Optimal control strategy of voltage source converter-based high-voltage direct current under unbalanced grid voltage conditions

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Abstract: This study presents an optimisation control strategy for the power control of voltage source converter-based high-voltage direct current transmission under unbalanced grid voltage conditions. To facilitate simple implementation and flexible operation, the current references are derived and synthesised into one generalised equation that introduces two individually adaptable parameters. The two parameters can be adapted to eliminate the oscillations of instantaneous active and reactive power, as well as the currents at the grid side under unbalanced grid voltage conditions. The optimisation method based on particle swarm optimisation algorithm is presented to determine the two parameters. The simulation is conducted with PSCAD/EMTDC. The results show that the proposed strategy is effective and feasible.

1 Introduction

Voltage source converter-based high-voltage direct current transmission (VSC-HVDC) system offers many significant advantages over conventional line-commutated converter HVDC transmission systems because of superior operating characteristics of the VSC [1]. Recently, the growing installations of large-scale offshore wind farms, as well as the rapid evolution of power electronics technology, enabled VSC-HVDC technology to gain wide acceptance. The longest HVDC light project (Sweden–Lithuania) in the world commissioned in 2015 shows the vital role of VSC-HVDC in the transmission era [2]. Modelling and simulating the VSC-HVDC transmission system has been an interest for years and control of VSC-HVDC is mostly focused on balanced AC grid conditions [3–8].

Many technological breakthroughs are required to maximise the potential of VSC-HVDC. One requirement is to reduce the DC voltage double line-frequency ripples that the fault AC grid conditions cause. The dual current control scheme that uses two synchronous rotating frames is presented in [9–14]. The priority in other cases has been to assure balanced sinusoidal currents from the converter, independent of the grid voltage unbalance [15]. Therefore, the VSCs are required to undertake the operating capability during the grid voltage asymmetry. The control strategy designed for balanced voltage conditions will deteriorate if the grid voltage is unbalanced [16]. With the increased use of VSCs in renewable energy systems and the emergence of grid codes that require the capability for delivering reactive power to the grid during voltage disturbances, reactive power oscillation has been considered in [17–22]. The operating performance of VSCs under unbalanced conditions will mainly depend on the control objectives. However, these control strategies of VSC-HVDC systems under grid asymmetric faults can only cope with one specific objective, such as zero instantaneous active powers, balanced current outputs, or unity power factors. Converters or grid requirements for grid-fault ride-through control always constrain multiple objectives because voltage dips are as diverse as grid faults.

To consider the overall performance of VSC-based system, these control objectives have to be compromised and adapted under different grid faults. In the paper, an optimal active and reactive power control strategy adapted is proposed to fulfill multi-objectives for VSC-HVDC under unbalanced faults. For different control objectives, the derived current references that are implemented directly in a stationary reference frame are synthesised into one general equation by specifying two individually adaptable parameters. Instead of being set at the two extremes of the parameter range, a method of parameter optimisation based on particle swarm optimisation (PSO) algorithm is presented to determine the value of parameters.

2 Dynamic model of VSC-HVDC

A schematic view of VSC is shown in Fig. 1. The three-phase AC grid voltage instantaneous value is denoted by \(u_{abc} \). Using \(abc\) transformation, (1)–(3) can be rewritten as

\[
\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + u_{abc} - u_{dcb} \tag{1}
\]

\[
p = u \cdot i = u_a i_a + u_b i_b + u_c i_c \tag{2}
\]

\[
q = \frac{1}{\sqrt{3}} \left( u_a i_a - u_b i_b + u_c i_c \right) \tag{3}
\]

Using \(abc\) transformation, (1)–(3) can be rewritten as

\[
\frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + u_{abc} - u_{dcb} \tag{4}
\]

\[
p = (u_a i_a + u_b i_b + u_c i_c) \tag{5}
\]

\[
q = (u_a i_a - u_b i_b + u_c i_c) \tag{6}
\]

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Considering the sinusoidal but unbalanced three-phase voltages and currents at the fundamental frequency, the active and reactive powers can be expressed through the positive sequence and negative sequence components of the voltages and currents, respectively

\[ p = u \cdot i = (u^+ + u^-) \cdot (i^+ + i^-) \]  
\[ q = u_{\perp} \cdot i = (u_{\perp}^+ + u_{\perp}^-) \cdot (i^+ + i^-) \]

(7)

(8)

To analyse separately the contributions of currents to independent active and reactive power controls, sequence currents \(i_{\pm}\) can be decoupled into two quantities, \(i_{\mp}\) and \(i_{\perp}\), as depicted in Fig. 2. The subscripts 'p' and 'q' are related to the active and reactive power controls, respectively.

Rewriting (7) and (8) in terms of \(i_{\mp}\) and \(i_{\perp}\)

\[ p = (u^+ + u^-) \cdot (i_{\mp}^+ + i_{\mp}^- + i_{\mp, p} + i_{\mp, q}) \]
\[ q = (u_{\perp}^+ + u_{\perp}^-) \cdot (i_{\mp}^+ + i_{\mp}^- + i_{\perp, p} + i_{\perp, q}) \]

(9)

(10)

where

\[ P = u^+ \cdot i_{\mp}^+ + u^- \cdot i_{\mp}^- \]

\[ P_{2u} = P_{2u,p} + P_{2u,q} \]

\[ P_{2u,p} = u^+ \cdot i_{\mp, p} + u^- \cdot i_{\mp, q} \]

\[ P_{2u,q} = u_{\perp}^+ \cdot i_{\mp, p} + u_{\perp}^- \cdot i_{\mp, q} \]

\[ Q = u_{\perp}^+ \cdot i_{\mp}^+ + u_{\perp}^- \cdot i_{\mp}^- \]

\[ Q_{2u} = Q_{2u,p} + Q_{2u,q} \]

\[ Q_{2u,p} = u_{\perp}^+ \cdot i_{\mp, p} + u_{\perp}^- \cdot i_{\mp, q} \]

\[ Q_{2u,q} = u_{\perp}^+ \cdot i_{\mp, p} + u_{\perp}^- \cdot i_{\mp, q} \]

From (9) and (10), the oscillations of active and reactive powers can be eliminated through the active and reactive power control currents \(i_{\mp} = i_{\mp, p}^+ + i_{\mp, q}^-\) and \(i_{\perp} = i_{\perp, p}^+ + i_{\perp, q}^-\), respectively. The following section derives the active and reactive power control currents \(i_{\mp}\) and \(i_{\perp}\) from three aspects.

### 2.1 Current reference calculation

#### 2.1.1 Calculation of active current reference \(i_{\mp}^+\): i. Elimination of the corresponding double-frequency active power oscillations.

The \(p_{2u,p} = 0\) is imposed. These two terms can compensate each other. The first individual parameter \(k_p\) is introduced, and a scalar coefficient is used as a weighting factor for the elimination of \(p_{2u,p}\).

\[ u^+ \cdot i_{\mp, p} = k_p u^- \cdot i_{\mp, q}^- \quad (-1 \leq k_p \leq 0) \]  

(11)

Negative sequence current \(i_{\mp, q}^-\) is derived from (11) as

\[ i_{\mp}^+ = \frac{k_p u^- \cdot i_{\mp, q}^-}{||u^-||^2} \]

(12)

Remark: Operator \(||.||\) means the norm of a vector.

By substituting (12) into the average active power flow \(P\) in (9), the following equation can be obtained

\[ i_{\mp}^+ = \frac{P}{||u^+||^2 + k_p ||u^-||^2} u^+ \]

\[ i_{\mp}^- = \frac{k_p P}{||u^+||^2 + k_p ||u^-||^2} u^- \]  

(13)

The total current reference is the sum of \(i_{\mp}^+\) and \(i_{\mp}^-\), that is

\[ i_{\mp} = \frac{P}{||u^+||^2 + k_p ||u^-||^2} (u^+ + k_p u^-) \quad (-1 \leq k_p \leq 0) \]  

(14)

ii. Balanced positive sequence currents: The balanced three-phase currents can be found by (9) requiring the negative sequence active current component to be zero. The resulting current reference be can expressed with the following equation

\[ i_{\mp}^+ = \frac{P}{||u^+||^2} u^+ \]

(15)

iii. Elimination of corresponding double-frequency reactive power oscillations: A reference value of zero is imposed for the oscillating power component, that is \(q_{2u,p} = 0\). These two terms can compensate each other

\[ u_{\perp}^+ \cdot i_{\mp, p} = k_p u_{\perp}^- \cdot i_{\mp, q}^- \quad (-1 \leq k_p \leq 0) \]  

(16)

Negative sequence current \(i_{\mp, q}^-\) is deduced from (16) as

\[ i_{\mp}^+ = \frac{k_p u_{\perp}^+ \cdot i_{\mp, q}^-}{||u^-||^2} \]

(17)
because of

\[ u^+ u^+ = -u^- u^+ \]  \( (18) \)

By substituting (17) and (18) into (9), the positive sequence current reference can be given as

\[ i^p_+ = \frac{P}{\|u^+\|^2 - k_p \|u^-\|^2} u^+ \]  \( (19) \)

From (17) to (19), the total current reference is given in the following equation

\[ i^p_t = \frac{P(u^t + k_p u^-)}{\|u^t\|^2 + k_p \|u^-\|^2} \quad (-1 \leq k_p \leq 0) \]  \( (20) \)

Considering the active current reference given in (14), (15), and (20), a generalised expression that includes the three above mentioned objectives is deduced by setting the interval of independent parameters \( k_p \) to \([-1, 1]\)

\[ i^p_0 = \frac{P(u^+ + k_p u^-)}{\|u^+\|^2 + k_p \|u^-\|^2} \quad (-1 \leq k_p \leq 1) \]  \( (21) \)

2.1.2 Calculation of active current reference \( i^p_0 \): The second individual parameter \( k_p \) is introduced and similar steps as described in cases where active power control are followed. The reactive current reference can be derived as follows

\[ i^q_t = \frac{Q(u^t + k_p u^-)}{\|u^t\|^2 + k_p \|u^-\|^2} \quad (-1 \leq k_p \leq 1) \]  \( (22) \)

The total current reference for the average active power \( (P^* = P) \) and reactive powers \( (Q^* = Q) \) is given as follows

\[ i^* = i^p_0 + i^q_t = \frac{P^*(u^+ + k_p u^-)}{\|u^+\|^2 + k_p \|u^-\|^2} + \frac{Q^*(u^t + k_p u^-)}{\|u^t\|^2 + k_p \|u^-\|^2} \]  \( (23) \)

In the \( a\beta \) stationary frame

\[
\begin{bmatrix}
    i^*_a \\
    i^*_b \\
\end{bmatrix} = \frac{P^*}{\|u^+\|^2 + k_p \|u^-\|^2} \begin{bmatrix}
    u^+_a + k_p u^-_a \\
    u^+_b + k_p u^-_b \\
\end{bmatrix} + \frac{Q^*}{\|u^t\|^2 + k_p \|u^-\|^2} \begin{bmatrix}
    u^t_b - u^-_b \\
    u^t_a + k_p u^-_a \\
\end{bmatrix}
\]

2.2 Analysis of power oscillations

Assuming that the currents of the converter are equal to the reference values, introducing the generalised current reference equations from (24) back into the active and reactive power equations from (9) and (10) will lead to the active and reactive power flow characteristics resulting from different power control objectives that can be expressed in a generalised way

\[ p = P^* + P_{2ap} + P_{2aq} = P^* + \frac{P^*(1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2}{\|u^+\|^2 + k_p \|u^-\|^2} \cos(2\omega t + \delta^-) + Q^* \frac{(1 - k_p) \|u^t\|^2 + k_p \|u^-\|^2}{\|u^t\|^2 + k_p \|u^-\|^2} \sin(2\omega t + \delta^-) \]  \( (25) \)

\[ q = Q^* + q_{2ap} + q_{2aq} = Q^* + \frac{Q^*(1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2}{\|u^+\|^2 + k_p \|u^-\|^2} \cos(2\omega t + \delta^-) - \frac{P^*(1 - k_p) \|u^t\|^2 + k_p \|u^-\|^2}{\|u^t\|^2 + k_p \|u^-\|^2} \sin(2\omega t + \delta^-) \]  \( (26) \)

where \( \delta^- \) is the phase angle between the positive and negative sequence (PNS) components and can be obtained as follows

\[ |p_{2ap}| = \sqrt{\frac{P^*(1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2}{\|u^+\|^2 + k_p \|u^-\|^2} \left( (1 - k_p) \|u^t\|^2 + k_p \|u^-\|^2 \right) + \frac{Q^*(1 - k_p) \|u^t\|^2 + k_p \|u^-\|^2}{\|u^t\|^2 + k_p \|u^-\|^2} \left( (1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2 \right)} \]  \( (27) \)

\[ |q_{2ap}| = \sqrt{\frac{Q^* \left( (1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2 \right) + \frac{P^* \left( (1 - k_p) \|u^t\|^2 + k_p \|u^-\|^2 \right)}{\|u^t\|^2 + k_p \|u^-\|^2} \left( (1 + k_p) \|u^+\|^2 + k_p \|u^-\|^2 \right)} \]  \( (28) \)

The active power oscillations can be eliminated when \( k_p \) is equal to \(-1\) and \( k_q \) is equal to \(-1\). When \( k_p \) is equal to \(1\) and \( k_q \) is equal to \(-1\), the reactive power oscillations can be eliminated. When \( k_p \) and \( k_q \) are equal to \(0\), the three-phase currents can be balanced. When \( k_p \) and \( k_q \) are set at the two extremes of the parameter range, the double-frequency active or reactive power ripples are possible. However, the uncontrolled oscillations will increase widely. Fig. 3 shows the amplitudes of active and reactive power oscillations with the parameters \( k_p \) and \( k_q \), respectively, when \( |u^+| = 0.5, |u^-| = 0.3, P^* = 1.0, Q^* = 1.0 \text{ p.u.} \). It can be seen that: (i) the elimination of the double-frequency oscillations of active and reactive powers can be achieved by adjusting the value of the parameters \( k_p \) and \( k_q \); (ii) the objective of eliminating active power oscillation and reactive power oscillation are contradictory.

Thus, considering the elimination of both active and reactive power oscillations is necessary by setting reasonable parameters \( k_p \) and \( k_q \). This suggests that the amplitude of oscillating active (reactive) power within a certain and acceptable range can be limited while minimising the double-frequency reactive (active) power oscillations.

3 Optimal control strategy

3.1 Control strategy

The applied method for inherent sequence separation in the stationary \( a\beta \) reference in this study is based on the utilisation of a second-order generalised integrator (SOGI) that is configured as a quadrature signal generator (QSG). The scheme of the frequency-locked loop (FLL) is described in Fig. 4. The structure shown in Fig. 4 is proposed for the detection of the PNSs on the \( a\beta \) reference frame. This structure is used to track the fundamental angular frequency \( \omega' \) where \( \phi_a = u_a - u_b, \phi_b = u_b - u_c, \omega_0 = 314 \text{ rad/s,} \) and parameters \( k_0 \) and \( \Gamma \) can be chosen. The frequency estimation of FLL can be achieved using the error signals of the SOGI-QSGs. The structure of the SOGI-QSG is shown in Fig. 5.

The second output signal \( q' \) from the SOGI-QSG, which is usually labelled as the SOGI-QSGs. The structure of the SOGI-QSG is shown in Fig. 5.

The total output signal, is a 90° phase-shifted version of the input signal \( u \), and \( \phi' \) is the phase angle between the positive and negative sequence (PNS) components and can be obtained as follows

\[ D(s) = \frac{u'}{u} = \frac{k_0 s}{s^2 + k_0 \omega' s + \omega'^2} \]  \( (29) \)
The expressions for the PNS components shown in Fig. 6 which are based on the outputs of the two SOGI-QSGs are given

\[
\begin{align*}
\left[ \begin{array}{c} u'_m \\ u'_b \\
\end{array} \right] &= \frac{1}{2} \left[ \begin{array}{c} u'_a - qu'_b \\ u'_a + qu'_b \\
\end{array} \right], \\
\left[ \begin{array}{c} u''_m \\ u''_b \\
\end{array} \right] &= \frac{1}{2} \left[ \begin{array}{c} u''_a + qu''_b \\ -qu''_a + u''_b \\
\end{array} \right]
\end{align*}
\]  

(31)

Compared with PI control, a PR controller is preferred that can achieve zero steady-state error under αβ stationary coordinate. The PR controller is applied in (4)

\[
\begin{align*}
\begin{align*}
\hat{u}_{ia} &= u_{ia} - (i_a - i_{ia}) \left( k_p + \frac{K_s}{s^2 + \omega_0^2} \right) \\
\hat{u}_{ib} &= u_{ib} - (i_b - i_{ib}) \left( k_p + \frac{K_s}{s^2 + \omega_0^2} \right)
\end{align*}
\end{align*}
\]  

(32a, b)

where \(K_p\) is the proportional gain, \(K_s\) is the resonant gain.

The block diagram of the overall controller based on PR control can be obtained in Fig. 7.

Compared with the PNS separation and compensation methods in \(d–q\) rotational coordinates, the currents do not need to be PNS decomposition. Thus, it decreases the errors of current due to the PNS components separation. On the other hand, the proposed method reduces the number of the controllers. There are four PI controllers under the traditional method. However, there are only two PR controllers (32) shown in Fig. 7 under the proposed method. It simplifies the controller structure and cuts down the control parameters.

### 3.2 Optimal strategy based on PSO

Taking the minisation of double-frequency reactive power oscillations as an example, the mathematical formulation of this problem can be described as follows

\[
\begin{align*}
\min f(x) &= \min f\{ (k_p, k_q) \} = |q_{2ω}| \\
&= \sqrt{P^*(1 - k_p) \cdot \| u^* \| \cdot \| u^- \|^2 + Q^*(1 + k_q) \cdot \| u^+ \| \cdot \| u^- \|^2} \\
\text{s.t.} \\
g(x) &= g\{ (k_p, k_q) \} = |p_{2ω}| - \Delta P_{lim} \leq 0
\end{align*}
\]  

(33)

Fig. 4  Structure of the FLL.
\[ \Delta P_{\text{lim}} \text{ represents the limited range of active power oscillations,} \]
\[ \vec{x} = (k_p, k_q) \text{ is the variables,} \]
\[ f(\vec{x}) \text{ represents the objective function to be minimised.} \]
\[ F(\vec{x}) = f(\vec{x}) + \lambda(\vec{x})H(\vec{x}) \]
\[ p_m(\vec{x}) = \max \{0, g_m(\vec{x})\} \quad m = 1, 2, \ldots, n \]

where \( n \) is the number of constraints, \( g_m(\vec{x}) \) is the constraints, \( p_m(\vec{x}) \) is a relative violated function of the constraints, \( \theta(p_m(x)) \) is an assignment function, \( \alpha \) is the power of the penalty function, and the following values were used for the penalty function.

If \( p_m(x) < 1 \), then \( \alpha = 1 \)

\[ \theta(p_m(x)) = \begin{cases} 
10 & (0 < p_m(x) \leq 0.001) \\
20 & (0.001 < p_m(x) \leq 0.1) \\
100 & (0.1 < p_m(x) \leq 1) 
\end{cases} \]

If \( p_m(x) \geq 1 \), then \( \alpha = 2 \), \( \theta(p_m(x)) = 300 \).

The procedure of PSO is summarised in [23]. PSO can also minimise double-frequency active power oscillations while limiting the amplitude of oscillating reactive power using the proposed method.

### 4 Simulation

To verify the validity of the dynamic model and the feasibility of the proposed control strategies, simulation is conducted using PSCAD/EMTDC. The VSC-HVDC connecting active network during single-phase line to ground fault has been adopted. All results in Figs. 8 and 9 are logged with the same voltage sag, which correspond to a single-phase fault at grid voltage. Grid voltages are emulated to be faulty at \( t = 0.5 \) s. The main parameters of VSC-HVDC transmission system are listed in Table 1. \( ||u'|| = 0.5 \) p.u., \( ||\vec{u}'|| = 0.3 \) p.u., \( P'^* = 1.0 \) p.u., \( Q'^* = 1.0 \) p.u.

Figs. 8–10 show the results with single control objective without optimal control. Result from the control objective to eliminate double-frequency active power oscillations by selecting \( k_p = -1 \), and \( k_q = 1 \) is shown in Fig. 8. The resulting active and reactive powers during the unbalanced conditions show that the objective of eliminating double-frequency active power oscillations is achieved, although the currents have distortions. However, the reactive power oscillations increase significantly. Fig. 9 shows the result of eliminating double-frequency reactive power oscillations by setting \( k_p = 1 \), and \( k_q = -1 \). Inspecting the plot, it can be seen the reactive power is kept at \( Q'^* = 1.0 \) p.u. when the unbalanced
voltage dip occurs, while the double-frequency oscillations appear in both active power and current in the grid as expected. The result to eliminate the oscillation of current in the grid by choosing $k_p = 0$, and $k_q = 0$ is in Fig. 10. Though the current is balanced, both the active and reactive power oscillations are larger.

Comparing the results plotted in Figs. 8–10, the current, active and reactive powers cannot operate good performance simultaneously under single objective control. The objective is accomplished to damage other variable states performance.

In the following section, results illustrating the performance of the proposed control in the paper for unbalanced voltage condition are presented and discussed for six cases with different double-frequency oscillation amplitudes of active power.

Table 1 System parameters

| Variables                  | Value       |
|----------------------------|-------------|
| rated active power         | 50 MVA      |
| rated RMS voltage          | 50 kV       |
| inductance                 | 20 mH       |
| equivalent loss resistance | 0.2 Ω       |
| frequency                  | 50 Hz       |
| DC capacitance             | 500 μF      |
| DC capacitor voltage       | 120 kV      |
| PWM carrier frequency      | 1950 Hz     |

Fig. 8 Simulation results with $k_p = -1$ and $k_q = 1$

a Currents $i_{abc}$
b Instantaneous active power $p$ and reactive power $q$

Fig. 9 Simulation results with $k_p = 1$ and $k_q = -1$

a Currents $i_{abc}$
b Instantaneous active power $p$ and reactive power $q$

Fig. 10 Simulation results with $k_p = 0$ and $k_q = 0$

a Currents $i_{abc}$
b Instantaneous active power $p$ and reactive power $q
Table 2  Parameter optimal results of PSO

| ΔP_{lim} | k_p | k_q | min|q|2|ω|
|----------|-----|-----|----|----|----|
| 0        | -1  | 1   | 2.0722 |
| 5%       | -0.9459 | 0.9880 | 1.9752 |
| 10%      | -0.8873 | 0.9739 | 1.8809 |
| 15%      | -0.8257 | 0.9585 | 1.7868 |
| 20%      | -0.7600 | 0.9414 | 1.6941 |
| 25%      | -0.6899 | 0.9219 | 1.6030 |

Table 2 shows parameters $k_p$ and $k_q$ obtained by PSO algorithm and min|$q_2$|ω| under six different values of $\Delta P_{lim}$. It can be seen that the active power oscillation can be restrained in an acceptable bound while the minimum reactive power oscillation can be guaranteed via optimisation.

When the amplitude of active power fluctuation $\Delta P_{lim}$ is set to 5%, the double-frequency reactive power oscillations decrease by ~10% comparing with the case that eliminates double-frequency active power oscillations ($k_p = -1$, $k_q = 1$). Increasing the amplitude of active power oscillation $\Delta P_{lim}$, the value of the optimal parameter $k_p$ becomes bigger and more and more far away from -1, meanwhile, the value of the optimal parameter $k_q$ becomes smaller and more and more far away from +1. Furthermore, the reactive power oscillation gets decreased. The results reflect the relationship between the active and the reactive power oscillation and the individual parameters $k_p$ and $k_q$ described by (27) and (28). The individual parameters $k_p$ and $k_q$ chosen as (-1, 1), (1, -1), and (0, 0) are the special cases.

Fig. 11 shows the active and reactive powers using optimal parameters $k_p$ and $k_q$.

Fig. 12 shows the comparison of instantaneous power waveforms when the $\Delta P_{lim}$ is set to different values.

In Fig. 12, $p_1$ is the active power and $q_1$ is the reactive power when $\Delta P_{lim}$ is set as 0; $p_2$ is the active power waveforms, and $q_2$ is the reactive power waveforms when $\Delta P_{lim}$ is set as 0.05; $p_3$ is the active power waveforms, and $q_3$ is the reactive power waveforms when $\Delta P_{lim}$ is set as 0.1. A comparison of the waveforms of $q_1$, $q_2$, and $q_3$ shows that the double-frequency reactive power oscillations steadily decrease while using parameters $k_p$ and $k_q$. The simulation results are consistent with the theoretical results shown in Table 2.

![Waveforms of instantaneous active power p and reactive power q](image-url)
Fig. 12 Comparison of instantaneous power waveforms when the $\Delta P_{\text{lim}}$ is set to different values

5 Conclusion

This paper proposes a novel method for independent active and reactive power control of VSC under unbalanced grid voltage conditions. The method of SOGI-QSG with inherent sequence separation in the stationary reference frame is used to get positive-sequence and negative-sequence components at the point of connection to the grid. On this basis, expressions for current reference calculation corresponding to three different objectives of active and reactive power controls have been derived and analysed. The derived current reference equations have been synthesised into generalised equations where the objectives of achieving balanced three-phase currents, elimination of double-frequency active power oscillations, or elimination of double-frequency reactive power oscillations can be selected separately for the active and reactive current reference components by specifying the value of two scalar coefficients. An optimisation method to identify parameters $k_p$ and $k_q$ based on PSO algorithm that can cope with multiple constraints of both double-frequency active power and reactive power oscillations is presented. The results have been given, which can verify the validity of the proposed method.

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