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Operational characteristics of a filtering rectifier transformer for industrial power systems

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Abstract: Many conventional methods focus on reducing the harmful impact of the poor power quality in industrial rectifier systems, but they focus more on the harmonic problems of the utility grid than they do on that of the rectifier transformer; hence, the rectifier transformer would still be adversely affected by harmonic pollution. In order to solve the problem, a filtering rectifier transformer is proposed that adopts a harmonic current drainage system that incorporates tertiary winding and tuned harmonic filters. The impedance of the tertiary winding is specially designed and the tuned harmonic filters work together to restrain the harmonic current and give a good performance in the reactive power compensation close to the harmonic source. By deducing the current relationships between the windings of the filtering rectifier transformer, the principles of the harmonic suppression and reactive compensation are elaborated. The theoretical analysis shows that if the harmonic current drainage system is out of service, the characteristics of the operation parameters of the filtering rectifier transformer are the same as those of the conventional one. While it is in service, the filtering rectifier transformer could improve the total harmonic distortion of the grid side current, decrease the grid side current, reduce the grid side power, and enhance the grid side power factor. A prototype filtering rectifier transformer was built and installed in an aluminum smelting plant. Both the simulation and the field measurement results verify the correctness of the theoretical analysis. The mathematical relationships deduced in the paper will contribute to further study of the filtering rectifier transformer on the vibration and temperature rise suppression of the windings. The project has demonstrated that the proposed filtering rectifier transformer has promising prospects in various industrial power applications.

Key words: Reactive compensation, harmonic suppression, operational parameters, rectifier system

1. Introduction

With the development of industry, harmonic distortion is increasing in industrial power systems due to the constant growth of nonlinear loads such as rectifiers, inverters, or cycloconverters. These devices are likely to introduce significant harmonic pollution into the power system, which may result in equipment malfunction and premature equipment failure, communication interference, or even the malfunction of protective devices. In addition, the harmonic distortion limits are being enforced by the utility grid, and so large industrial facilities whose loads are primarily rectifiers face severe penalties due to their poor power factors [1–5]. Thus, harmonic suppression and reactive power support are becoming important subjects among electric power engineers these days. To tackle the problems, some of the methods are installing passive filters consisting of tuned inductor-capacitor filters and high-pass filters or active power filters [6–9]; multipulse conversion using phase-shifting

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transformers is also an available solution [10,11]. However, these conventional technologies have been used to prevent harmonic load currents from flowing into the utility grid, and so the harmfulness of the harmonic is still serious in industrial rectifier systems. Specifically, the rectifier transformer is directly connected to the nonlinear devices such that it would be adversely affected by harmonics and the reactive power, which can cause problems such as additional harmonic loss, heat, vibration, and noise in the transformer. Meanwhile, more margins should be considered during the design of rectifier transformers. Herein, the harmonic suppression and power factor compensation at the grid side are of no benefit to the electrical facilities.

It is necessary to find a way of providing harmonic suppression and reactive compensation close to the harmonic resource; hence, a filtering rectifier transformer is proposed in this paper. Aside from the basic function that transfers electrical energy, the filtering rectifier transformer can participate in harmonic current elimination, and its operational parameters are also improved due to the reactive power compensation in the transformer. The special structure of the filtering rectifier transformer is introduced in Section 2. The principles of the harmonic current suppression and reactive compensation are then described in Section 3. In Section 4, a filtering rectifier transformer is developed for an 11-MV aluminum smelting plant, and its simulation and the experimental results are presented to validate the theoretical analysis.

2. Wiring scheme

A conventional wye/delta rectifier transformer that is commonly applied in rectifier systems is shown in Figure 1, where it is clear that the filters are placed at the transformer's primary side. This may cause a problem where all of the reactive power and harmonics from the rectifiers would pass through the rectifier transformer, so that they must decrease the power factor, increase the harmonic loss, and then lead to the local overheating in the oil tank and metal parts of the transformer, and there will be the noise in the core generated by the harmonic flux.

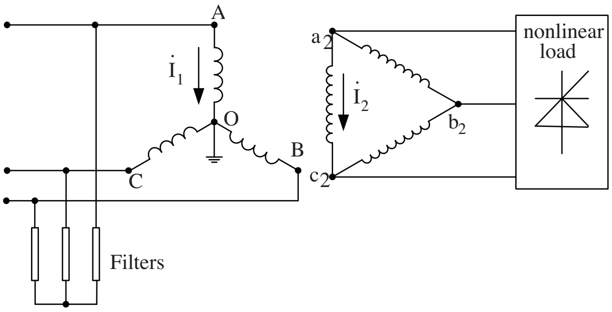


Figure 1. The winding connection scheme of the conventional rectifier transformer and its filters.

Figure 2 shows the winding connection scheme of the filtering rectifier transformer. It can be divided into 2 parts: the first part is composed of the primary and the secondary winding, which transfers electrical energy like a conventional wye/delta transformer does, and the other is a harmonic current drainage system composed of the tertiary winding and the harmonic filters, which supplies a low-impedance path for harmonic flow and furnishes the reactive power to the system.

The single-phase equivalent circuit of the filtering rectifier transformer is shown in Figure 3. According to Figure 3, we see that $\dot{U}_1$, $\dot{U}_2'$, and $\dot{U}_3'$ are the phasor voltages of the primary, the secondary, and the tertiary windings, respectively; $\dot{I}_1$, $\dot{I}_2'$, and $\dot{I}_3'$ are the phasor currents of the primary, the secondary, and the tertiary windings, respectively; and Z_1, Z_2', and Z_3' are the impedances of the primary, the secondary, and the tertiary windings, respectively. All of the variables are referred to the primary side in Figure 3.

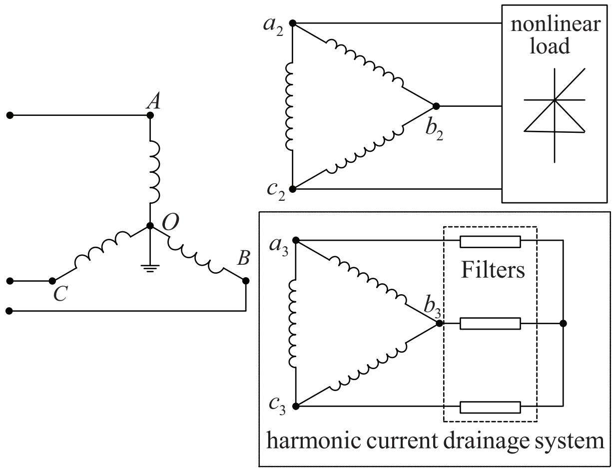


Figure 2. The winding connection scheme of the filtering rectifier transformer.

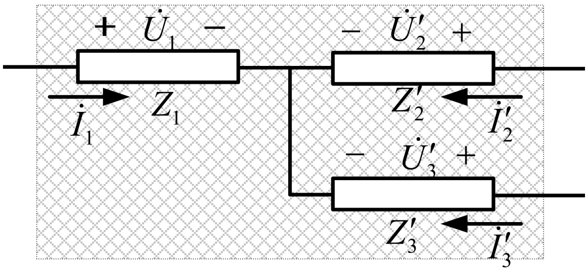


Figure 3. The equivalent circuit of the filtering rectifier transformer.

Based on the fundamental theory of the multiwinding transformer, and ignoring the excitation current, the basic equations of the filtering rectifier transformer are given by:

$$\dot{I}_1 = -\dot{I}'_2 - \dot{I}'_3, \tag{1}$$

$$\dot{U}_1 - \dot{U}_2' = -\dot{I}'_2 Z_{12} - \dot{I}'_3 Z_1, \tag{2}$$

$$\dot{U}_1 - \dot{U}_3' = -\dot{I}'_3 Z_{13} - \dot{I}'_2 Z_1, \tag{3}$$

where Z_{12} represents the short circuit impedance between the primary and secondary windings, and Z_{13} represents the short circuit impedance between the primary and tertiary windings. Moreover, we can get $Z_{12} = Z_1 + Z_2'$ and $Z_{13} = Z_1 + Z_3'$.

3. Theoretical analysis

3.1. Principle of the harmonic current suppression

In a rectifier system, nonlinear loads such as rectifiers can be regarded as the harmonic source and feed harmonic currents into the supply network. Figure 4 depicts the principle diagram of the harmonic current for the filtering rectifier transformer, where the secondary winding is connected to a harmonic current-producing load. In Figure 4, $Z_f'^{(h)}$ indicates the harmonic impedance of the filters and $\dot{I}_1^{(h)}$, $\dot{I}_2'^{(h)}$, and $\dot{I}_3'^{(h)}$ indicate the harmonic currents of the primary winding, the secondary winding, and the tertiary winding respectively, where h is the harmonic order number, namely $h =$ 5, 7, 11,13,...

Under the assumption that the impedance of the supply source is negligible, the harmonic voltage of the primary winding shown in Figure 4 becomes zero:

$$\dot{U}_1^{(h)} = 0. \tag{4}$$

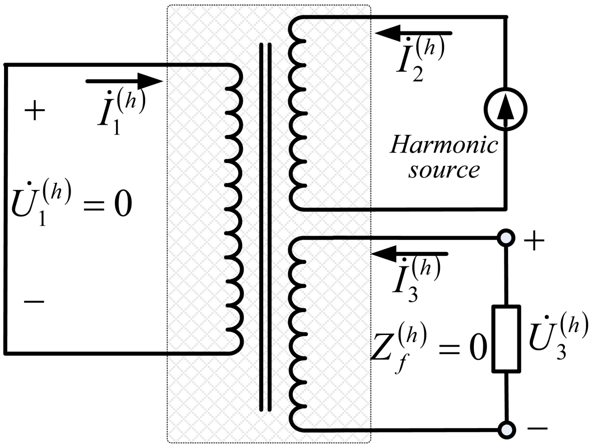


Figure 4. The principle diagram of the harmonic current for the filtering rectifier transformer.

The relationship between the harmonic voltage and the harmonic current of the tertiary winding is:

$$\dot{U}_3'^{(h)} = -Z_f'^{(h)} \dot{I}_3'^{(h)}. \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3) yields the following expression:

$$\dot{I}_3'^{(h)} = -\frac{Z_1^{(h)}}{Z_{13}^{(h)} + Z_f'^{(h)}} \dot{I}_2'^{(h)}. \tag{6}$$

By substituting Eq. (6) into Eq. (1), the relationship between the harmonic current of the secondary and that of the primary can be obtained:

$$\dot{I}_1^{(h)} = -\frac{Z_f'^{(h)} + Z_3'^{(h)}}{Z_1^{(h)} + Z_f'^{(h)} + Z_3'^{(h)}} \dot{I}_2'^{(h)}. \tag{7}$$

To reflect the effect of the harmonic suppression of the filtering rectifier transformer, a harmonic suppression factor $C^{(h)}$ is defined as:

$$C^{(h)} = \frac{Z_f'^{(h)} + Z_3'^{(h)}}{Z_1^{(h)} + Z_f'^{(h)} + Z_3'^{(h)}}. \tag{8}$$

Hence, the relationships of the harmonic currents between the windings of the filtering rectifier transformer can be expressed as:

$$\begin{cases} \dot{I}_1^{(h)} = -C^{(h)} \dot{I}_2'^{(h)} \\ \dot{I}_3'^{(h)} = \left(C^{(h)} - 1\right) \dot{I}_2'^{(h)} \end{cases}. \tag{9}$$

In the conventional rectifier transformer, according to Figure 1, the harmonic current relationship between the primary and secondary is not subject to the filters and can be expressed as:

$$\dot{I}_1^{(h)} = -\dot{I}_2'^{(h)}. \tag{10}$$

As for the filtering rectifier transformer, if the filters are not used, then $Z_f = \infty$, according to Eq. (8) $C^{(h)} = 1$, and so $\dot{I}_1^{(h)} = -\dot{I}_2'^{(h)}$ and $\dot{I}_3'^{(h)} = 0$; namely, the harmonic currents entirely flow through the primary winding of the transformer. Hence, in this situation, the harmonic current drainage system is out of service, so the filtering rectifier transformer operates as a conventional one, and the equivalent circuit of the harmonic current without filters can be shown as in Figure 5.

If the filters are used, then $Z_f^{(h)} \approx 0$ and the ratio $C^{(h)}$ can be written as:

$$C^{(h)} \approx \frac{Z_3'^{(h)}}{Z_1^{(h)} + Z_3'^{(h)}}. \tag{11}$$

In order to suppress the harmonic currents, the impedance of the tertiary winding Z_3' should be designed to be far less than the impedance of the primary winding Z_1, namely $Z_3' << Z_1$, so $Z_3'^{(h)} << Z_1^{(h)}$, the harmonic suppression factor $C^{(h)} \approx 0$. According to Eq. (9), the relationships of the harmonic currents between the windings can be obtained: $\dot{I}_3'^{(h)} \approx -\dot{I}_2'^{(h)}$ and $\dot{I}_1^{(h)} \approx 0$; namely, the harmonic current is short-circuited by the harmonic current drainage system, and thus it has little effect on the primary winding. Herein, through collaboration with a harmonic current drainage system, the filtering rectifier transformer can mitigate the harmonic currents in the transformer.

Figure 6 shows the equivalent circuit of the harmonic currents for the filtering rectifier transformer using the filters.

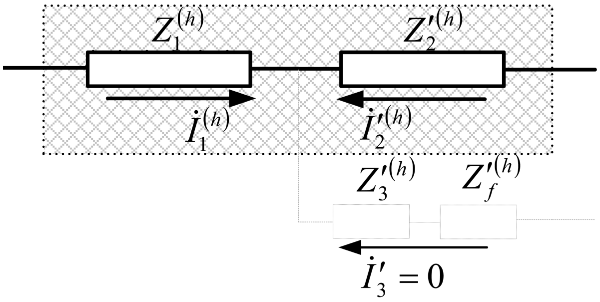


Figure 5. The equivalent circuit of the harmonic current for the filtering rectifier transformer without filters.

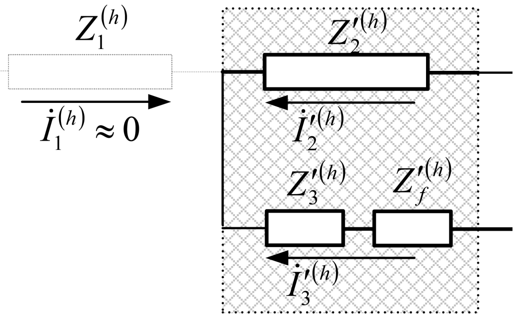


Figure 6. The equivalent circuit of the harmonic current for the filtering rectifier transformer with filters.

3.2. Principle of the reactive compensation

Under the fundamental frequency, the impedance of the filters can be regarded as a capacitive reactance, and so the filtering rectifier transformer can provide reactive power. Figure 7 shows the principal diagram of the reactive compensation for the filtering rectifier transformer.

The voltage of the tertiary winding can be obtained as:

$$\dot{U}_3' = -Z_f' \cdot \dot{I}_3', \tag{12}$$

in which Z_f is the fundamental impedance of the filters. The substituting of Eq. (12) into Eq. (3) gives:

$$\dot{U}_1 = -\dot{I}'_2 Z_1 - \dot{I}'_3 \left(Z_{13} + Z_f'\right), \tag{13}$$

and then substituting Eq. (1) into Eq. (13) yields:

$$\dot{I}_1 = \frac{\dot{U}_1}{Z_f' + Z_{13}} - \frac{Z_f' + Z_3'}{Z_f' + Z_{13}} \dot{I}'_2. \tag{14}$$

Because the winding impedances and the short-circuit impedances of the transformer are much less than the fundamental impedance of the filters, namely $Z'_f >> Z_{13}, Z'_f >> Z'_3$, Eq. (14) can be written as:

$$\dot{I}_1 = \frac{\dot{U}_1}{Z'_f} - \dot{I}'_2. \tag{15}$$

By substituting $Z'_f = -jX'_f$ into Eq. (15), the current relationship between the primary winding and the secondary winding can be obtained:

$$\dot{I}_1 = j\frac{\dot{U}_1}{X'_f} - \dot{I}'_2. \tag{16}$$

Based on Eq. (16), the phasor diagram of the voltages and currents for the filtering rectifier transformer is shown in Figure 8.

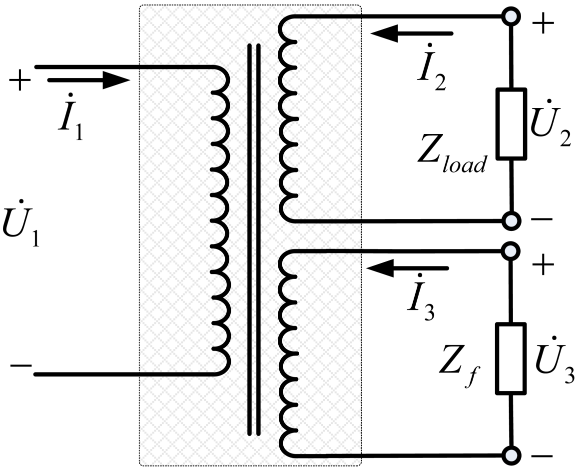


Figure 7. The principal diagram of the reactive compensation for the filtering rectifier transformer.

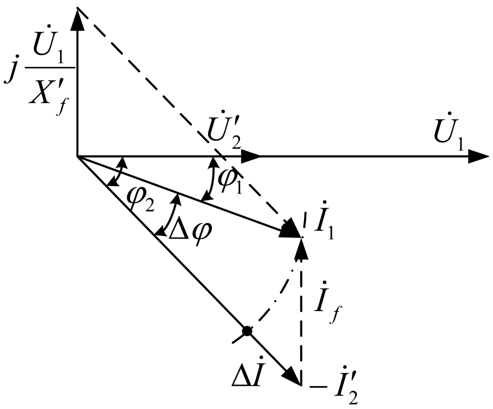


Figure 8. Phasor diagram of the winding voltages and currents for the filtering rectifier transformer.

In the conventional rectifier transformer, the primary current is not affected by the filters, so the active power could not be compensated in the transformer, and the current relationship between the primary and secondary is:

$$\dot{I}_1 = -\dot{I}'_2. \tag{17}$$

As for the filtering rectifier transformer, if the filters are not used, then $Z_f = \infty$. Eq. (16) can be expressed by $\dot{I}_1 = -\dot{I}'_2$; namely, the magnitude of the primary current and the secondary current are equal, and this is the same as the conventional transformer.

If the filters are used, as can be seen from Figure 8, due to the existence of the compensating current that leads the grid side voltage by 90°, the magnitude of the grid side current is decreased by ΔI, and the angle of the grid side current is also decreased by $\Delta\varphi$. Hence, the filtering rectifier transformer can compensate for the reactive power and improve its operational parameters, such as reducing the grid side power, enhancing the grid side power factor, and decreasing the grid side current by employing the harmonic current drainage system.

4. Experiments and simulations

Based on the principles of the filtering rectifier transformer presented above, an 11-MVA filtering rectifier transformer was designed, manufactured, and installed in an aluminum smelting plant. The picture of the filtering rectifier transformer is shown in Figure 9.

Figure 9. Picture of the filtering rectifier transformer.

To verify the performance of the filtering rectifier transformer for the plant, a simulation system model was established using MATLAB/Simulink, and, correspondingly, field tests were carried out and real-time power analyzer equipment (HIOKI-9624) was used for the online data acquisition. Figure 10 shows the simplified diagram of the filtering rectifier system.

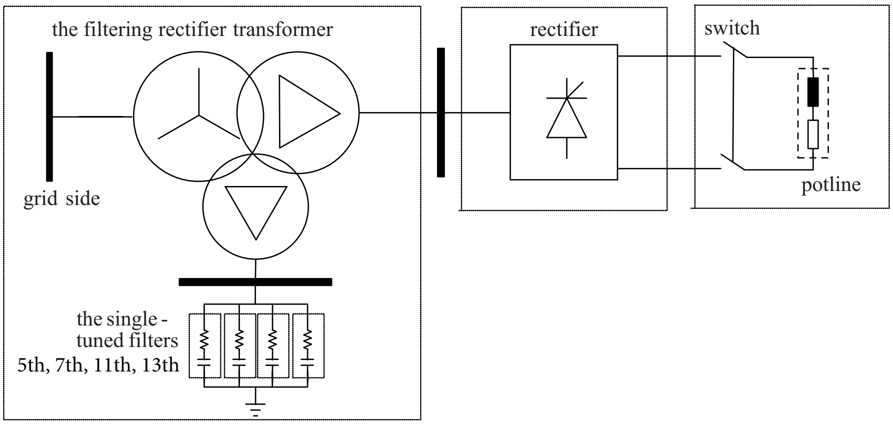


Figure 10. Schematic of the proposed filtering rectifier system.

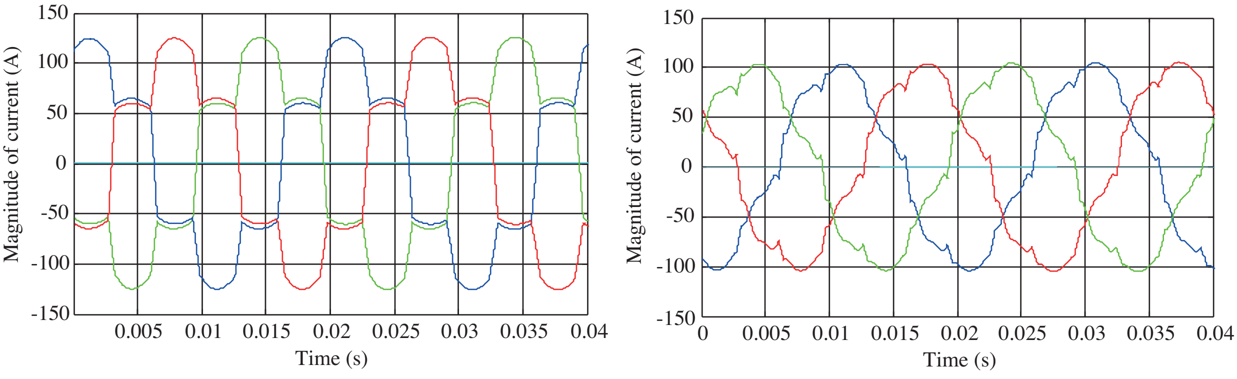
The parameters of the filtering rectifier transformer were as follows: rated capacity S = 11 MVA and rated voltages = 35 kV/ 210 V/ 6 kV. The system frequency was 50 Hz. The filters consisted of 4 banks tuned to the rectifier's characteristic harmonics, namely the 5th, 7th, 11th, and 13th harmonics, whose total capacity was 1.28 MVA. The potline load parameters were: DC voltage = 245 V and DC current = 16 kA.

According to the above analysis, without filters, the operational characteristic of the proposed filtering rectifier transformer is similar to the conventional transformers, with or without filters. In order to investigate the effect of the harmonic suppression and reactive compensation of the proposed rectifier transformer, it is necessary to compare the performance of the filtering rectifier transformer under 2 conditions, which are filters in service and not in service.

4.1. Analysis of the grid side harmonic currents

Figure 11 shows the simulation waveforms of the primary currents for the filtering rectifier transformer, where Figure 11a demonstrates the case without filters and Figure 11b demonstrates the case with filters. Figure 12 shows the experimental waveforms.

Figures 11a, 11b, 12a, and 12b obviously show that without filters the primary currents have serious harmonic distortions. After using the filters, namely the harmonic current drainage system that was in service, the waveforms of the primary currents were improved to be similar to a sinusoidal wave.



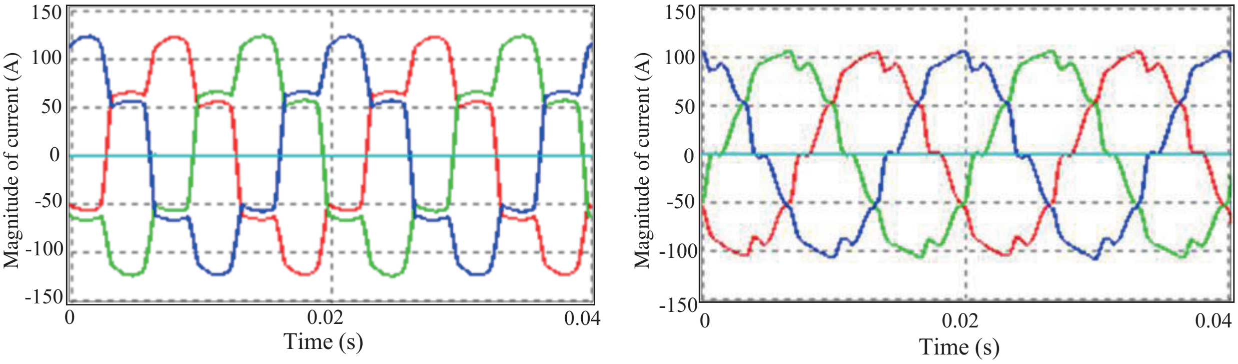
(a) No filters

(b) With filters

Figure 11. Simulation waveforms of the primary currents: a) without filters, b) with filters.

Figure 13 shows the simulation harmonic components of the primary currents extracted by the fast Fourier transform, where Figure 13a demonstrates the case without filters and Figure 13b demonstrates the case with filters. Figure 14 shows the experimental results.

Based on Figures 13a, 13b, 14a, and 14b, the results show that the total harmonic distortion (THD) of the simulation was reduced from 28.4% (without filters) to 9.75% (with filters) and that of the experience was reduced from 25.26% (without filters) to 8.54% (with filters).



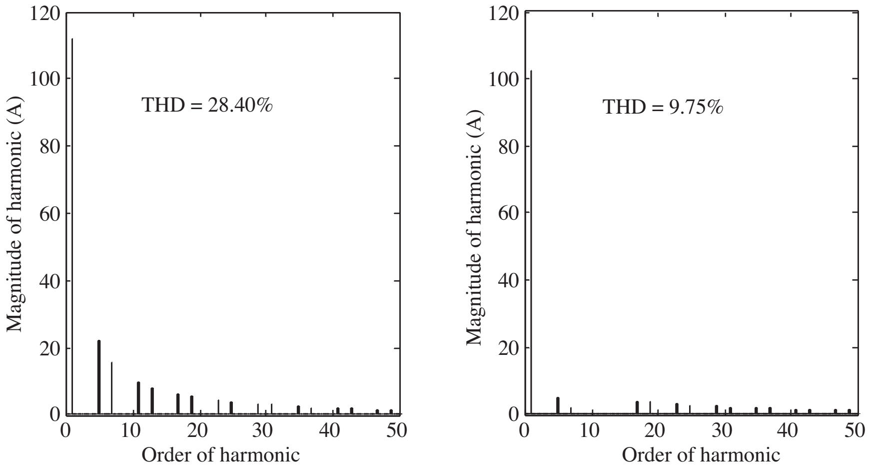
(a) No filters

(b) With filters

Figure 12. Experimental waveforms of the primary currents: a) without filters, b) with filters.

Table 1. The values of the harmonic suppression factor $C^{(h)}$ for the filtering rectifier transformer.

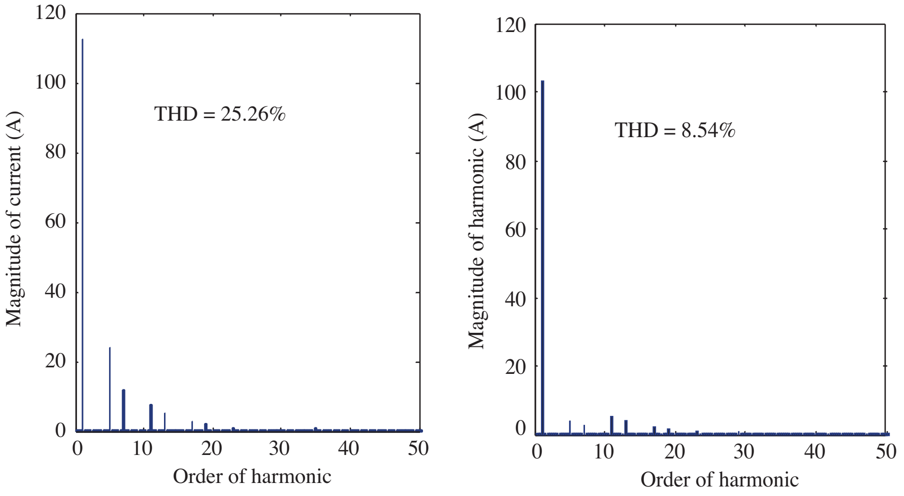
$C^{(h)}$	Calculation	Simulation	Experiment
5	0.0356	0.2323	0.2395
7	0.0357	0.1258	0.1785
11	0.0356	0.0445	0.0607
13	0.0361	0.0522	0.1463



(a) No filters

(b) With filters

Figure 13. Simulation harmonic spectrums of the primary currents: a) without filters, b) with filters.



(a) No filters

(b) With filters

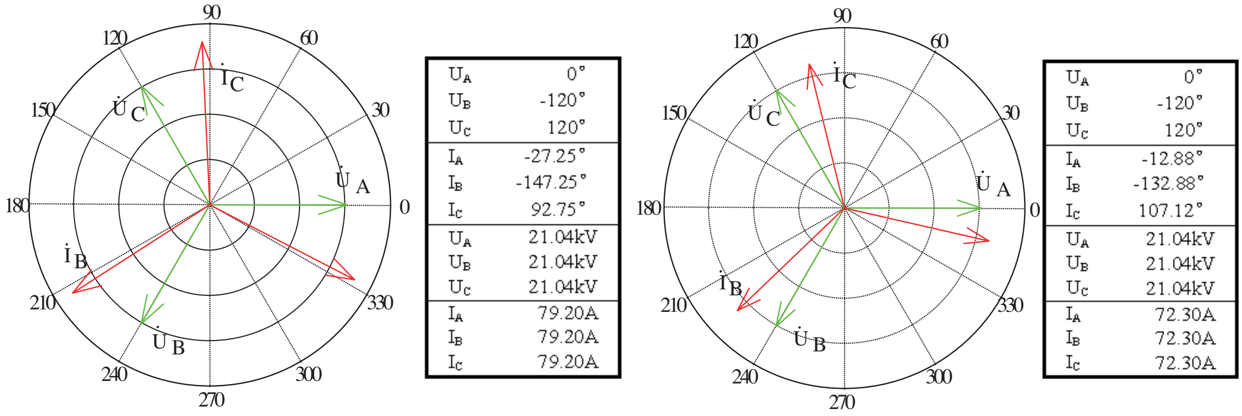
Figure 14. Experimental harmonic spectrums of the primary currents: a) without filters, b) with filters.

The calculation simulation and experimental values of the harmonic suppression factor $C^{(h)}$ with filters are shown in Table 1. As can be seen from Figures 13 and 14 and Table 1, once the impedances of the windings are appropriately designed as mentioned above, the harmonic distortions are alleviated greatly and the harmonic suppression factors of the characteristic harmonics are very tiny; namely, the domain harmonic currents in the primary winding are almost eliminated. This means that the harmonic suppression effect is obvious, and the harmonic currents are hard to get into the primary winding but are restrained in the harmonic current drainage system.

It should be noted that because of the existence of the source impedance during the experiment and the simulation, the values of $C^{(h)}$ of the simulation and the experiment were both higher than that of the theoretical calculation.

4.2. Analysis of the reactive compensation

Figure 15 shows the vector diagram of the primary voltages and currents for the simulation results, where Figure 15a demonstrates the case without filters and Figure 15b demonstrates the case with filters. Figure 16 shows the experimental results.



U_A	0°
U_B	-120°
U_C	120°
I_A	-27.25°
I_B	-147.25°
I_C	92.75°
U_A	21.04kV
U_B	21.04kV
U_C	21.04kV
I_A	79.20A
I_B	79.20A
I_C	79.20A

U_A	0°
U_B	-120°
U_C	120°
I_A	-12.88°
I_B	-132.88°
I_C	107.12°
U_A	21.04kV
U_B	21.04kV
U_C	21.04kV
I_A	72.30A
I_B	72.30A
I_C	72.30A

(a) No filters

(b) With filters

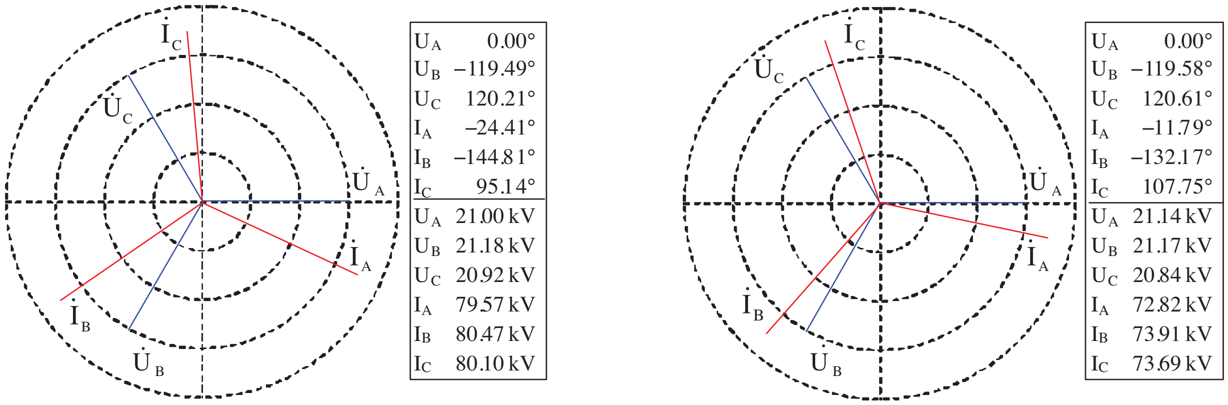
Figure 15. Simulation vector diagrams of the primary voltages and currents (the voltages and currents are root mean square [RMS] values): a) without filters, b) with filters.

Figures 15a, 15b, 16a, and 16b demonstrate that the phase angles between the primary voltages and the primary currents were reduced (from 27.25° to 12.88° in the simulation and from 24.41° to 11.79° in the experiment, respectively), and the magnitudes of the primary currents were decreased (from 79.2 A to 72.3 A in the simulation and from 79.57 A to 72.82 A in the experiment, respectively).

Table 2 shows the values of the operational parameters at the primary. It obviously illustrates that with the filters, the primary power factor was greatly enhanced (from 0.89 to 0.97 in the simulation and from 0.88 to 0.97 in the experiment), the reactive power was reduced (from 2.29 MVar to 1.02 MVar in the simulation and from 2.48 MVar to 1.10 MVar in the experiment), and the apparent power of the grid side was decreased (from 5.05 MVA to 4.56 MVA in the simulation and from 5.22 MVA to 4.66 MVA in the experiment).

Table 2. The operational parameters at the primary of the filtering rectifier transformer.

Parameters	Experiment results		Simulation results	
	Without filters	With filters	Without filters	With filters
P(MW)	4.59	4.53	4.44	4.45
Q(MVar)	2.48	1.10	2.29	1.02
S(MVA)	5.22	4.66	5.00	4.56
pf	0.88	0.97	0.89	0.97



(a) (b)

Figure 16. Experimental vector diagrams of the primary voltages and currents (the voltages and currents are RMS values): a) without filters, b) with filters.

5. Conclusion

The filtering rectifier transformer provides a simplistic and effective technology to address the problem of harmonic pollution and improve the power quality in the industrial rectifying application, and it especially offers a number of useful benefits in the rectifier transformer itself.

Both the simulation and experimental results have verified the correctness of the theoretical analysis of this paper. As an integral part of the filtering rectifier transformer, the dedicated harmonic filters are required to be installed at the transformer tertiary winding to improve the operational parameters, so the design and manufacturing of this transformer would be more complex. However, the advantages of the filtering rectifier transformer were obvious: on the one hand, using its harmonic current drainage system, the filtering rectifier transformer itself was involved in the harmonic currents' elimination in the primary winding, which has the potential to mitigate some unfavorable consequences brought by the harmonic currents, like heat, vibration, and noise in the transformer. On the other hand, the filtering rectifier transformer can compensate for the reactive power, which will improve the operational parameters at the primary, such as reducing the primary currents, enhancing the power factor of the system, and decreasing the electrical power loss in the transformer, and this, in turn, will increase the utilization rate of the power equipment.

This study may provide a theoretical basis for following the research of the filtering rectifier transformer on energy conservation, noise reduction, and so on. From the above, the proposed filtering rectifier transformer can be applied in various power rectifying applications, such as an aluminum smelting plant, steel manufacturing facility, copper electrowinning, and electric arc furnace systems.

Acknowledgments

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