Coordinated Control of Power and Current for Grid-connected Inverter under Unbalanced Voltage

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Abstract. Grid-connected inverter is the grid-connected interface of new energy, but in unbalanced power grid, there will be output power oscillation, current imbalance and other problems. Based on the mathematical model of Grid-connected inverter alpha beta stationary reference system, the generalized power reference compensation expressions of adjustable current imbalance and power fluctuation are derived, which suppresses the active-power oscillation, reactive-power oscillation and balanced current respectively. It is established to achieve the coordinate control of power and current, which enhances the operation performance of the system. Finally, the simulation results verify the effectiveness of the proposed control strategy.

1. Introduction
Grid-connected inverters play an important role in the new energy generation system and power grid energy conversion device, and are often used as an important interface to transfer the direct current energy into high quality ac energy into the power grid. Reliable and stable operation of inverter plays a key role in system safety, stability and high quality operation. Ideally, the control strategy of the inverter can easily meet the requirements of the grid connection. However, when the grid voltage is unbalanced, the traditional control strategy will cause the output current imbalance, and the output active and reactive power will fluctuate to different degrees, which is not conducive to maintaining the stability of the power system.

In [1], the resonant controller is introduced in the traditional control loop of the system, which enables the inverter with unbalanced load to maintain the balance of three-phase output voltage. In [2], The instantaneous power is used to calculate the current reference instruction directly, and the coordinated control of the power/current quality of grid-connected inverters is realized by using the weighted idea, but the selection of the regulation coefficient is not analyzed further. In [3], The direct power control strategy of grid-connected inverter under unbalanced and harmonic grid is proposed in the static coordinate system, and the control goal of the inverter output current sinusoidal or power stationary is achieved, but the coordinated control of the two control goals is not involved. In [4], a multi-objective optimal control strategy of grid-connected inverter based on fruit fly algorithm is proposed in the rotating coordinate system, but using PLL and rotating coordinate system makes the control complicated.

By analyzing the mathematical model of instantaneous power fluctuation of grid-connected inverter under the condition of unbalanced power network, the uniform power compensation value of different control targets in the two-phase static coordinate system is obtained. Finally, the effectiveness of the proposed control strategy is verified by simulation experiments.
2. Modeling of grid-connected inverter under unbalanced voltage

As shown in figure 1, is the grid-connected inverter model, and \( U_d \) is the dc side voltage; \( e_a, e_b, e_c \) are the terminal voltage of the inverter; \( i_a, i_b, i_c \) are three-phase current, and the reference direction is the grid pointing to the inverter. \( R \) and \( L \) are line impedance and filter inductance respectively, and \( u_a, u_b, u_c \) are grid voltage, so it can be concluded that the grid-connected inverter steady-state model in two static coordinate systems as[5]

\[
\begin{align*}
    u_\alpha &= R_i_\alpha + L \frac{d i_\alpha}{dt} + e_\alpha \\
    u_\beta &= R_i_\beta + L \frac{d i_\beta}{dt} + e_\beta
\end{align*}
\]

(1)

Where, the subscripts \( \alpha \) and \( \beta \) represent the alpha and beta axial components in the two-phase static coordinate system.

According to the instantaneous power theory, the instantaneous power of the inverter can be expressed as

\[
P + jQ = u_\alpha i_\alpha + u_\beta i_\beta + j(-u_\alpha i_\beta + u_\beta i_\alpha)
\]

(2)

Take the derivative of equation (2), and get the derivative of power as

\[
\begin{align*}
    \frac{dP}{dt} &= u_a \frac{di_a}{dt} + u_a \frac{du_a}{dt} + u_\beta \frac{di_\beta}{dt} + i_\beta \frac{du_\beta}{dt} \\
    \frac{dQ}{dt} &= -u_\alpha \frac{di_\alpha}{dt} - u_\alpha \frac{du_\alpha}{dt} + u_\beta \frac{di_\beta}{dt} + i_\beta \frac{du_\beta}{dt}
\end{align*}
\]

(3)

When grid-connected inverter runs under unbalanced grid voltage, its output power and current will be strongly affected by the voltage of parallel grid point, and negative sequence voltage component will appear under unbalanced grid.[6] Therefore, sequence components of voltage and current of the inverter in the two-phase static coordinate system can be expressed as

\[
\begin{align*}
    u_a^+ &= U^+ \sin(\omega t + \phi^+), u_a^- = U^- \sin(\omega t + \phi^-) \\
    u_\beta^+ &= -U^+ \cos(\omega t + \phi^+), u_\beta^- = U^- \cos(\omega t + \phi^-) \\
    i_a^+ &= I^+ \sin(\omega t + \phi^+), i_a^- = I^- \sin(\omega t + \phi^-) \\
    i_\beta^+ &= -I^+ \cos(\omega t + \phi^+), i_\beta^- = I^- \cos(\omega t + \phi^-)
\end{align*}
\]

(4)

Where, \( U^+, U^- \) are the amplitude of the positive sequence component and the amplitude of the negative sequence component of the voltage respectively; \( \omega \) for grid voltage angular frequency; \( \phi^+, \phi^- \) is the phase Angle of the voltage positive sequence component and the voltage negative sequence component, respectively. \( I^+, I^- \) are respectively the amplitude of the positive sequence component of the fundamental current and the amplitude of the negative sequence component of the fundamental current. \( \theta^+, \theta^- \) are phase angles of positive sequence component and negative sequence component of fundamental current respectively.

According to equation (4), the derivative of network voltage with respect to time under unbalanced condition can be expressed as

\[
\begin{align*}
    \frac{du_a^+}{dt} &= \omega U^+ \cos(\omega t + \phi^+) \\
    \frac{du_a^-}{dt} &= -\omega U^- \cos(\omega t + \phi^-) \\
    \frac{du_\beta^+}{dt} &= -\omega I^+ \cos(\omega t + \phi^+) \\
    \frac{du_\beta^-}{dt} &= \omega I^- \cos(\omega t + \phi^-)
\end{align*}
\]
\begin{align*}
\frac{du_a}{dt} &= \frac{du_a^+}{dt} + \frac{du_a^-}{dt} = -\omega u^+_\beta - \omega u^-_\beta \\
\frac{du_\beta}{dt} &= \frac{du_\beta^+}{dt} + \frac{du_\beta^-}{dt} = \omega u^+_\alpha + \omega u^-_\alpha
\end{align*}

According to equation (1), the derivative of current with respect to time in the two-phase static coordinate system as

\begin{align*}
\frac{di_a}{dt} &= \frac{1}{L}(u^+_a - R_i - e^+_a) \\
\frac{di_\beta}{dt} &= \frac{1}{L}(u^-_\beta - R_i - e^-_\beta)
\end{align*}

By substituting equation (5) and equation (6) into equation (3), the governing equation of grid-connected inverter under unbalanced grid condition can be obtained

\begin{align*}
\begin{bmatrix}
e^+_\alpha \\
e^-_\beta
\end{bmatrix} &= T \begin{bmatrix}
u^+_a + v^-_\beta - RP - \frac{dP}{dt} \\
-RQ - \frac{dQ}{dt}
\end{bmatrix} + L \begin{bmatrix}
\Delta u^+_\alpha \\
\Delta u^-_\beta
\end{bmatrix} \\
T &= \begin{bmatrix}
u^+_a & v^-_\beta \\
v^-_\beta & -v^+_a
\end{bmatrix}^{-1} \\
\begin{bmatrix}
\Delta u^+_\alpha \\
\Delta u^-_\beta
\end{bmatrix} &= \begin{bmatrix}
i^+_a - \frac{du^+_a}{dt} + i^-_\beta - \frac{du^-_\beta}{dt} \\
i^-_\beta - \frac{du^-_\beta}{dt} - i^+_a - \frac{du^+_a}{dt}
\end{bmatrix}
\end{align*}

3. Power compensation strategy under unbalanced power network

Substitute equation (4) into equation (2) to get

\begin{align*}
P &= P_0 + P_i + P_u \\
Q &= Q_0 + Q_i + Q_u
\end{align*}

\begin{align*}
P_0 &= \frac{3}{2}U^+I^+ \cos(\phi^- - \theta') + \frac{3}{2}U^-I^- \cos(\phi^- - \theta') \\
P_i &= -\frac{3}{2}U^+I^- \cos(2\omega t + \phi^- + \theta') \\
P_u &= -\frac{3}{2}U^-I^+ \cos(2\omega t + \phi^- + \theta') \\
Q_0 &= \frac{3}{2}U^+I^+ \sin(\phi^- - \theta') + \frac{3}{2}U^-I^- \sin(\phi^- - \theta') \\
Q_i &= -\frac{3}{2}U^+I^- \sin(2\omega t + \phi^- + \theta') \\
Q_u &= -\frac{3}{2}U^-I^+ \sin(2\omega t + \phi^- + \theta')
\end{align*}
Where, \( P_0 \) and \( Q_0 \) are the average components of active and reactive power, \( P_1, Q_1, P_u, Q_u \) are the double frequency fluctuation components of reactive active power, \( P_i \) and \( Q_i \) are caused by negative sequence current and positive sequence voltage, \( P_u \) and \( Q_u \) are caused by negative sequence voltage and positive sequence current.

From equation (9), it can be concluded that it is difficult to achieve the control goal of simultaneously suppressing power oscillation and current balance by controlling 6 power variables with 4 current sequence components.

The reference value of active power is mainly composed of two parts: the given value of power and the compensation value of power. According to the direct power control principle, the given value of power and the compensation value of power satisfy the equation:

\[
P_{\text{ref}} + P_{\text{com}} = P_0 + P_u + P_i \]
\[
Q_{\text{ref}} + Q_{\text{com}} = Q_0 + Q_u + Q_i \]

Where, \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) are respectively the given value of active power and reactive power. \( P_{\text{com}} \) and \( Q_{\text{com}} \) are active and reactive compensation values respectively, which are key parameters to realize multi-objective control.[7]

The given value of active power and reactive power is usually set as the average component of instantaneous power. In the balanced power grid, there is no oscillation component of instantaneous power. The reference value of power follows the average power component as:

\[
P_{\text{ref}} = P_0 \]
\[
Q_{\text{ref}} = Q_0 \]

(12)

Generally, since the negative sequence current value is too small compared with the negative sequence voltage value, it is difficult to extract accurately, so the value of power compensation is set to be proportional to the power component caused by the negative sequence voltage and positive sequence current, and the power compensation as:

\[
P_{\text{com}} = mP_u \]
\[
Q_{\text{com}} = nQ_u \]

(13)

Substitute equation (12) and equation (13) into equation (11) to get:

\[
(m-1)P_u = P_i \]
\[
(n-1)Q_u = Q_i \]

(14)

Substitute equation (10) into equation (14) to get:

\[
(m-1)U^- I^+ \cos(2\omega t + \varphi^- + \theta^-) =
\]
\[
U^+ I^- \cos(2\omega t + \varphi^+ + \theta^-) \]
\[
(n-1)U^- I^+ \sin(2\omega t + \varphi^- + \theta^-) =
\]
\[
-U^+ I^- \sin(2\omega t + \varphi^+ + \theta^-) \]

(15)

By analyzing equation (15), it can be concluded that the condition for equation (15) to be valid is \( (m-1) = -(n-1) \), that is, \( m+n=2 \). Therefore, by using the differences between \( m \) and \( n \), various flexible control targets can be set to meet the requirements of different working conditions.[8]

3.1. Balance current control

The goal is to eliminate the negative sequence current component to obtain sinusoidal and symmetric grid current. According to equation (10), in order to eliminate negative sequence current, the power fluctuation generated by negative sequence current component should be suppressed. Therefore, \( P_i \) and \( Q_i \) must be zero in order to balance the current, but the power components generated by negative sequence voltage and positive sequence current still exist in instantaneous active and reactive power.
Therefore, $P_u$ and $Q_u$ should be injected into active and reactive power for reference, so that the negative sequence current component is zero, and the power compensation as

$$
\begin{align*}
P_{\text{com}} &= P_u \\
Q_{\text{com}} &= Q_u
\end{align*}
$$

(16)

3.2. Constant reactive power control

The control goal is to allow the existence of negative sequence current components but to eliminate reactive power fluctuations. In order to obtain constant reactive power, the reference of reactive power must remain constant, so the fluctuating component of reactive power $Q_u + Q_i$ must be zero. According to equation (15), both the reactive power ripple and the active power ripple cannot be zero at the same time. Therefore, when the fluctuating component of reactive power is zero, the oscillating component of active power must be included in the active power. At this time, the power compensation as

$$
\begin{align*}
P_{\text{com}} &= 2P_u \\
Q_{\text{com}} &= 0
\end{align*}
$$

(17)

3.3. Constant active power control

Similarly, the control target needs to control the active power fluctuation component $P_u + P_i$ to be zero, and the power compensation as

$$
\begin{align*}
P_{\text{com}} &= 0 \\
Q_{\text{com}} &= 2Q_u
\end{align*}
$$

(18)

After the above analysis, the grid-connected inverter control equation given in equation (7) is drawn, as shown in FIG. 3, the power and current coordination control block diagram of grid-connected inverter. Firstly, voltage and current are sampled and measured and 2s/3s transformation is performed to obtain $u_{a\beta}$ and $i_{a\beta}$ components in the two-phase static coordinate system. Then, instantaneous active power $P$ and instantaneous reactive power $Q$ of the inverter are calculated according to equation (2). A second-order generalized integrator (SOGI) was used to separate and extract $u_{a\alpha}$, $u_{a\beta}$, $i_{a\alpha}$, $i_{a\beta}$ components. Power compensation module is crucial to realize multi-objective control.[9] Power fluctuation and current balance degree can be coordinated by adjusting the value of $\lambda$. $P_{\text{ref}}$ and $Q_{\text{ref}}$ are given power reference values. PIR controller is used to control instantaneous power error. Detailed parameter design can be referred to [10]. Since power fluctuation is mainly frequency doubling, the frequency of resonant controller can be set as 2 omega. $\Delta u_a$ and $\Delta u_\beta$ are voltage compensated components in formula (7), and $T$ is the conversion matrix for converting power signal into voltage signal.

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**Figure 2.** power-current coordination control strategy.
4. Simulated analysis
In order to verify the effectiveness of the control strategy proposed in this paper, a simulation model for power-current coordination control of grid-connected inverter is established in Matlab/Simulink software environment, as shown in figure 2, and its simulation parameters are shown in table 1.

| The parameter name      | Value and unit |
|-------------------------|----------------|
| Dc power supply $U_{dc}$| 700V           |
| line voltage            | 380V           |
| Inductance $L$          | 3.2mH          |
| Filter capacitor $C$    | 5.5 μF         |
| Active power reference value $P_{rel}$ | 6 kW |
| reactive power reference value $Q_{rel}$ | 500 var |

The control strategy of grid-connected inverter under unbalanced grid voltage is simulated and verified. The set value of grid voltage is: A phase voltage drops to 70% of rated grid voltage, while BC phase voltage remains at rated grid voltage.

Under the condition of unbalanced grid voltage, FIG.3 is the simulation result of balanced current control. The current amplitude is 13.4a, and the current harmonic distortion rate THD=1.35%. FIG. 4 shows the simulation result of constant reactive power control. The reactive power basically has no fluctuation, while the active power fluctuates, with the fluctuation peak of about 1300W. FIG. 5 shows the simulation results of constant active power control. The active power basically has no fluctuation, while the reactive power fluctuates, and the fluctuation peak is about 200var.

Figure 3. balanced current control

Figure 4. constant reactive power control
FIG. 6 shows the fluctuation amplitude of active power and reactive power when m=0.5 and n=1.5. The reactive power fluctuates, and the fluctuation peak is about 150 var, and the active power fluctuates, and the fluctuation peak is about 350 W. However, the three-phase current is unbalanced, and the amplitude of power fluctuation is greatly reduced compared with that of constant active power control and constant reactive power control. Therefore, the values of m and n can be adjusted according to the actual demand, and the degree of active power fluctuation, reactive power fluctuation and current balance can be comprehensively considered to achieve coordinated control of power and current.

5. Conclusion
This paper presents a power-current coordination control strategy for grid-connected inverters based on static coordinate system. According to instantaneous power, the reference value of negative sequence current is calculated, and the multi-objective expressions of constant active power, reactive power and
current balance are established. This control strategy needs no phase-locked loop and has a simple control structure. Simulation results verify the effectiveness of the proposed scheme.

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