

ANALYSIS ON THE OPERATION PARAMETERS OF THE NEW CONVERTER TRANSFORMER

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Abstract. This paper presents a new converter transformer which is applied in multipulse diode/SCR rectifiers/inverter. Comparison of operational characteristics of a conventional converter transformer and the proposed transformer was studied. Results show that the new converter transformer can not only decrease the grid side current, increase the valve side voltage but also greatly reduce the harmonics of the grid side currents. Simulation results verify the correctness of the theoretical analysis.

Keywords. Converter transformers, multipulse rectifiers/inverter, filters.

1 INTRODUCTION

The conventional converter transformer (Y/ Δ /Y) is an important device in 12-pulse diode/SCR converters. It provides a phase displacement between primary side and valve side voltages for harmonic cancellation, supplies a proper valve side voltage, and also makes an electric isolation between the rectifiers and the utility supply. However, because the filters are always placed at the grid side of the transformer, they do not have any influence on the transformer. With or without filters, the operational parameters of the transformer are not changed. [1-17].

Unlike the conventional converter transformer (CCT), the new converter transformer (NCT) with its filters can enhance the operational characteristics [18, 19]. The new converter transformer with its filters is a special kind of converter transformer whose grid side windings are connected to power grid, the valve side windings are connected to the rectifier, and the common side windings are connected to the filters. Similar to the conventional converter transformers of 12 pulses line commutated converter HVDC with Y/ Δ /Y winding connection, the new converter transformer also has an upper and lower bridge which corresponds to Δ and Y respectively. In [18], the basic operating principle and wiring scheme are presented. In [19], the characteristic parameters of the new converter transformer are studied in detail.

Different from the already achieved research results in [18, 19], in this paper, the mathematical models of the grid side current and valve side voltages of CCT and NCT are established and analyzed, which demonstrates that the NCT with its filters can decrease the grid side current, and increase the valve side voltage. Besides that, the mathematical relationships of harmonic components between the grid side and the valve side of CCT and NCT are also established. The results show that the CCT could greatly reduce the grid side harmonic currents, so could minimize the effect of the harmonics on the transformer. Finally, the detailed simulation results verify the correctness of the theoretical analysis.

2 THE OPERATIONAL CHARACTERISTICS OF THE CONVENTIONAL CONVERTER TRANSFORMER

In DC transmission system, the most common way of arranging the thyristor valves is in a 12-pulse group. The thyristor valves are fed by converter transformers connected in Y/ Δ and Y/Y arrangements (Y/ Δ /Y). The configuration of a 12-pulse converter is shown in Figure 1, where the AC filters are placed at the AC busbar, U_{load} is the phase voltage of the valve side, and Z_R is the impedance of power supply.

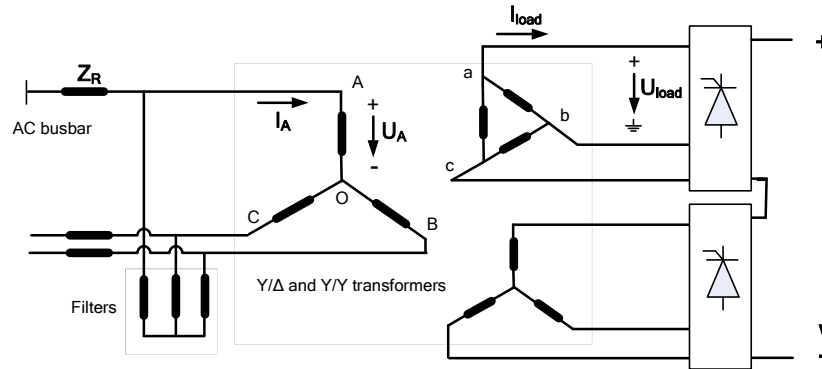


Figure 1. The winding connection scheme of the Y/Δ /Y transformers in the 12-pulse converter

Assume that the voltage ratios of these transformers are equal to 1 ($U_{AB}/U_{ab} = 1$).

2.1 The grid side current

Based on Figure 1, the relationship of the currents between the grid side and the valve side for the Y/Δ transformer can be expressed by

$$\dot{I}_A = e^{-j30^\circ} \dot{I}_{load} \tag{1}$$

2.2 The valve side voltage

The relationship of the voltages between the grid side and the valve side is

$$\dot{U}_{load} = e^{j30^\circ} \dot{U}_A - \dot{I}_{load} Z_k \tag{2}$$

where Z_k is the short-circuit impedance of the Y/Δ transformer.

2.3 The grid side harmonic current

The harmonic equivalent diagram of the Y/Δ transformer is shown in Figure 2, where the converter load is replaced by a harmonic currents source.

Assume that the impedance of power supply Z_R is equal to zero, so the harmonic voltages do not exist at the AC busbar.

$$\dot{U}_A = 0 \tag{3}$$

(Note that in a 12-pulse configuration, the 5th, 7th, 17th, and 19th harmonic currents are ignored, and the other harmonics can be suppressed by the AC high-pass filters. So the harmonic voltages at the grid side are also equal to zero)

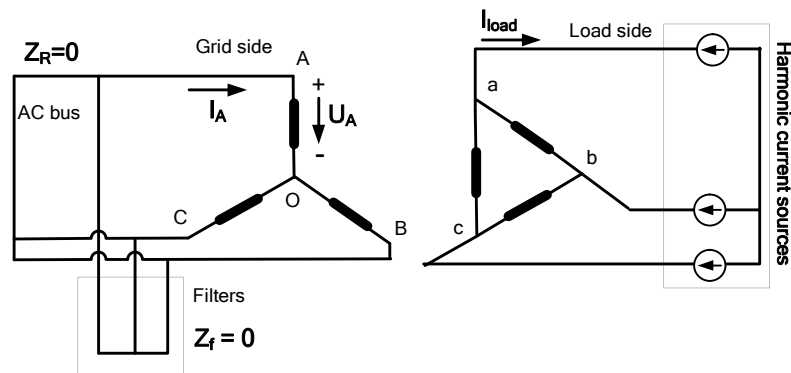


Figure 2. The harmonic equivalent diagram of Y/Δ transformer.

From (1), the relationship of the harmonic currents between the grid side and the valve side can be derived as

$$\frac{\dot{I}_A}{\dot{I}_{load}} = e^{-j30^\circ} \quad (4)$$

3 THE OPERATIONAL CHARACTERISTICS THE NEW CONVERTER TRANSFORMER

Corresponding to the 12-pulse DC transmission system with the Y/ Δ /Y transformers, Figure 3 shows the the Y/ZF-1/ ZF-2 new converter transformer (Z indicates zigzag, F: filters, 1: upper bridge, 2: lower bridge). In Figure 3, the AC filters are connected to the common windings of the Y/ZF-1/ZF-2 transformers.

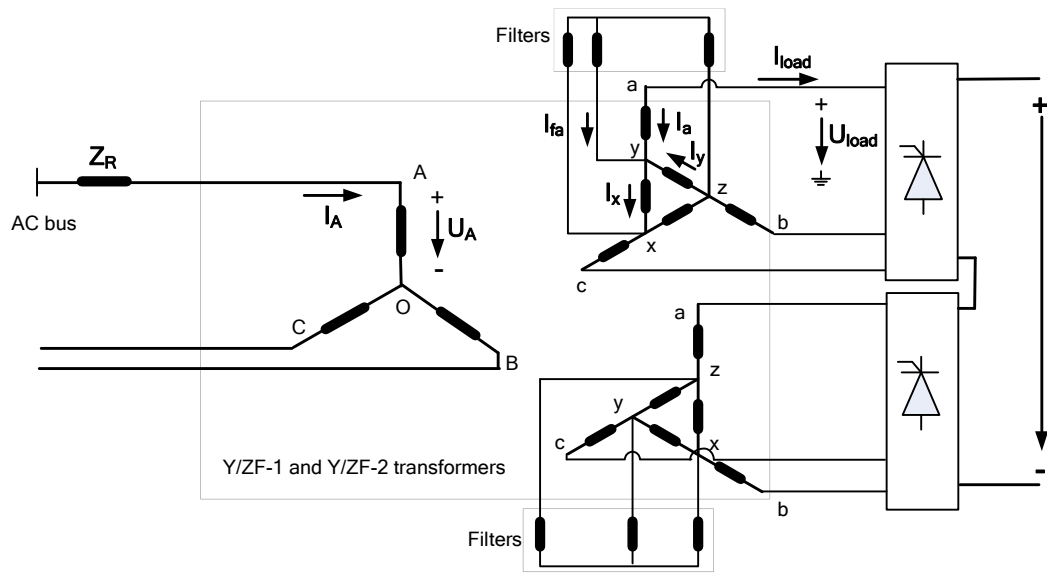


Figure 3. The winding connection scheme of the Y/ZF-1/ ZF-2 transformers in the 12-pulse converter

According to the theory of multi-winding transformer, the mathematical models of the Y/ZF-1 new converter transformers can be written as

$$\dot{I}_A = -k_a \dot{I}_a - k_x \dot{I}_x \quad (5)$$

$$\begin{cases} \dot{U}_{ay} = k_a \dot{U}_A + k_a^2 Z_{13} \dot{I}_a + k_a k_x Z_{11} \dot{I}_x \\ \dot{U}_{yx} = k_x \dot{U}_A + k_x^2 Z_{12} \dot{I}_x + k_a k_x Z_{11} \dot{I}_a \end{cases} \quad (6)$$

where:

$Z_{12} = Z_1 + Z'_2, Z_{13} = Z_1 + Z'_3, Z_{23} = Z'_2 + Z'_3, Z_1, Z'_2, Z'_3$: are the impedance of the grid side, common side and valve side winding, respectively.

$\dot{I}_A, \dot{U}_A, Z_1, W_1; \dot{I}_x, \dot{U}_{yx}, Z'_2, W_2; \dot{I}_a, \dot{U}_{ay}, Z'_3, W_3$: are the phasor current, phasor voltage, phasor impedance and number of turns of the grid side winding (AO winding); common side winding (yx winding) and valve side winding (ay winding), respectively.

In this paper, the mathematical model of the new converter transformer is based on voltage ratio which is equal to 1 ($U_{AB}/U_{ab} = 1$), so the values of k_a and k_x are [19]:

$$k_a = W_3 / W_1 = 0.5176$$

$$k_x = W_2 / W_1 = \sqrt{3}k_x = 0.8966$$

3.1 The grid side current

The filter current is obtained by Kirchhoff's Current Law

$$\dot{I}_{fa} = \dot{I}_x - \dot{I}_y - \dot{I}_a = \sqrt{3}e^{j30^\circ} \dot{I}_x - \dot{I}_a \quad (7)$$

The relationship between the voltage and the current of the filters can be expressed by the filter impedance Z_f

$$\dot{U}_{yx} = Z_f (\dot{I}_{fc} - \dot{I}_{fa}) = \sqrt{3}e^{j150^\circ} Z_f \dot{I}_{fa} \quad (8)$$

where Z_f is the equivalent impedance at the fundamental frequency of the filters

By substituting (7) into (8), then substituting the result into (6):

$$k_x \dot{U}_A + k_x^2 Z_{12} \dot{I}_x + k_a k_x Z_1 \dot{I}_a = \sqrt{3}e^{j150^\circ} Z_f (\sqrt{3}e^{j30^\circ} \dot{I}_x - \dot{I}_a) \quad (9)$$

From (9), the relationship between the common side winding and valve side winding can be expressed by

$$\dot{I}_x = -\frac{k_x}{3Z_f + k_x^2 Z_{12}} \dot{U}_A - \frac{\sqrt{3}e^{j150^\circ} Z_f + k_a k_x Z_1}{3Z_f + k_x^2 Z_{12}} \dot{I}_a \quad (10)$$

By substituting (10) into (5):

$$\dot{I}_A = \frac{k_x^2}{3Z_f + k_x^2 Z_{12}} \dot{U}_A + \frac{3e^{-j150^\circ} Z_f + k_a k_x^2 Z_2'}{3Z_f + k_x^2 Z_{12}} \dot{I}_{load} \quad (11)$$

Because the equivalent impedance of the filters is much bigger than the impedances of the transformers at the fundamental frequency, the following results can be obtained

$$\begin{cases} |3Z_f| \gg k_x^2 |Z_{12}| \\ |3Z_f| \gg k_a k_x^2 |Z_2'| \end{cases} \quad (12)$$

By substituting (12) into (11), the grid side current can be written as

$$\dot{I}_A = j \frac{k_x^2}{3X_f} \dot{U}_A + e^{-j150^\circ} \dot{I}_{load} \quad (13)$$

where $X_f = 1/(wC)$ is the equivalent capacitive reactance of the filters.

3.2 The valve side voltage

Also, from Figure 3:

$$\dot{U}_{ab} = \dot{U}_{ay} - \dot{U}_{zy} - \dot{U}_{bz} = \sqrt{3}e^{j30^\circ} \dot{U}_{ay} - e^{-j120^\circ} \dot{U}_{yx} \quad (14)$$

By substituting (6) into (14):

$$\begin{aligned} \dot{U}_{ab} = & \dot{U}_A (\sqrt{3}e^{j30^\circ} k_a - e^{-j120^\circ} k_x) + \dot{I}_a (\sqrt{3}e^{j30^\circ} k_a^2 Z_{13} - e^{-j120^\circ} k_a k_x Z_1) \\ & + \dot{I}_x (\sqrt{3}e^{j30^\circ} k_a k_x Z_1 - e^{-j120^\circ} k_x^2 Z_{12}) \end{aligned} \quad (15)$$

By substituting (10) into (15):

$$\dot{U}_{ab} = \sqrt{3}e^{j30^\circ} \frac{e^{j15^\circ} 3Z_f + k_a k_x^2 Z_2'}{3Z_f + k_x^2 Z_{12}} \dot{U}_A + \sqrt{3}e^{j30^\circ} \frac{3Z_f Z_k + k_a^2 k_x^2 (Z_{12} Z_{13} - Z_1^2)}{3Z_f + k_x^2 Z_{12}} \dot{I}_a \quad (16)$$

where Z_k is the basic short-circuit impedance of the Y/ZF-1/ZF-2 new converter transformer

$$Z_k = k_a^2 (Z_{12} + Z_{13} + \sqrt{3}Z_1)$$

By using the phase load voltage U_{load} and the load current I_{load} , (16) can be written as

$$\dot{U}_{load} = \frac{e^{j15^\circ} 3Z_f + k_a k_x^2 Z_2'}{3Z_f + k_x^2 Z_{12}} \dot{U}_A - \frac{3Z_f Z_k + k_a^2 k_x^2 (Z_{12} Z_{13} - Z_1^2)}{3Z_f + k_x^2 Z_{12}} \dot{I}_{load} \quad (17)$$

The relationships of the filters impedance and the transformer impedances can be obtained

$$\begin{cases} |3Z_f| \gg k_a k_x^2 |Z_2'| \\ |3Z_f Z_k| \gg k_a^2 k_x^2 |Z_{12} Z_{13} - Z_1^2| \end{cases} \quad (18)$$

By substituting (18) into (17):

$$\dot{U}_{load} = \frac{e^{j15^\circ} 3Z_f}{3Z_f + k_x^2 Z_{12}} \dot{U}_A - \frac{3Z_f Z_k}{3Z_f + k_x^2 Z_{12}} \dot{I}_{load} \quad (19)$$

So the load voltages can be expressed as

$$\dot{U}_{load} = k_0 (e^{j15^\circ} \dot{U}_A - Z_k \dot{I}_{load}) \quad (20)$$

where k_0 is the voltage increase factor

$$k_0 = \frac{3Z_f}{3Z_f + k_x^2 Z_{12}} \quad (21)$$

3.3 The grid side harmonic current

The harmonic equivalent diagram of the Y/ZF-1 transformer is shown in Figure 4, where the converter load is replaced by a harmonic currents source

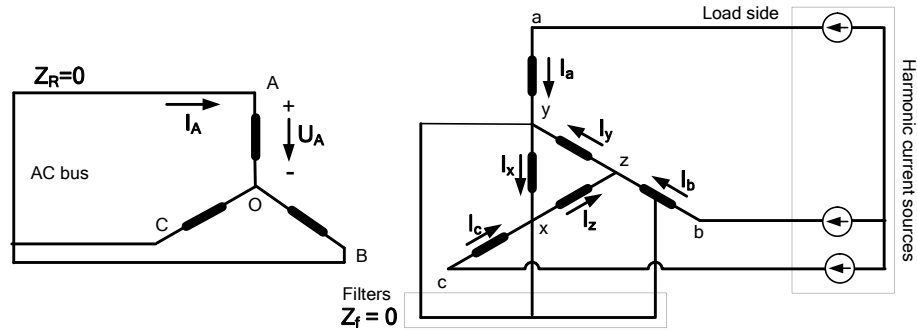


Figure 4. The harmonic equivalent diagram of Y/ZF-1 transformer

Assume that the impedance of power supply Z_R is equal to zero, so the harmonic voltages do not exist at the AC busbar

$$\dot{U}_A = 0 \quad (22)$$

Because the common winding of Y/ZF-1 transformer is connected to the filters, so the common winding is short-circuited at the tuned frequencies

$$\dot{U}_{yx} = \dot{U}_{zy} = \dot{U}_{xz} = 0 \quad (23)$$

By substituting (22) and (23) into (6)

$$\begin{aligned}
k_x^2 Z_{12} \dot{I}_x + k_a k_x Z_1 \dot{I}_a &= 0 \\
\Rightarrow \dot{I}_x &= -\frac{k_a Z_1}{k_x Z_{12}} \dot{I}_a
\end{aligned} \tag{24}$$

By substituting (24) into (5), the relationship of the harmonic currents between the grid side and valve side can be derived as

$$\frac{\dot{I}_A}{\dot{I}_a} = \frac{-k_a Z_2'}{Z_{12}} \tag{25}$$

4 ANALYSIS OF THE OPERATIONAL CHARACTERISTICS OF THE CONVENTIONAL AND NEW CONVERTER TRANSFORMERS

Table 1 shows the reactive power compensation characteristics for the Y/ Δ conventional converter transformer and the Y/ZF-1 new converter transformer. In Table 1, the operational parameters of the Y/ Δ transformer are obtained from (1), (2) and (4); and the operational parameters of the Y/ZF-1 transformer are obtained from (13), (20), (25).

Table 1. The operational parameters of converter transformers

Operational parameters	Transformers	
	Y/ Δ	Y/ZF-1
Secondary shifting angle	30	15
Grid side current \dot{I}_A	$e^{-j30^\circ} \dot{I}_{load}$	$j \frac{k_x^2}{3X_f} \dot{U}_A + e^{-j15^\circ} \dot{I}_{load}$
Valve side voltage \dot{U}_{load}	$e^{j30^\circ} \dot{U}_A - \dot{I}_{load} Z_k$	$k_0 (e^{j15^\circ} \dot{U}_A - Z_k \dot{I}_{load})$
The ratio of harmonic components $ \dot{I}_A / \dot{I}_{load} $	1	$\frac{k_a Z_2'}{Z_{12}}$

Note:

Because the mathematical models of the Y/ Δ and Y/ZF-1 transformers are established based on the voltage ratios equal to 1, namely, so in Table 1, the values of the load current which is referred to grid side and the value of the grid side voltage which is referred to valve side do not contain the voltage ratio of the transformer.

In a similar manner, the mathematical model of the lower bridge (Y/Y and Y/ZF-2 transformers) can be obtained and have the same results with Table 1.

4.1 The grid side current

The vector diagrams of the grid side current for the Y/ Δ and Y/ZF-1 transformers are shown in Figure 5, in which the mathematical equations of the grid side currents are obtained from Table 1.

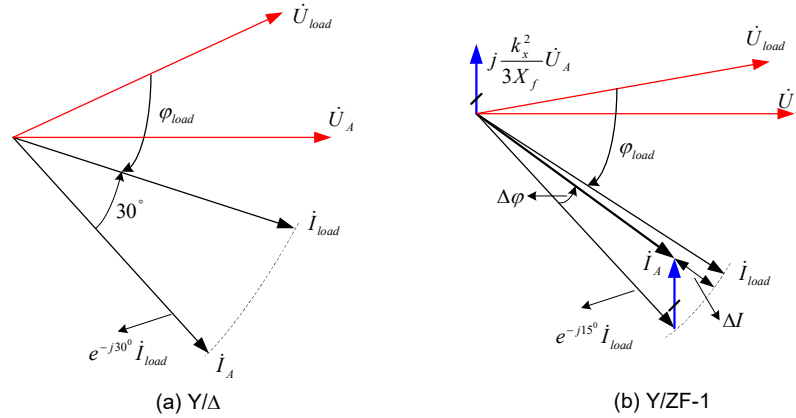


Figure 5. The vector diagrams of the grid side currents

For the Y/Δ transformer, the magnitudes of the grid side currents are equal to the valve side currents; the filters placed in front of the transformer do not have any effect on the grid side current. For the Y/ZF-1 transformer, due to existence of the compensating current which leads the grid side voltage by 90°, the magnitude of the grid side current is decreased by ΔI. So the Y/ZF-1 transformer with filters can decrease the grid side current.

4.2 The valve side voltage

Figure 6 shows the curves of the voltage increase factors versus the ratio between filters power and transformer power. In Figure 6, the mathematical equations of the voltage increase factors are obtained from Table 1, and noting that the voltage increase factor for the Y/Δ is equal to 1.

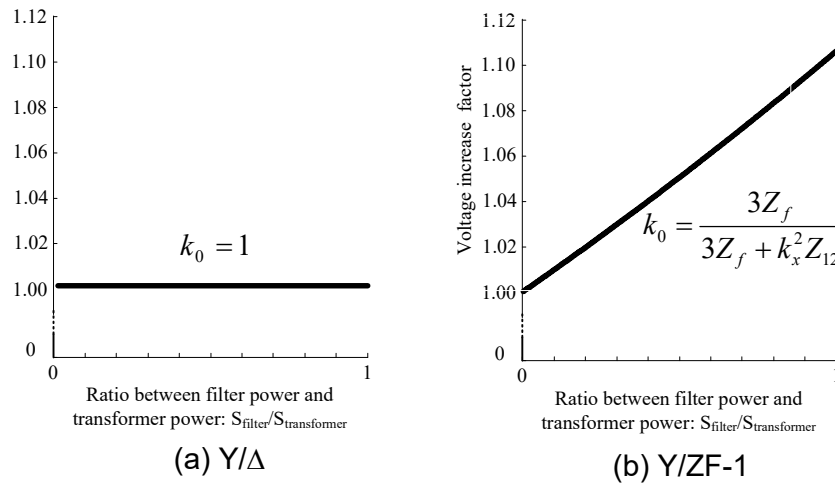


Figure 6. The curve of voltage increase factor k_0

For the Y/Δ transformers, the load voltage equals to no-load voltage minus voltage drop, the voltage drop is equal to the load current multiplied by the short-circuit impedance. So the load voltage does not depend on the filters.

For the Y/ZF-1 transformer, the magnitude of the load voltage is proportion to the voltage increase factor k_0 , when power of the filters is increased, the factor k_0 is increased. So the Y/ZF-1 transformer with filters can increase the load voltage.

4.3 The grid side harmonic current

Assume that the load harmonic currents \dot{I}_{load} are the same for the Y/ Δ and Y/ZF-1 transformers. For the purpose of suppressing the harmonic components in the Y/ZF-1/ZF-2 new converter transformer, the impedance of the common winding of this transformer is designed much smaller than the impedance of the grid side winding, namely, $Z'_2 \ll Z_1$.

Based on analyzing Table 1, the results show that:

- For the Y/ Δ transformers, the harmonic ratios $|\dot{I}_A / \dot{I}_{load}| = 1$, all the harmonic currents pass through the load and grid side windings of the Y/ Δ transformers, the filters do not have any effect on the transformers.
- Whereas, for the Y/ZF-1 transformer, the ratio $|\dot{I}_A / \dot{I}_{load}| = k_a Z'_2 / Z_{12} \approx 0$ because of $Z'_2 \ll Z_1$, so the Y/ZF-1 transformer can greatly reduce the harmonic currents on the grid side.

5 THE SIMULATION RESULTS

5.1 Simulation Model

To verify the operational characteristics of the CCT and NCT, a 12-pulse DC transmission system simulink model was designed. Figure 7 shows the simulation scheme of the 12-pulse DC transmission system. The rated values of power, voltage and current at the DC side are 100kW, 1000V and 100A, respectively.

At the rectifier side, the 400V/400V rated voltage new converter transformers are used; the controllers of the rectifiers adjust the DC current; the filters include single tuned 5th, 7th, 11th, 13th order filters. At the converter side, the 400V/400V rated voltage conventional converter transformers are used; the controllers of the converters adjust the DC voltage; the filters include single tuned 11th, 13th order filters.

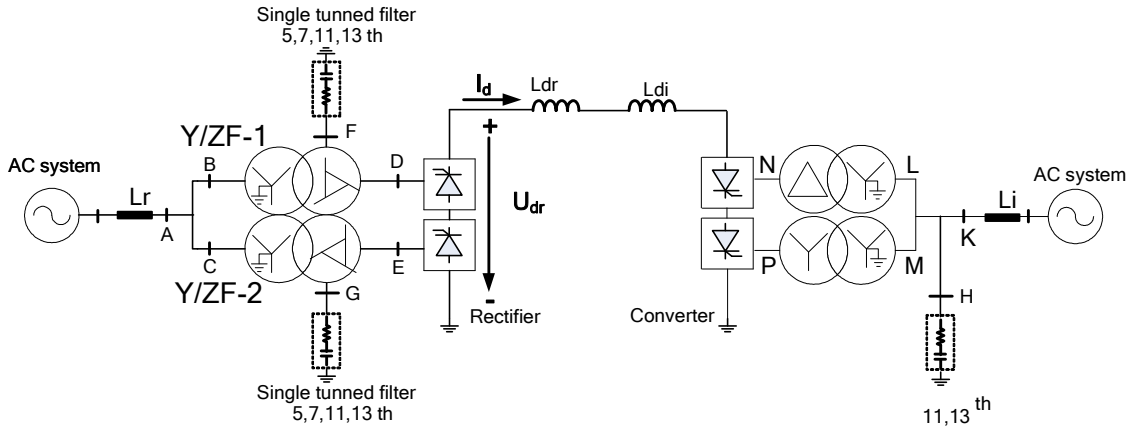


Figure 7. The simulation diagram of the DC transmission system

5.2 The Simulation Results

Table 2 shows the operational parameters of simulation results of the Y/ Δ /Y conventional converter transformers and Y/ZF-1/ZF-2 new converter transformers.

Table 2. The operational parameters of converter transformers

Parameters	Upper bridge				Lower bridge			
	Y/ Δ		Y/ZF-1		Y/Y		Y/ZF-2	
	L point	N point	B point	D point	M point	P point	C point	E point
Current-A	41.42 $\angle -133.68^0$	40.69 $\angle -105.55^0$	33.87 $\angle -25.25^0$	40.82 $\angle -30.35^0$	41.48 $\angle -133.38^0$	40.71 $\angle -135.36^0$	33.90 $\angle -25.31^0$	40.70 $\angle -60.50^0$
Voltage-V	410.10 $\angle 29.90^0$	381.36 $\angle 65.28^0$	409.41 $\angle 27.22^0$	392.14 $\angle 38.61^0$	410.10 $\angle 29.90^0$	382.76 $\angle 35.20^0$	409.41 $\angle 27.22^0$	392.03 $\angle 8.62^0$
THD I-%	26.03	26.65	5.80	30.12	26.15	26.70	5.80	30.33
Firing angle α	130.32 ⁰		43.61 ⁰		130.32 ⁰		43.61 ⁰	

Based on comparing the operational parameters of CCT and NCT of the upper bridge (the same results for the lower bridge), the results show that:

- NCT can decrease the grid side current (41.42 A for Y/ Δ and 33.87 A for Y/ZF-1).
- NCT can increase the valve side voltage (381.36 V for Y/ Δ and 392.14 V for Y/ZF-1).

Figure 8 and Figure 9 show the waves and its fast Fourier transform of the valve side currents, grid side currents of the CCT and NCT, respectively.

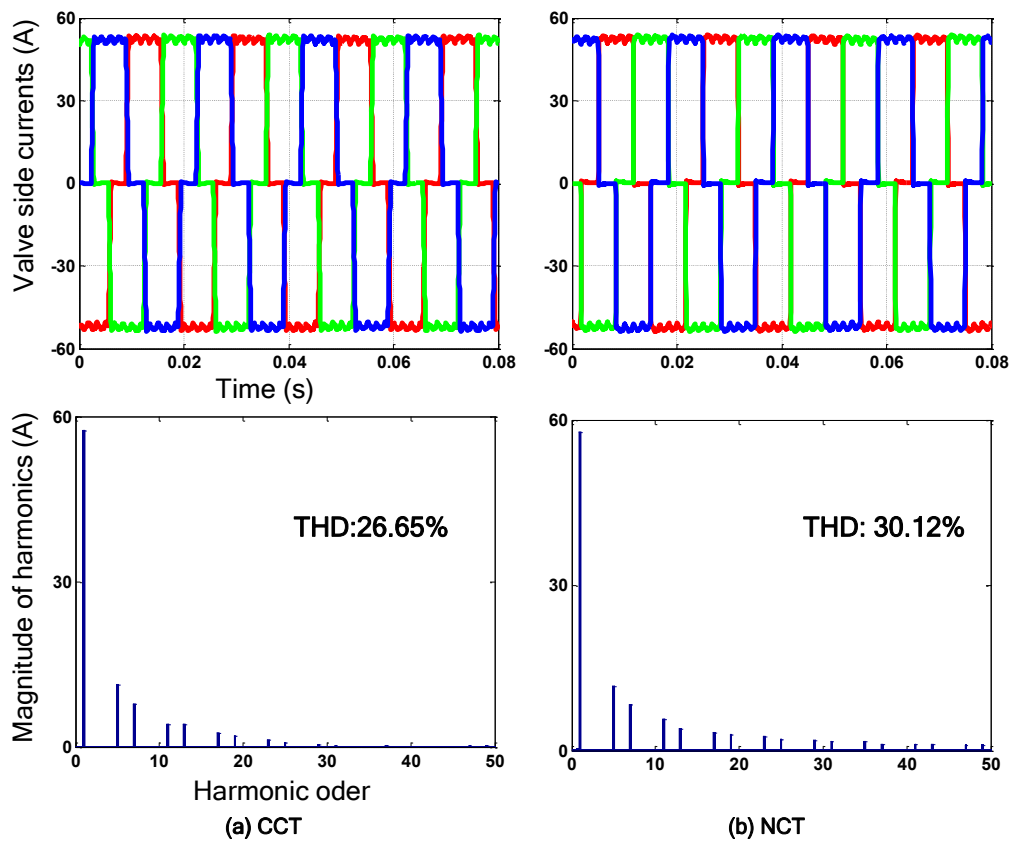


Figure 8. The valve side currents and its fast Fourier transform

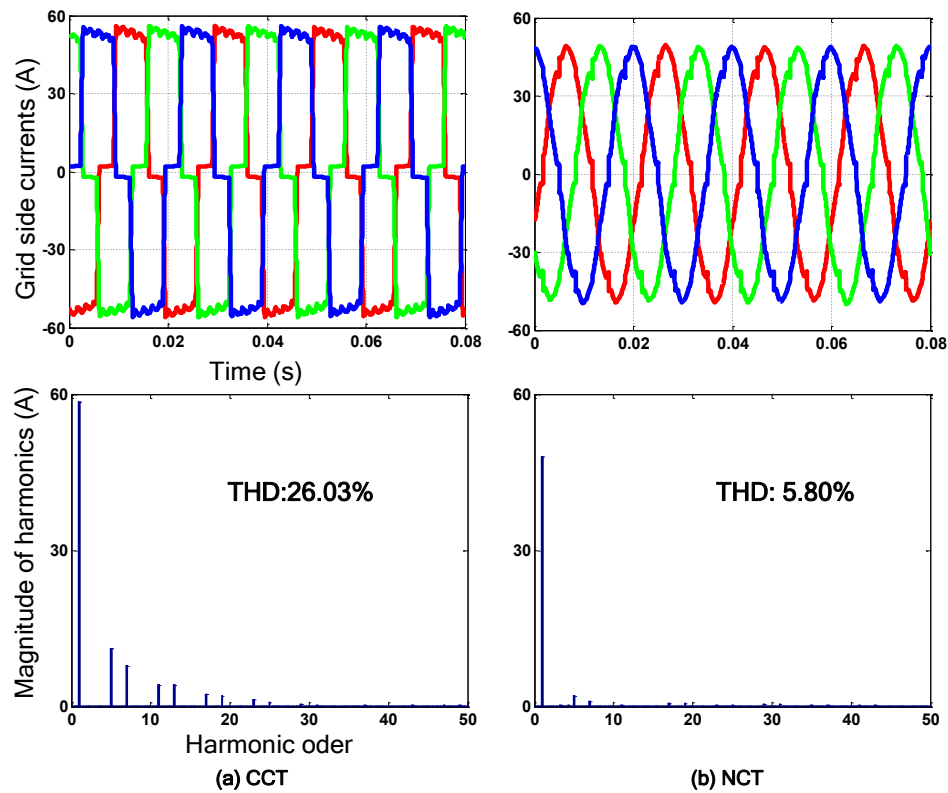


Figure 9. The grid side currents and its fast Fourier transform

Based on analyzing the Figure 8 and Figure 9, the results show that:

- The valve side currents: The valve side harmonic currents are almost the same for the CCT and NCT, the waves of load currents are much distorted; THD is approximately 26% for Y/ Δ CCT and 30% for Y/ZF-1 NCT.
- Grid side currents: The waveforms of the grid side current of CCT are much distorted; THD is 26.03%; whereas the waveforms of NCT are clearly sine-shaped, THD is 5.8%.

Note that under the grid side voltage is not changed. With NCT, the voltage of the valve side is increased; hence the delay angle of the 12 pulses converter in HVDC also is increased to maintain the DC load constant. So that is the reason why the THD of the valve side currents of NCT is higher than CCT.

6 CONCLUSIONS

This paper presents a new converter transformer which can be applied for multipulse converter. The mathematical models of the conventional converter transformer and the new converter transformer are established, which have made it possible to analyze the operational parameters of the transformers. The results show that the new converter transformer can improve the operational parameters, such as decreasing the grid side current, increasing the valve side voltage and can be greatly decrease the harmonic components in the grid side currents. The simulation results are recorded to verify the theoretical analysis

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PHÂN TÍCH ĐẶC TÍNH VẬN HÀNH CỦA MÁY BIẾN ÁP BIẾN ĐỔI MỚI

Tóm tắt. Bài báo giới thiệu một mô hình máy biến áp biến đổi mới được áp dụng trong bộ chỉnh lưu/nghịch lưu diode/SCR đa xung. So sánh đặc tính vận hành của máy biến áp biến đổi kiểu truyền thống với đặc tính vận hành của máy biến áp biến đổi kiểu mới đã được nghiên cứu. Kết quả chỉ ra rằng máy biến áp biến đổi kiểu mới không những có thể làm giảm dòng điện phía lưới, làm tăng điện áp phía tải mà còn có thể triệt tiêu đáng kể thành phần sóng hài của dòng điện phía lưới của máy biến áp. Các kết quả mô phỏng được thực hiện đã chứng minh sự chính xác của các phân tích lý thuyết.

Từ khóa. Máy biến áp biến đổi, bộ chỉnh lưu/ nghịch lưu đa xung, bộ lọc.

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