Development on Compensating Unbalanced Load of Energy Storage Converter in Distribution Network

Tianchong Chen¹, Weimin Chen¹*, Jianming Chen², Ruijin Dai² and Yilin He²
¹College of Mechanical and Electrical Engineering, China Jiliang University, Hangzhou, China
²Zhejiang Huayun Information Technology Co. Ltd, Hangzhou, China

*Corresponding author e-mail: cwm@cjlu.edu.cn

Abstract. By analyzing the current equivalent circuit of unbalanced load, the mathematical model of the three-phase four-wire energy storage converter in the dq0 coordinate system is established. Comparing the characteristics of the Decouple Double Synchronous Reference Frame (DDSRF) and the Delay Signal Cancellation (DSC) to decompose the positive and negative sequence line parameters, the DSC with faster dynamic response is selected for the practical application effect. Compensate the decomposed zero sequence component and negative sequence component. The DC component is adjusted by Proportional Integral (PI) controller, and the AC component is controlled by Proportional Resonance controller (PR) to achieve no static error. Finally, a split capacitive energy storage converter system is built in Matlab/Simulink for simulation verification, which proves that the control strategy can effectively compensate the current asymmetry caused by load unbalance.

Keywords: Unbalanced Load, Distribution Network, Delay Signal Cancellation, Current Compensation

1. Introduction
In 10kV distribution networks, Y/yn0 wiring is generally used in distribution transformers, the commonly used distribution line structure is the three-phase (3P) four-wire (4W) structure with a three-phase symmetrical voltage and a neutral line [1]. With the diversification of electricity load types and the complexity of the structure, as well as the characteristics of peaks and valleys in different periods of time, the three-phase current output of the distribution transformer is unbalanced [2]. In order to balance the three-phase current at the network source and improve the power quality of the distribution network, the energy storage system is used to compensate the current [3].

The structure of the distribution transformer determines that the energy storage three-phase unbalanced compensation converter has the same wiring [4]. Common four-wire converters are divided into two-level, three-level and multi-level according to the number of levels [5]. Two-level converter structures include four-arm type, split capacitor type, single-phase H-bridge combined type; three-level four-wire topology is mainly based on a midpoint clamp type; multi-level is generally derived from a three-level circuit [6]. In engineering application, the structure of three-level and
multi-level circuits is relatively complex, there are many factors that affect power devices, and the actual working performance of the system is difficult to quantitatively analyze, so it is not been widely used in engineering application [7]. In order to compensate the three-phase unbalanced current, the first thing is to detect the unbalanced component in the current [8]. The traditional current detection methods contain p-q method, dq method, FFT method, etc [9]. These methods work well under three-phase balanced conditions, but in unbalanced conditions, these test results are somewhat unsatisfactory [10].

This paper uses a two-level split-capacitor 3P-4W energy storage converter as the topological structure, and separates the positive and negative sequences of the unbalanced current when the three-phase load is unbalanced [11]. The Decouple Double Synchronous Reference Frame (DDSRF) and the Delay Signal Cancellation (DSC) method are compared. At last, the latter is used to separate the positive and negative sequences to obtain the command current. The command current \( dq \) component is controlled by Proportional Integral (PI), and the zero sequence component is adjusted by the Proportional Resonance (PR) controller. The current compensation structure simulation of an energy storage converter for an unbalanced load under three-phase symmetrical voltage is built in Matlab/Simulink.

2. Analysis of Sequence Separation

2.1. Modelling of 3P-4W Inverter

The main circuit is composed of a Ca energy storage module, a voltage-type inverter circuit, an LCL filter, and a 380V AC of the distribution network transformer; S1-S6 are the IGBT module with freewheeling diode; the capacitor C1C2 in DC side is used for DC voltage stabilization and absorption of unbalanced power. The capacitor Ln is used to suppress the and the harmonics generated at high switching frequencies.

Assuming that the power tube, the output filter inductor and capacitor, and the connecting line are ideal devices, the dead time and the influence of higher harmonics are not considered, and the parameters of each phase are the same. According to Kirchhoff's law, the KCL and KVL equations of each phase can be listed. Among them, \( i_{1k} \) is the inductor current on the bridge arm, \( i_{2k} \) is the grid-connected current, and \( i_{nk} \) is the neutral current of each phase. \( Z_k \) is the load impedance, \( U_k \) is the output voltage of the bridge arm, \( U_{ck} \) is the voltage across the filter capacitor, \( e_k \) is the grid voltage, \( k=a, b, c \).

\[
\begin{align*}
L \frac{d i_{1k}}{dt} &= U_k - U_{ck} - L \frac{d i_{2k}}{dt} \\
L \frac{d i_{2k}}{dt} &= U_{ck} - e_k \\
C \frac{d U_{ck}}{dt} &= i_k - i_{3k}
\end{align*}
\]  

(1)
After Clark transformation and Park transformation are performed on the mathematical model in the three-phase stationary coordinate system, the model in the \(dq0\) coordinate system can be obtained. When the three phases are balanced, the neutral current is zero. In order to facilitate the calculation, set the capacitance \(L_n\) in Formula (1) to 0 when converting to a rotating coordinate system. At the same time, the L filter is used instead of the LCL filter, that is, \(L=L_1+L_2\). The Clark transformation matrix and Park transformation matrix of constant amplitude are as follows.

\[
\begin{bmatrix}
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\
0 & 1 & 0
\end{bmatrix}
\]

\[
T_{abc-\alpha\beta} = \frac{2}{3}
\begin{bmatrix}
\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
T_{\alpha\beta-dq0} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\]

It can be seen that there are coupling components \(\omega L_i\) and \(-\omega L_i\) between the transformed \(dq\) axis. Therefore, decoupling control is required between the \(dq\) axis. The 0-axis component and the \(dq\) axis remain independent.

2.2. Mathematical Model of Unbalanced Load

When the load is unbalanced, according to the symmetrical component method, the unbalanced load current can express a unique equation in positive sequence, negative sequence, and zero sequence.

\[
\begin{bmatrix}
Z_{pp} & Z_{pn} & Z_{pn} \\
Z_{np} & Z_{nn} & Z_{np} \\
Z_{np} & Z_{np} & Z_{nn}
\end{bmatrix}
\begin{bmatrix}
i_{p} \\
i_{n} \\
i_{0}
\end{bmatrix}
= \begin{bmatrix}
\cos(\omega t + \phi_p) \\
\cos(\omega t + \phi_n + \frac{2\pi}{3}) \\
\cos(\omega t + \phi_n + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
i_{p}^p \\
i_{p}^n \\
i_{p}^0
\end{bmatrix}
\]

\[
\begin{bmatrix}
i_{p}^p \\
i_{p}^n \\
i_{p}^0
\end{bmatrix}
= \begin{bmatrix}
\cos \phi_p \\
\sin \phi_p \\
-\sin \phi_p
\end{bmatrix}
\begin{bmatrix}
i_{p} \\
i_{n} \\
i_{0}
\end{bmatrix}
+ \begin{bmatrix}
\cos(2\omega t + \phi_n) \\
\cos(2\omega t + \phi_n) \\
\sin(2\omega t + \phi_n)
\end{bmatrix}
\begin{bmatrix}
i_{p}^p \\
i_{p}^n \\
i_{p}^0
\end{bmatrix}
\]

It can be seen from the Formula (5) that in the positive sequence coordinate system, the positive sequence component is the DC component, and the negative sequence component is the double frequency alternating component. In the same way, in the negative sequence coordinate system, the positive sequence component is the AC component of the double frequency. Therefore, to control the transformed \(dq\) component without static error, it is necessary to eliminate the AC component and then perform PI control. Formula (5) is further simplified to obtain Formula (6).
3. Current Compensation Control Strategy

3.1. Calculation Method of Positive and Negative Sequence Decomposition

As the figure 2 shows, using the DDSRF to decouple the current signal, the main process is to collect the three-phase symmetrical grid voltage, $\theta_0$ is the grid voltage phase angle obtained from the phase-locked loop (PLL). Perform positive and negative sequence $dq$ coordinate transformation on the collected three-phase load current, while constructing a coupling quantity of the same size and opposite sign to be superimposed on the positive and negative sequence $dq$ axis to cancel the coupling term, and then pass the low-pass filter to obtain the DC component, that is, the last two items of equation (6) are eliminated, leaving only the DC component.

$$
\begin{align*}
\begin{bmatrix}
i_p(t) \\
i_n(t)
\end{bmatrix} &=
\begin{bmatrix}
\cos(\omega t + \phi_p) \\
\sin(\omega t + \phi_p)
\end{bmatrix}
\left[\begin{bmatrix}
\cos(\omega t + \phi_p) \\
\sin(\omega t + \phi_p)
\end{bmatrix} + i_p
\begin{bmatrix}
\cos(\omega t + \phi_p) \\
\sin(\omega t + \phi_p)
\end{bmatrix} - \sin(\omega t + \phi_p)
\end{bmatrix}
\end{align*}
$$

After delaying the current component of the above equation by 1/4 period, the obtained expression is as equation (9), $\theta_0 = \omega t$, 1/4 period is $\pi / 2$ phase angle.

$$
\begin{align*}
\begin{bmatrix}
i_p(t - T/4) \\
i_n(t - T/4)
\end{bmatrix} &=
\begin{bmatrix}
\sin(\omega t + \phi_p) \\
-cos(\omega t + \phi_p)
\end{bmatrix}
\left[\begin{bmatrix}
\sin(\omega t + \phi_p) \\
-cos(\omega t + \phi_p)
\end{bmatrix} + i_p
\begin{bmatrix}
\sin(\omega t + \phi_p) \\
-cos(\omega t + \phi_p)
\end{bmatrix} - \sin(\omega t + \phi_p)
\end{bmatrix}
\end{align*}
$$

Add and subtract equations (7) and (8) to get the positive and negative sequence current components of the $\alpha\beta$ axis, and then get the positive and negative sequence components of the current on the $dq$ axis after Park transformation (the phase angle required for the Park transformation is also determined by the phase-locked loop). At this point, the positive and negative sequence has become a DC value, that is, equation (9). In the three-phase balance, the q-axis component of the positive sequence and the $dq$ axis component of the negative sequence are both 0, that is, the positive sequence part is the three-phase balance current. Therefore, the command current that the energy storage inverter needs to output is the negative sequence and zero sequence components. In the $3P$-$4W$ system, the neutral current is the sum of the three-phase currents. When the load is unbalanced, the neutral current is not zero. The positive sequence component and the negative sequence component of the
current are symmetrical, so 1/3 of the neutral current is the zero sequence component.

3.2. Current loop Control Strategy

This paper aims to realize that the grid-side transformer outputs three-phase symmetrical current when the three-phase load is unbalanced, so the negative sequence and zero-sequence components provided by the energy storage converter can compensate for the unbalance of the load current, and finally make the grid-side output current three-phase balance, figure 3 is the current sequence control diagram.

![Current control strategy](image1)

**Figure 3.** Current control strategy

The current is sampled from the output of the energy storage converter, and the positive and negative sequence $dq$ components obtained by the DSC are direct currents, and the PI controller can be used to track the command current without static difference. At the same time, there are coupling components $\omega L_i$ and $-\omega L_i$, so the dq axis needs to be decoupled. The power grid feedforward is added to improve the control accuracy and stability simultaneously. The command current of the zero-sequence component is an AC value, and the PI controller cannot accurately track the current, so the PR controller is selected to control the output of the zero-sequence current. The PR controller can produce a great gain at the resonance frequency, and there is no obvious attenuation outside this frequency. However, due to the uncertainty of measurement sampling and the actual power system, the grid voltage has certain frequency fluctuations; it is difficult to accurately implement ideal PR control. Therefore, the quasi-PR controller is selected, which can output the high gain of the PR controller near a specific frequency and can reduce the interference caused by the frequency offset of the grid. Finally, the sequence current commands are converted into $abc$ coordinate system and output to SPWM. The Formula (10) and Formula (11) are the expression of ideal PR controller and quasi-PR controller.

\[
G_{\text{ideal-PR}}(s) = K_p + \frac{K_i s}{s^2 + \omega_0^2}
\]  
(10)

\[
G_{\text{quasi-PR}}(s) = K_p + \frac{2K_i \omega_0 s}{s^2 + 2\omega_0 s + \omega_0^2}
\]  
(11)

4. Simulation Results and Analysis

In order to verify the effectiveness of the control strategy proposed in this article, a simulation model of the energy storage converter to compensate for the unbalanced load current is built in the Matlab/Simulink. $U_{dc}=800V$, inductance of bridge arm $L_1=5mH$, on-grid side inductance $L_2=1mH$, output filter capacitor $C=50\mu F$; IGBT switching frequency is 10kHz; the three-phase unbalanced load is set to 10kW, 5kW, 3kW; The AC line voltage is 380V and the frequency is 50Hz. Figure 4 is the load current, and figure 5 is the load unbalanced current positive sequence component and negative sequence superimposed zero sequence component, that is, the command current waveform. Figure 6(a) is the grid-side current waveform diagram after the energy storage converter is compensated. Figure 6(b) is the inverter output current waveform.
Figure 4. Load current waveform

Figure 5. (a) Waveform diagram of load current positive sequence component and (b) command current

Figure 6. (a) Grid-side current waveform after compensation. (b) The inverter output current waveform.

It can be seen from Figure 5(a) and Figure 6(a) that the compensated grid-side current waveform is roughly the same as the positive sequence component of the unbalanced current. It can be seen from Figure 5(b) and Figure 6(b) that the current waveform output by the inverter is roughly the same as the command current. In summary, it is verified that the energy storage grid-connected inverter has an effect on compensating the unbalanced load current.

5. Conclusion
When the 3P-4W low-voltage distribution transformer keeps the three-phase output voltage unchanged, the load current contains positive and negative zero sequence current components due to the unbalanced three-phase load. Compared DDSRF and DSC, the latter is chosen to decompose positive and negative sequence currents due to its small calculation amount and fast dynamic response. Using a split capacitor energy storage converter to compensate for zero negative sequence current can effectively compensate for the current unbalance of the grid-side transformer. The distribution transformer achieves the compensation goal of three-phase current balanced output.

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