Low-voltage power supply system based on three-phase to two-phase and integrated power quality control method

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Abstract. The two-input single-phase transformer is widely used in the 10kV power distribution system. However, this power supply mode has the disadvantage of the 10kV side three-phase unbalance problem. In response to this problem, the paper proposes a new 220V single-phase low-voltage power supply system based on a three-input single-phase transformer. The power supply system consists of a three-phase transformer and a two-phase transformer and a phase-to-phase power controller. The three-phase to two-phase transformer is used to realize two low-voltage single-phase power supply, and the phase-to-phase power controller is used to realize the negative sequence and harmonic control of the low voltage side. This power supply mode is suitable for large-capacity low-voltage power supply systems with single-phase load intensive. The paper analyzes the transformation theory and control strategy of the power supply mode. Finally, the superiority and effectiveness of the proposed technical scheme and control strategy are verified by simulation analysis.

1. Introduction

With the development of power supply systems, low-voltage large-capacity single-phase loads are increasing, such as electric vehicle charging piles and heating equipment. Leading to three-phase current imbalance, voltage deviation, harmonics and other power quality problems in low-voltage power supply systems [1]. Single-phase transformer technology is an effective technical means to solve such problems, especially for power supply scenarios with a power supply radius of less than 100 meters, compared with the three-phase power supply scheme, its technical advantages are obvious [2]. However, the existing three-phase unbalance problem based on the two-input single-phase transformer greatly limits the development of single-phase power supply technology [3].

In order to solve such problems, the literature [1,2] carried out research work on the three-phase unbalance compensation technology of low-voltage distribution network. In the literature [1], according to the characteristics of the zero-sequence current flowing through the neutral line when the load imbalance occurs in the three-phase power supply mode, the three-level inverter is selected as the main circuit topology of the compensation device. The current extraction method based on cascaded filter is used. The simulation results show that the scheme can better compensate the three-phase unbalanced load. In the literature [2], for the universal wiring method on the low-voltage distribution network side, the three-phase four-bridge voltage source converter is selected as the converter topology of the active unbalance compensation device. An unbalanced current detection method based on unbalanced current...
detection method is adopted and simulated. Literature [3] proposed a solution to reduce the loss of distribution network by using reactive power compensation technology to achieve energy-saving effect and improve power quality. The above technology is aimed at a low-voltage distribution network using a three-phase power supply mode. With the development of the natural distribution of power load in many low-voltage distribution network power supply stations, there is often a phenomenon that the single-phase power load is too dense, and the high-voltage side three-phase load imbalance is increasing. Due to the limitation of geographical and economic problems, the negative sequence and harmonic compensation are performed under the original three-phase power supply mode, and it is difficult to meet the requirements of the distribution characteristics of the unbalanced power load. Aiming at the current situation that the uneven distribution of power load is gradually increasing and the shortcomings of the prior art research, this paper proposes a new 220V single-phase low-voltage power supply system based on three-input single-phase transformer. The power supply system consists of a three-phase to two-phase transformer and a phase-to-phase power controller. The three-phase to two-phase transformer is used to realize two low-voltage single-phase power supply, and the phase-to-phase power controller is used to realize the negative sequence and harmonic control of the low voltage side. This power supply mode is suitable for large-capacity low-voltage power supply systems with single-phase load intensive. The paper analyzes the transformation theory and control strategy of the power supply mode. Finally, the superiority and effectiveness of the proposed technical scheme and control strategy are verified by simulation analysis.

2. Low-voltage power supply system based on three-phase to two-phase

As shown in Figure 1, Three-phase-two-phase power supply solution includes two modules: Three-phase to two-phase transformer and power flow controller. The Three-phase to two-phase transformer is connected to the 10kV side A, B, C three-phase voltage on the primary side, Secondary side output is connected to low voltage 220V two load arms, The left power supply arm is defined as the α phase, and the right power supply arm is the β phase, These two power supply arms make it easy for users to directly access the power, Complete the three-phase-two phase preliminary step-down conversion. The phase-to-phase power controller is connected to the two load arms α and β. The phase-to-phase power controller includes a control module and two back-to-back voltage source converters that share a DC regulated capacitor. The control module is also connected to the α and β load arms, monitors and collects

![Diagram of Three-phase to Two-phase Low-voltage Power Supply System](image-url)
the real-time load current information of the two arms, and controls the output compensation amount of
the two back-to-back converters according to the corresponding control strategy, realizing the function
of power transfer and negative sequence harmonic compensation.

3. The basic principle of three-phase to two-phase low-voltage power supply system
Taking the A-phase voltage $U_a$ of the high-voltage side of the three-phase transformer two-phase
transformer as the reference. Let the leading phase angle be positive and the lag phase angle be negative.
As is easily seen from Figure 2, The α and β arm voltages are
\[ U_{\alpha} = U_{a} e^{j120^\circ}, \quad U_{\beta} = U_{b} e^{j30^\circ}, \]
The voltage phasor diagram of the three-phase to two-phase transformer wiring is as follows:

![Figure 2. Three-phase to two-phase transformer wiring voltage phasor diagram.](image)

The load current vector of the two arms of α and β is shown in Fig. 3. $I_{\alpha}$ is the α arm load current,
$I_{\beta}$ is the β arm load current. Most of the low-voltage distribution networks are inductive loads,
assuming that the two-arm load is inductive. Let $\theta_1$ be the angle of $I_{\alpha}$ lag $U_{\alpha}$, and $\theta_2$ be the angle
of $I_{\beta}$ lag $U_{\beta}$, and $\theta_1$ is not equal to $\theta_2$. It can be seen from Fig. 3 that the amplitude difference
between the two arms is large.

![Figure 3. α and β arm voltage and current vector before compensation.](image)
Assuming that the two voltage source converters do not consume power, first obtain the active component of the two arm currents. The active current component of the \( \alpha \) phase is \( \mathbf{i}_{\alpha L} \), and the active current component of the \( \beta \) phase is \( \mathbf{i}_{\beta L} \), as shown in Fig. 4.

\[
\begin{align*}
\mathbf{e}_{\alpha} &= I_a \cos \theta_1 \\
\mathbf{e}_{\beta} &= I_\beta \cos \theta_2
\end{align*}
\]  

(1)

As shown in Figure 5, At this time, if the active current component of \( \frac{1}{2}(I_{\alpha L} - I_{\beta L}) \) is transferred from the \( \alpha \) phase to the \( \beta \) phase, the \( \alpha \) phase and the \( \beta \) phase can achieve a symmetric balance of the active current. At the same time, the balanced active current vectors of \( \alpha \) and \( \beta \) arms are also the target vectors for realizing the balance of the two arms of \( \alpha \) and \( \beta \), eliminating the negative sequence and harmonics.

\[
\begin{align*}
\mathbf{e}_{\alpha} &= I_a \cos \theta_1 \\
\mathbf{e}_{\beta} &= I_\beta \cos \theta_2
\end{align*}
\]  

(1)

Figure 4. Active component of \( \alpha \) phase and \( \beta \) phase load current.

Figure 5. Current vector of \( \alpha \) phase and \( \beta \) phase after adjusting active component and reactive component.

It is easy to know from the phasor diagram of Figure 5:
\[
\begin{align*}
\mathbf{f}_{aL1} &= \left[ I_{al} - \frac{1}{2}(I_{aL} - I_{\beta L}) \right] e^{j120^\circ} \\
\mathbf{f}_{\beta L1} &= \left[ I_{\beta L} + \frac{1}{2}(I_{aL} - I_{\beta L}) \right] e^{j130^\circ}
\end{align*}
\] (2)

Simplify this formula:

\[
\begin{align*}
\mathbf{f}_{aL1} &= \frac{1}{2}(I_{aL} + I_{\beta L})e^{j120^\circ} \\
\mathbf{f}_{\beta L1} &= \frac{1}{2}(I_{aL} + I_{\beta L})e^{j130^\circ}
\end{align*}
\] (3)

It is easy to know from the above analysis, as shown in Figure 5, By subtracting the initial current vectors \( \mathbf{f}_a \) and \( \mathbf{f}_\beta \) from the current vectors \( \mathbf{f}_{aL1} \) and \( \mathbf{f}_{\beta L1} \) of the ideal \( \alpha \) phase and \( \beta \) symmetry, the finally required compensated current vectors \( \mathbf{f}_{aL} \) and \( \mathbf{f}_{\beta L} \) can be obtained.

\[
\begin{align*}
\mathbf{f}_{aL} &= \mathbf{f}_{aL1} - \mathbf{f}_a \\
\mathbf{f}_{\beta L} &= \mathbf{f}_{\beta L1} - \mathbf{f}_\beta
\end{align*}
\] (4)

The situation at \( I_{\beta L} > I_{aL} \) is similar to the above. In the general case, the negative sequence compensation current of the phase power controller in the two power supply arms is:

\[
\begin{align*}
\mathbf{f}_{caL} &= \frac{1}{2}(I_{aL} + I_{\beta L})e^{j120^\circ} - I_a e^{j120^\circ} - \theta_a \\
\mathbf{f}_{c\beta L} &= \frac{1}{2}(I_{aL} + I_{\beta L})e^{j130^\circ} - I_\beta e^{j130^\circ} - \theta_\beta
\end{align*}
\] (5)

In the formula: \( \mathbf{f}_{caL}, \mathbf{f}_{c\beta L} \) ——Negative sequence compensation current of two converters on the \( \alpha \) phase and \( \beta \) phase side in the phase-to-phase power controller, the direction of the inflow phase flow controller is the positive direction.

The phase-to-phase power controller generates a current equal to the amplitude of the load harmonic current and opposite in phase to cancel the load harmonic current. Let the load harmonic currents of the \( \alpha \) phase and the \( \beta \) phase be \( i_a \) and \( i_\beta \), respectively, and the harmonic compensation current generated by the phase to phase current power controller is:

\[
\begin{align*}
\mathbf{f}_{c\alpha h} &= -\mathbf{f}_{aLh} \\
\mathbf{f}_{c\beta h} &= -\mathbf{f}_{\beta Lh}
\end{align*}
\] (6)

Therefore, the comprehensive compensation current of the phase current controller is:

\[
\begin{align*}
\mathbf{f}_{ca} &= \frac{1}{2}(I_{\beta L} + I_{aL})e^{j120^\circ} - I_a e^{j120^\circ} - \theta_a - \mathbf{f}_{aLh} \\
\mathbf{f}_{c\beta} &= \frac{1}{2}(I_{aL} + I_{\beta L})e^{j130^\circ} - I_\beta e^{j130^\circ} - \theta_\beta - \mathbf{f}_{\beta Lh}
\end{align*}
\] (7)
4. Negative sequence and harmonic compensation current detection principle

Based on the above analysis, the principle of negative sequence and harmonic detection and control of the power flow controller proposed in this paper is shown in the figure:

![Figure 6. Negative sequence and harmonic current detection principle.](image)

Let the low-voltage side α, β phase converter two power supply arm load instantaneous current are:

\[
\begin{align*}
    i_{\alpha L} &= \sqrt{2} I_{\alpha LF} \cos(\omega t + \frac{2}{3} \pi - \theta) + \sum_{h=2}^{\infty} \sqrt{2} I_{\alpha h} \cos(h\omega t + \theta_{ah}) \\
    i_{\beta L} &= \sqrt{2} I_{\beta LF} \cos(\omega t + \frac{1}{6} \pi - \theta_{2}) + \sum_{h=2}^{\infty} \sqrt{2} I_{\beta h} \cos(h\omega t + \theta_{bh})
\end{align*}
\]  

(8)

Easy to get, the instantaneous active power of the two arms is:

\[
\begin{align*}
    P_{\alpha} &= i_{\alpha L} \cos(\omega t + \frac{2}{3} \pi) = \sqrt{2} I_{\alpha LF} \cos(\omega t + \frac{2}{3} \pi - \theta) \cos(\omega t + \frac{2}{3} \pi) + \sum_{h=2}^{\infty} \sqrt{2} I_{\alpha h} \cos(h\omega t + \theta_{ah}) \cos(\omega t + \frac{2}{3} \pi) \\
    P_{\beta} &= i_{\beta L} \cos(\omega t + \frac{1}{6} \pi) = \sqrt{2} I_{\beta LF} \cos(\omega t + \frac{1}{6} \pi - \theta_{2}) \cos(\omega t + \frac{1}{6} \pi) + \sum_{h=2}^{\infty} \sqrt{2} I_{\beta h} \cos(h\omega t + \theta_{bh}) \cos(\omega t + \frac{1}{6} \pi)
\end{align*}
\]  

(9)

Further simplify this formula:

\[
\begin{align*}
    P_{\alpha} &= \frac{\sqrt{2}}{2} I_{\alpha LF} \cos \theta_{1} + \frac{\sqrt{2}}{2} I_{\alpha LF} \cos(2\omega t + \frac{4}{3} \pi - \theta) + \sum_{h=2}^{\infty} \sqrt{2} I_{\alpha h} \cos(h\omega t + \theta_{ah}) \cos(\omega t + \frac{2}{3} \pi) \\
    P_{\beta} &= \frac{\sqrt{2}}{2} I_{\beta LF} \cos \theta_{2} + \frac{\sqrt{2}}{2} I_{\beta LF} \cos(2\omega t + \frac{1}{3} \pi - \theta_{2}) + \sum_{h=2}^{\infty} \sqrt{2} I_{\beta h} \cos(h\omega t + \theta_{bh}) \cos(\omega t + \frac{1}{6} \pi)
\end{align*}
\]  

(10)

\[P_{\alpha}\] and \(P_{\beta}\) contain a DC component and an AC component, and \(P_{\alpha}\) and \(P_{\beta}\) are added together, and a low-pass filter (LPF) is used to obtain the sum of the DC components of the two components:

\[
\bar{P}_{\alpha} + \bar{P}_{\beta} = \frac{\sqrt{2}}{2}(I_{\alpha LF} \cos \theta_{1} + I_{\beta LF} \cos \theta_{2})
\]  

(11)
After low pass filtering, the DC portion of the sum of the powers is numerically equal to the average of the peak values of the fundamental wave currents of the two power supply arms. Multiply this average by $2/\sqrt{3}$, then multiplied by the synchronization signals $\cos(\omega t + \frac{2}{3}\pi)$ and $\cos(\omega t + \frac{1}{6}\pi)$ generated by the two arm voltages $U_\alpha$ and $U_\beta$ via the phase locked loop. When converted to fully compensated $\alpha, \beta$ phase power supply arm current value, the following formula is obtained:

\[
\begin{align*}
    i_\alpha &= \sqrt{2}/4(I_{a1p}\cos\theta_1 + I_{b1p}\cos\theta_2)\cos(\omega t + \frac{2}{3}\pi) \\
    i_\beta &= \sqrt{2}/4(I_{a1p}\cos\theta_1 + I_{b1p}\cos\theta_2)\cos(\omega t + \frac{1}{6}\pi)
\end{align*}
\]  

(12)

In the equation, $i_\alpha$ and $i_\beta$ are the current values of the $\alpha$ and $\beta$ phase power supply arms after compensating the negative sequence and the harmonics, respectively. The compensated alpha and beta phase currents contain the active and reactive current components that are required to compensate the two arm currents for a symmetrical current.

By subtracting the actual current of the $\alpha$ and $\beta$ phase arms from the target current after the $\alpha$ and $\beta$ arm compensation, the compensation current reference amount of the two converters connected to the $\alpha$ and $\beta$ arms of the phase-to-phase power controller can be obtained:

\[
\begin{align*}
    i_{\alpha L} &= i_\alpha - i_{\alpha L} = \sqrt{2}/4(I_{a1p}\cos\theta_1 + I_{b1p}\cos\theta_2)\cos(\omega t + \frac{2}{3}\pi) - i_{\alpha L} \\
    i_{\beta L} &= i_\beta - i_{\beta L} = \sqrt{2}/4(I_{a1p}\cos\theta_1 + I_{b1p}\cos\theta_2)\cos(\omega t + \frac{1}{6}\pi) - i_{\beta L}
\end{align*}
\]  

(13)

Substituting equation (8) into equation (13), and then simplifying can be obtained:

\[
\begin{align*}
    i_\alpha &= \frac{\sqrt{2}}{4}I_{a1p}\cos\theta_1 - 3\frac{\sqrt{2}}{4}I_{a1p}\cos\theta_2 \cos(\omega t + 2/3\pi) - \sqrt{2}I_{a1b}\sin(\omega t + 2/3\pi)\sin\theta_1 - \\
    &\sum_{n=2}^{\infty}\frac{\sqrt{2}}{4}I_{a1n}\cos(\omega t + n\theta_1) \\
    i_\beta &= \frac{\sqrt{2}}{4}I_{b1p}\cos\theta_1 - 3\frac{\sqrt{2}}{4}I_{b1p}\cos\theta_2 \cos(\omega t + 1/6\pi) - \sqrt{2}I_{b1b}\sin(\omega t + 1/6\pi)\sin\theta_2 - \\
    &\sum_{n=2}^{\infty}\frac{\sqrt{2}}{4}I_{b1n}\cos(\omega t + n\theta_1)
\end{align*}
\]  

(14)

5. Interphase power flow controller control principle

The phase-to-phase power controller should realize the compensation of the negative sequence and harmonics of the low voltage 220V side, and the two converters should track the reference quantity of the compensation current. However, for the two converters to work properly, a stable DC side voltage must be obtained. Therefore, the actual compensated reference current of the phase-to-phase power controller should be based on the negative sequence of the original $\alpha$ and $\beta$ and the harmonic compensation currents A and B, plus an active current component generated to control the stability of the DC side voltage, the control principle block diagram is as follows:
6. Simulation analysis and verification

6.1. Simulation parameter.
In order to prove the correctness of the low-voltage three-phase variable two-phase power supply system proposed in this paper and its detection compensation strategy, the simulation model is built in the Matlab/Simulink environment to simulate the operation of the three-phase to two-phase power supply system under various working conditions. The following table shows the parameters used in the simulation:

| Parameter                  | Value          |
|----------------------------|----------------|
| Three-phase voltage/kV     | 10             |
| Transformer ratio          | 45.5           |
| DC regulated capacitor/mF  | 1.7            |
| Converter AC side output inductor/mH | 5       |

6.2. Simulation Analysis of DC Side Capacitor Voltage.
The stability of the DC side capacitor voltage is the premise of the normal and stable operation of the phase-to-phase power controller. The α arm load is 30 kW, the β arm load is 50 kW, and the simulation time is 0.6 s. Figure 8 shows the DC stabilized capacitor voltage simulation waveform.

![Figure 8. DC side capacitor voltage waveform.](image)

It can be seen from Fig. 8 that under the specified working conditions, the DC stabilized capacitor voltage of the phase-to-phase power controller is stably maintained within the normal voltage range of 400V, which provides a sufficiently stable DC voltage for the normal operation of the two back-to-back voltage source converters.
6.3. Working condition 1
Realize the balance control of α and β two-arms, and the balance of three-phase side load current is the key technical index for realizing the three-phase two-phase power supply system of low-voltage distribution network of power system. Let α load arm load be 80kW, β power supply arm load 40kW, Figure 9 is the simulation results of α and β load currents before and after compensation, and Figure 10 is the simulation result of three-phase side load current before and after compensation.

![Figure 9. α and β arm currents before and after compensation.](image)

![Figure 10. Three-phase current before and after compensation.](image)

It can be seen from Fig. 9 that before the compensation, the difference between the load currents of the two arms of α and β is large, and the load distribution of the two arms is seriously uneven. After the compensation scheme of this paper, the two arm currents are balanced, and the two arm loads achieve important technical goals of symmetrical balance. The phase-to-phase power controller of this paper can stably realize the important functions of controlling and transferring the two-arm power flow.

It can be seen from Fig. 10 that before the compensation, the three-phase load current of the 10kV side of the low-voltage distribution network of the power system is extremely unbalanced, which will bring serious power quality problems. These problems have adverse effects on the high quality and reliable power supply of the power system. After implementing the compensation scheme of this paper, it can be seen from the results that the three-phase side current can achieve the important goal of three-phase load current equalization.

6.4. Working condition 2
Higher harmonic emission levels will affect the reliability of the power supply system. Harmonic resonance in the power supply system may even cause some safety accidents and cause economic losses. Let the α arm load be 30 kW and the β arm load be 50 kW. Both arm currents have higher harmonic content. Figure 11 (a) shows the load current waveform before the simulation, and Figure 11 (b) shows the load current waveform after the α and β arms are compensated. Fig. 11(b) is a comparison diagram of the current waveforms before and after the α-arm compensation, and Fig. 12 is a comparison diagram of the load current waveforms of the three-phase side before and after the compensation.
Figure 11. Compensation current of α-arm and β-arm before and after harmonic compensation.

As shown in Fig. 11 (a) and (b), it can be seen that the current harmonic content of the two arms before α and β is large. After compensation, the current harmonic content of the two arms is significantly reduced. Fig. 11(c) shows the comparison of the load current before and after the α-arm compensation. The current distortion rate before and after the α-arm compensation is reduced from 9.06% to 2.71%, respectively, indicating that the harmonic compensation effect is obvious.

Figure 12. Three-phase side current before and after compensation.

It can be seen from Fig. 12(a) that the three-phase side harmonic content of the low-voltage distribution network before compensation is high, the three-phase load current imbalance is high, and the power quality problem is outstanding. After compensation by the compensation scheme of this paper, it can be seen from Fig. 12(b) that the three-phase load current after compensation is symmetrically balanced, and the harmonic content reduction effect is obvious. The current distortion rate of the three-phase side before and after compensation is reduced from 10.09% to 4.61%, which indicates that the compensation scheme has a good effect of compensating harmonics, and the power quality is obviously improved.

7. Conclusion
This paper proposes that the three-phase-two-phase transformation scheme can realize the goal of changing the three-phase power supply mode into the two-phase power supply mode in the low-voltage distribution network of the power system. It can solve the problem that the distribution of the electric load in the power supply station of the low-voltage distribution network is not uniform and the negative-sequence current on the high-voltage side is too large. The negative sequence and harmonic current detection methods proposed in this paper provide an accurate reference for the normal compensation
phase sequence and harmonics of the phase-to-phase power controller. The simulation proves that the compensation scheme can stably implement the functions of power flow control and compensation of negative sequence and harmonics, which has important practical application significance.

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