 0.78                                           | 1.2                                             | 1.2                                             | 1                                | 1.2                              |

TABLE 10  Simulation results in the case that the negative-sequence current suppression control strategy is not started and the load power factor is 0.9

| Load level (%) | Peak value of phase voltage during non-full phase operation (p.u.) | Effective value of positive-sequence voltage during non-full phase operation (p.u.) | Peak value of phase current during non-full phase operation (p.u.) | Effective value of positive-sequence current during non-full phase operation (p.u.) | Peak value of closing voltage (p.u.) | Peak value of closing current (p.u.) |
|----------------|---------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|----------------------------------|----------------------------------|
| 50             | 1.36                                                         | 1.16                                           | 1.1                                             | 0.86                                            | /                                | /                                |
| 70             | 1.22                                                         | 1.06                                           | 1.13                                            | 0.94                                            | 1.22                             | 1.13                             |
| 80             | 1.18                                                         | 1.01                                           | 1.16                                            | 0.99                                            | 1.18                             | 1.16                             |
| 100            | 1                                                            | 0.95                                           | 1.2                                             | 1.05                                            | 1                                | 1.2                              |
| 150            | 1                                                            | 0.86                                           | 1.2                                             | 1.16                                            | 1                                | 1.2                              |
| 200            | 1                                                            | 0.81                                           | 1.2                                             | 1.2                                             | 1                                | 1.2                              |

and the three-sequence current effective values and three-phase current waveform of the tie line are shown in Figure 11(b) and (c), respectively. In Figure 11(a), the solid line and the broken line represent the fundamental frequency and the third harmonic current, respectively.

As shown in Figure 11(a) and (b), when there is a third harmonic voltage at PVS port during the non-full phase operation, the effective values of fundamental frequency current and third harmonic current of fault phase are 0.7 and 0.08 p.u., respectively. And since the effective value of the positive-sequence voltage during the non-full phase operation increases to 1.21 p.u. (as shown in Figure 10(b)), the effective value of the positive-sequence current of PVS decreases to 0.83 p.u., while the effective value of the negative-sequence current increased to 0.16 p.u. Besides, it can be seen from Figure 11(c) that due to the presence of the third harmonic current, the three-phase current of PVS during the non-full phase operation is distorted, and the peak value of the phase current is 1.03 p.u. Meanwhile, when the over-voltage protection operates at 2.1 s, the PVS output current becomes 0. From the above simulation analysis, it can be seen that when the neutral point of the step-up transformer is ungrounded and the load level is 50%, due to the over-voltage problem, PVS will quit operation before the action of the single-phase reclosing, resulting in the single-phase reclosing failure.

4.2.2  Analysis of simulation results under the circumstances of different control strategies and load levels

When the neutral point on the high-voltage side of step-up transformer is ungrounded and the load power factor is 1, the simulation results of the non-full phase operation current and voltage in the cases of different PVS control strategies and load levels are shown in Tables 5 and 6, and the comparison of simulation and theoretical calculation results is shown in Tables 7 and 8. To indicate the influence of the load power factor on the calculation method proposed here, the simulation results when the load power factor is 0.9 are shown in Tables 9 and 10.

It can be seen from Tables 5 and 6 that when the neutral point of the step-up transformer is ungrounded, regardless of whether the negative-sequence current suppression control strategy is started, as the load level increases, the effective value of the positive-sequence voltage decreases, while the effective value of the positive-sequence current increases. When the load level is less than 70%, since the peak value of the phase voltage during the non-full phase operation is greater than the over-voltage protection setting value of 1.3 $V_n$, PVS will be disconnected from the grid due to the operation of over-voltage protection, resulting in the single-phase reclosing failure.
However, when the load level is greater than 80%, the peak value of the phase voltage is always less than 1.3 $V_n$, and there is nearly no impulse current or voltage at the moment of reclosing. Therefore, the protections on both sides of tie line can successfully achieve the single-phase reclosing.

It can be seen from Table 7 that when the negative-sequence current suppression strategy of PVS is started, in the cases of different load levels, the simulation results of the fault phase voltage, three-sequence voltage and so on are almost equal to the theoretical calculation results. And as shown in Table 8, when the negative-sequence current suppression strategy is not started, under the circumstances of different load levels, simulation results of the fault phase voltage, three-sequence voltages and so on are also almost equal to theoretical calculation results. The above comparative analysis of simulation results and theoretical calculation results verifies the correctness of the non-full phase operating voltage calculation model in Section 3.2.

In addition, comparing Tables 5 and 9, Tables 6 and 10, it is obvious that when the neutral point of the step-up transformer is ungrounded, the effective values of the positive-sequence voltage and current are also almost equal in the case that the load power factor is 1 and 0.9. Under the same load level, the positive-sequence voltage in the case that the load power factor is 0.9 will be also less than or equal to that in the case that the load power factor is 1. Meanwhile, when the load level is less than 70%, the peak value of the phase voltage in the case that the load power factor is 0.9 will be less than that in the case that the load power factor is 1. The reason is that when the load level is low, the phase voltage and phase current of PVS during the non-full phase operation will be distorted due to the presence of third harmonics, as shown in Figures 10(c) and 11(c). This third harmonic is caused by the double-frequency fluctuation of the DC bus voltage. When the proportion of the active load is larger, the double-frequency fluctuation of the DC voltage under the same load level is larger, and the third harmonic voltage is also larger, which finally leads to a larger peak value of the phase voltage. According to the above simulation analysis, it can be seen that for the single-phase reclosing on the tie line of PVS, taking the local load power factor as 1 is the most harmful application scenario. Therefore, it is reasonable to focus on this scenario for analysis.

1. As for the single-phase reclosing, the main problem is the over-voltage phenomenon that may be caused by the non-full phase operation of PVS, and the effect of neutral point grounding modes (directly grounded or ungrounded) of the step-up transformer on the over-voltage is particularly significant. Besides, if there is no over-voltage phenomenon and PVS remain operational during the non-full phase operation, since the sound phases of PVS is still in electrical contact with the grid system, there will be nearly no reclosing impulse voltage or current at the moment of single-phase reclosing.
2. When the neutral point on the high-voltage side of step-up transformer is directly grounded, there will always be no over-voltage phenomenon during the non-full phase operation or impulse voltage and current at the moment of reclosing, under the circumstance of any control strategy and load level. Consequently, it can fully play the role of the single-phase reclosing of tie line that the neutral point on the high-voltage side of step-up transformer is directly grounded.
3. When the neutral point on the high-voltage side of step-up transformer is ungrounded, as the load level decreases, the effective value of the positive-sequence voltage and the peak value of the fault phase voltage will both increase. This may result in the disconnection of PVS from the grid before reclosing due to the over-voltage. Theoretical analysis and simulation results show that if the neutral point of the step-up transformer is ungrounded, only when the local load level is higher than 80%, can the normal operation of PVS during the non-full phase operation be guaranteed. However, when the load level is less than 80%, PVS will be disconnected from the power grid due to the fault phase voltage being higher than the setting value of over-voltage protection during the non-full phase operation, thereby reducing the application effect of single-phase reclosing. Consequently, when the local load level is low, the neutral point on the high-voltage side of step-up transformer should be directly grounded in order to fully play the role of single-phase reclosing.
4. The novelty of this paper is mainly reflected in the following aspects: (a) the theoretical calculation method of the voltage and current during the PVS non-full phase operation is proposed, which solves the theoretical analysis problem; (b) according to the theoretical analysis and digital simulation, the main factors affecting the voltage and current during the PVS non-full phase operation are analysed; (c) on the basis of the above-mentioned research work, the application suggestions for the single-phase reclosing on the tie line of PVS are proposed, in order to prevent the single-phase reclosing failure due to the over-voltage disconnection of PVS.

The above research conclusions can provide an important guidance and reference for the application of single-phase reclosing technology in tie line of renewable energy power plant.

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