Research on adaptability of unbalanced three-phase pv after asynchronous networking

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Abstract. After the asynchronous network of Yunnan Power Grid and China Southern Power Grid, the characteristics of small capacity and poor anti-disturbance capability of Yunnan Power Grid are highlighted. Changes in the power grid environment make the problem of three-phase voltage imbalance more likely to occur and may deteriorate. This paper studies the ability of photovoltaic three-phase unbalanced adaptability after asynchronous networking. A double-synchronized reference coordinate model for PV in the three-phase unbalanced condition was established. The influence of the voltage negative-sequence component of the grid on the DC voltage, output current and power of the inverter was studied. A scheme for suppressing oscillation by adding a notch filter is proposed. In Matlab/Simulink, the whole process simulation of wind turbine adaptability under three-phase unbalanced change is realized. The simulation results verify the correctness of the theoretical analysis and the effectiveness of the proposed solution.

1. Introduction
Photovoltaic power plants are mostly located in remote areas where the power grid is relatively weak and generally adopt a centralized production and long-distance transmission development model. Longer power transmission lines may cause unbalanced voltages at the connection points of wind farms. The single-phase and two-phase ground faults of the power grid, the single-phase power supply conditions of the high-speed rail and the uncontrollable rectification methods used in the high-power drag converters for power plants and mines will also make the grid voltage appear unbalanced in three phases. Unbalanced voltage will cause PV power output power and DC voltage to fluctuate, adversely affecting the power quality of the power grid [1-2].

At present, more and more studies have been conducted on the impact of three-phase unbalanced grid on photovoltaics. The literature [3-4] pointed out that the current instruction has influence on the control target of the inverter and the control performance of the corresponding control strategy under different control targets is analyzed. The literature [5] adopts positive and negative sequence decoupling to realize the independent control of the subsystem and then still meet the requirement of the output power of the grid-connected inverter when the grid voltage is unbalanced. The grid-connected current will contain a large amount of harmonics when grid-connected power is to be controlled in a constant manner under the condition of unbalanced voltage. If measures are taken to eliminate the harmonics in the grid-connected current, the grid-connected power will fluctuate greatly. To balance these two points, the literature [6] uses the weighted idea to realize the coordinated control of the power/current quality of photovoltaic grid-connected inverters which improves the system performance but ignores the effects of DC voltage fluctuations. The literature [7] considered the...
influence of DC voltage fluctuations, rationally optimized the DC voltage control, and realized the control of the VSI under the voltage imbalance condition of the grid. However, this paper aims at maximizing the exchange power of the bidirectional converter interface. These studies are mainly directed at photovoltaics under traditional AC-DC hybrid power grids. Due to the small capacity of the Yunnan power grid after asynchronous networking and the large generator capacity and multi-DC characteristics [8], the range of variation of the system voltage unbalance is more likely to increase than before. Therefore, the operating characteristics of PV and the adaptability of the grid must be taken into account when imbalance of the voltage becomes large. This paper establishes a double synchronous reference coordinate model for photovoltaic in three-phase unbalanced conditions. The influence of the voltage negative-sequence component of the grid on the inverter DC voltage, output current and power is studied. Based on this, using the method of adding a notch filter, the power oscillation and bus voltage fluctuation of the grid-connected photovoltaic system are suppressed. A large number of simulations verify the accuracy of the theoretical analysis and the effectiveness of the method.

2. Three-phase imbalance adaptability analysis
When the external grid voltage is unbalanced in three phases, according to the theory of the symmetrical component method, the negative sequence component of the grid voltage will stimulate the rapid rise of the negative sequence component of the output current of the PV. As the grid-connected photovoltaic system generally adopts the mathematical model of the three-phase three-wire photovoltaic grid-side converter, it is necessary to use the negative sequence component model under the condition of asymmetry:

\[
\begin{align*}
    u_{dq+}^+ &= e_{dq+}^+ + L \frac{dI_{dq+}^+}{dt} + j \omega_1 L I_{dq}^+ \\
    u_{dq-}^- &= e_{dq-}^- + L \frac{dI_{dq-}^-}{dt} + j \omega_1 L I_{dq}^+
\end{align*}
\]  

(1)

![Fig.1 Voltage/current vector and axis in double synchronous reference frame.](image)

Under the condition of ideal grid voltage with stable frequency, the grid voltage is not affected by harmonic distortion and voltage asymmetry. The photovoltaic system can quickly and accurately obtain the amplitude and phase of the grid voltage vector through single-synchro-phasic phase locking. However, under the condition of asymmetric grid voltage, it is generally necessary to rely on positive and negative-sequence component decoupling to achieve accurate detection of positive and negative sequence components. According to the theory of the double synchronous reference frame, the
positive and negative sequence decoupling of the voltage and the current is illustrated with reference to FIG. 1: \( E^+ \), \( E^- \) represent the positive and negative sequence components of the grid voltage. \( I^+ \), \( I^- \) Indicates the positive and negative sequence components of the grid current. \( e_{d+}, e_{q+} \) is the dq axis component of the positive sequence voltage of the network. \( e_{d-}, e_{q-} \) is the dq axis component of the negative sequence voltage of the grid. \( i_{d+}, i_{q+} \) is the dq axis component of the positive sequence current of the grid. \( i_{d-}, i_{q-} \) is the dq axis component of the negative sequence current of the grid.

In the case of a single synchronous reference frame, the negative-sequence component of the grid voltage and current is represented as a second-order oscillating component in a positive-sequence synchronous reference frame. This kind of second-order oscillation corresponds to the coupling effect on the synchronous reference coordinate system of voltage in the opposite direction of rotation.

\[
i_{dq} = i_{dq}^{+1} + i_{dq}^{-1} e^{-j2\omega t}
\]

(2)

\[
e_{dq} = e_{dq}^{+1} + e_{dq}^{-1} e^{-j2\omega t}
\]

(3)

In the condition of three-phase unbalanced grid voltage, the original control strategy can only be used to effectively regulate the positive sequence current and the port cannot implement the negative sequence voltage response adjustment. The negative-sequence voltage difference on both sides is almost superimposed on the limited resistance of the external power grid, which cannot effectively limit the negative-sequence current. A large negative-sequence current component superimposed on the original positive-sequence current may make single-phase or two-phase overcurrent situation. On the other hand, due to the absence of the negative sequence control loop, the secondary frequency AC component in the control variable of the original control loop will cause the PI controller to fail to maintain the performance of static and no-difference control. At the same time, the port voltages \( u_d \) and \( u_q \) will also contain a second-frequency oscillation component. After the conversion to the stationary synchronous reference axis, the port voltage contains the third harmonic, making the third-harmonic content of the grid-connected current higher. According to instantaneous power theory, the instantaneous active power and reactive power components are composed of the interaction of each sequence of voltage and current. The instantaneous active power and reactive power can be obtained by calculating the inner product of the voltage and current and cross-products:

\[
p = e \cdot i; l = e \times i
\]

(4)

When the voltage and current are expressed in the form of different components, the instantaneous power contains both the constant component and the oscillating component. In the simulation, the effects of the positive and negative fundamental waves interacting with the positive third harmonic are considered. That is:

\[
\overline{p} = \frac{3}{2} [E^+ I^{+1} \cos(\phi^{+1} - \delta^{+1}) + E^+ I^{-1} \cos(\phi^{-1} - \delta^{-1})]
\]

(5)

\[
\overline{p} = \frac{3}{2} [E^+ I^{+3} \cos(-2\omega t + \phi^{+1} - \delta^{+1}) + E^+ I^{-1} \cos(2\omega t + \phi^{+1} - \delta^{-1}) +
E^{-1} I^{+3} \cos(-4\omega t + \phi^{-1} - \delta^{+1}) + E^{-1} I^{-1} \cos(-2\omega t + \phi^{-1} - \delta^{+1})]
\]

(6)

\[
\overline{q} = \frac{3}{2} [E^+ I^{+1} \sin(\phi^{+1} - \delta^{+1}) + E^+ I^{-1} \sin(\phi^{-1} - \delta^{-1})]
\]

(7)

\[
\overline{q} = \frac{3}{2} [E^+ I^{+3} \sin(-2\omega t + \phi^{+1} - \delta^{+1}) + E^+ I^{-1} \sin(2\omega t + \phi^{+1} - \delta^{-1}) +
E^{-1} I^{+3} \sin(-4\omega t + \phi^{-1} - \delta^{+1}) + E^{-1} I^{-1} \sin(-2\omega t + \phi^{-1} - \delta^{+1})]
\]

(8)
According to the result of the above formula, the fourth-order frequency component with less influence is ignored and it can be seen that the output power of the photovoltaic inverter mainly consists of two parts: a constant component and an oscillation component. The organized typical output of instantaneous active power and reactive power of inverter output is:

\[
\begin{align*}
    p &= P_0 + P_{c2} \cos(2\omega t) + P_{s2} \sin(2\omega t) \\
    q &= Q_0 + Q_{c2} \cos(2\omega t) + Q_{s2} \sin(2\omega t)
\end{align*}
\]  

(9)  

(10)

Where: \( P_0 \) and \( Q_0 \) are the average values of the output active and reactive power. \( PC_2, QC_2, PS_2, QS_2 \) represent the second-order oscillation components in the instantaneous power. By converting to the positive and negative sequence synchronous reference frame, these power amplitudes can be quantitatively analyzed by the formula:

\[
\begin{align*}
    P_0 &= \frac{3}{2} (e_d^+ i_d + e_q^- i_q + e_d^- i_d + e_q^+ i_q) \\
    P_{c2} &= \frac{3}{2} (e_d^+ i_d + e_q^- i_q + e_d^- i_d + e_q^+ i_q + e_d^+ i_d^3 + e_q^- i_q^3) \\
    P_{s2} &= \frac{3}{2} (e_d^+ i_d^- - e_q^- i_q^- + e_d^- i_d^+ + e_q^+ i_q^+ + e_d^+ i_d^3 + e_q^- i_q^3) \\
    Q_0 &= \frac{3}{2} (e_q^+ i_d - e_d^+ i_q + e_q^- i_d - e_d^- i_q) \\
    Q_{c2} &= \frac{3}{2} (e_q^+ i_d^- - e_d^+ i_q^- + e_q^- i_d^+ - e_d^- i_q^+ + e_d^+ i_d^3 + e_q^- i_q^3) \\
    Q_{s2} &= \frac{3}{2} (-e_d^+ i_d^- - e_q^- i_q^- + e_d^- i_d^+ + e_q^+ i_q^+ - e_d^+ i_d^3 - e_q^- i_q^3)
\end{align*}
\]  

(11)

The voltage and current components of each order dq axis can be obtained by Park transformation.

Ignoring the inverter's own loss, the output power of the DC bus should have an equal relationship with the active power of the inverter output:

\[
U_{dc,inv} = P_0 + P_{c2} \cos(2\omega t) + P_{s2} \sin(2\omega t)
\]  

(12)

Photovoltaic power generation does not have a mechanical rotating part. During the three-phase unbalanced period, the positive sequence voltage of the power grid does not drop. The output power of the photovoltaic inverter is not limited and the power balance on both sides can be maintained. Therefore, photovoltaic MPPT is not cut out during the process and the power of the photovoltaic power transmission is basically stable. The photovoltaic DC bus voltage will cause secondary frequency fluctuation due to the external second-order oscillation component. In addition, the outer loop of the DC bus voltage for calculating the reference value of the direct-axis current is maintained on-line. The DC bus voltage fluctuation may have an adverse effect on the output current of the grid-side converter and aggravate the oscillation of the outgoing direct-current current \( i_d \), but the overall external oscillation components can be determined by the amplitude formula.

3. Simulation analysis

For the simulation under three-phase unbalanced conditions, the voltage of the harmonic point of the photovoltaic power station after the asynchronous network connection is considered as 4% as the voltage unbalance degree step, and the simulation verification is performed. The voltage imbalance is 4% and 28%, as shown in Figure 2:
According to the results shown in the figure under standard external environmental conditions and in the case of three-phase voltage imbalance, due to the existence of MPPT, the transmission power level of the array side of the photovoltaic array is basically maintained at 1. The DC bus voltage increases due to the increase of the second-order oscillation component of the grid power. In the case of small voltage imbalance at the inverter side, the oscillation components of active power and reactive power exist but are not obviously (below 0.1p.u.) and the asymmetry of the three-phase currents in the network is maintained at a relatively small level. When the unbalance is increased to 28%, the power oscillation component expands to around 0.5p.u. The asymmetry of the grid-connected current increases. The maximum value of the phase current reaches 1.35p.u. The single-phase current exceeds the inverter overcurrent limit. Comparing the control variables of the inverter, the occurrence of the second-order oscillation component caused by the negative sequence component can be observed. At the same time, due to the adverse influence of the oscillating component, the direct-axis reference value oscillates more obviously, which affects the power transmission process of the inverter to some extent and even exacerbates the active oscillation amplitude.

In response to changes in the external environmental conditions, the results of voltage imbalances under various light and temperature conditions were compared in the simulation. Figure 3 compares the external light intensity of 1000 W/m² and 600 W/m².
Comparing the two cases in Figure 3, after the light changes, the operating point of the PV array is shifted compared with the standard external conditions and the weakening of the lighting conditions makes the PV array output power drop from 1 to about 0.59. Correspondingly, the power level of the grid-connected PV inverters dropped from 1 to about 0.58. Under the same external grid conditions, the amplitude of the output power oscillating component decreases due to the drop of the positive-sequence current of the output shaft. The positive correlation between the external power level and the power oscillation amplitude can be obtained. Under weaker light conditions, the three-phase imbalance has little effect on the power delivered by the grid-connected photovoltaic system.

The simulation also verified the response of the grid-connected photovoltaic system to three-phase unbalance under various external environmental conditions. Especially for three-phase unbalanced conditions, the magnitude of the negative-sequence voltage-to-photovoltaic power oscillation component and the amplitude of the corresponding DC bus voltage fluctuation in each case are statistically analyzed. Figure 4 shows the response curve of several monitoring groups of grid-connected photovoltaic generating units. By default, there is no protection switching in three-phase unbalanced conditions:
According to the results of Fig. 4, from the perspective of small and large changes in the degree of unbalance, the active power oscillation component of the grid-connected unit in the three-phase unbalanced condition does not satisfy the relationship that the power of the unit increases as the negative sequence component increases. As far as the trend is concerned, the oscillation component increases with the trend and grows steadily at the beginning of the increase in the degree of imbalance. When the unbalance degree reaches 16%~20%, there is no corresponding relationship between the increase of the external negative sequence component and the increase of the grid-connected power oscillation component. The oscillation component grows slowly, stagnates or even reverses. In the tail section of the rising trend of imbalance, the oscillating component accelerates. Because the DC bus oscillating is due to the presence of unmatched power on both sides of the DC bus capacitance, the external oscillating power will directly cause the DC bus voltage to fluctuate and there is a corresponding relationship between the two variations. The results in Fig. 4 can also prove that the amplitude of the DC bus voltage oscillation is basically the same as the trend of grid-connected active power oscillation and the reactive power is accelerating and increasing with the unbalanced degree. As
far as the external environmental conditions are concerned, the trend of response of photovoltaic generators to three-phase imbalance is relatively clear. The array power output level directly affects the magnitude of the oscillation amplitude. Under the same degree of imbalance, the higher the light intensity, the lower the operating temperature, the higher the power transmission level, and the larger the amplitude of the active/reactive power oscillation. When grid-connected PV generating units encounter a three-phase unbalanced grid condition at full power, the power shock caused to the grid is greater than when the grid-connected PV generating set is under full power. Due to the presence of the DC bus voltage outer loop, the DC bus voltage fluctuations may have an effect on the inverter output current. In order to avoid the existence of such influences, the average value of the DC bus voltage should be selected as the controlled quantity. If the effect is not achieved, a notch filter with a center frequency of twice the power frequency may be added to the DC bus voltage feedback channel to eliminate the influence of the DC voltage fluctuation on the control loop. After adding the notch filter, the photovoltaic unit response is shown in Figure 5.

Fig. 5. Unit monitoring response before and after the notch filter is added.
The addition of the notch filter makes the power oscillation amplitude within the 8%-20% range lower, but it has less effect on the power oscillation of the extreme scenario (28% imbalance). In general, bus voltage fluctuations are suppressed because the effect of bus voltage fluctuations on the control system is eliminated. Due to the existence of the trap, the fluctuation of the DC bus voltage will not aggravate the unit output power fluctuation. The addition of the notch filter significantly suppresses the power oscillation of the grid-connected photovoltaic system and the bus voltage fluctuation.

4. Conclusion
In this paper, the symmetry component method is used to analyze the mechanism of photovoltaic adaptability during three-phase unbalance, and clear and credible conclusions are obtained. Aiming at the problem of increasing the three-phase voltage imbalance range of Yunnan power grid after asynchronous networking, a full-process simulation analysis of photovoltaic adaptability under different three-phase imbalance changes was carried out. The simulation results show that when the three phases are unbalanced, the PV output power will appear 2 times frequency fluctuation, and the fluctuation amplitude will increase as the imbalance degree increases. When the amplitude of the fluctuation is small, the unit can still operate without disconnection within a certain period of time. Based on this, this paper proposes a method to increase the photovoltaic adaptability by adding a notch filter, and validates the effectiveness of the method by comparing the simulation waveforms before and after the filter.

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