A NEW 12-PULSE INDUSTRY RECTIFIER SYSTEM BASED ON INDUCTIVE FILTERING TECHNOLOGY

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High loss and low efficiency of the system and large noise of the transformer are always the difficult problems for the conventional industry rectifier systems. Aiming to solving these crucial problems, a new energy saving rectifier transformer and its 12-pulse DC(direct current) power supply system based on inductive filtering technology are presented. Firstly, the new four-winding transformer and its twelve-pulse rectifier systems are introduced. Then, the 5th- and 7th-order characteristic harmonics suppression is given. In addition, the harmonic magnetic flux suppressing mechanism of transformer core, inductive filtering method and synthesis energy saving of the new industry rectifier system are analyzed. Finally, the simulation results show the new industry rectifier system has good filtering and reactive power compensating performances, and high operating efficiency.

Keywords: DC power supply system; inductive filtering method; harmonic magnetic flux; harmonic suppression; energy saving

1. Introduction

High power rectifiers with power semiconductors have 50 years of development. The power semiconductors, such as power diode and thyristor, are widely used in metallurgy and electro-chemical industry[1-5], which establishes the capability to dissipate the losses appearing, rectifier operations, control mode and efficiency, and so on. However, a large number of harmonics are generated on the process of AC to DC energy conversion. It increases harmonic currents content of the power grid and reduces the power quality of the power conversion systems.

How to effectively suppress harmonics and their harmful effects on converter transformer is a problem that should be considered carefully. Now, the problem is solved by the widely use of passive filters and active filters [6-10]. The passive power filters at the ac gird side can absorb the harmonic currents and so reduce the harmonic currents flowing into the power system. They have the advantages of a simple structure, low prices and mature technology. However, due to the fact the passive filters are parallel with the power gird, the filtering

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characteristics are sensitive to the variation of power network impedance, and the series/parallel resonance between the system and filters may occur. The active power filters have the advantages of an automatic compensation, no risk of resonances, and ability to compensate harmonics without concerning on the reactive power, etc. Nevertheless, their application is restricted by high cost, low capacity, and difficulty to be used in high-voltage grids. In addition, multi-pulse rectifier is adopted in large current rectifiers [11-13]. However, there are some serious problems, such as high loss and lower efficiency of the system and larger noise of the transformer.

For all the reasons mentioned above, an energy saving 12-pulse rectifier system based on new rectifier transformer and inductive filtering technology is presented. References [14-17] show the differences between the conventional filtering (passive power filtering and active power filtering) method and the inductive filtering method. In this paper , the key techniques of inductive filtering technology, transformer core harmonic magnetic flux suppressing mechanism, and 5th- and 7th-order characteristic harmonics suppression are analyzed and finally, the simulation results and conclusion are given.

2. The new rectifier transformer and its rectifier schemes

Fig.1 shows the topology of the energy saving 12-pulse industry rectifier system based on the new rectifier transformer. Different from the conventional transformer, the impedance of the new transformer's filtering winding is close to zero, and that is the key to realize the inductive filtering technology. Based on the actual requirement, the upper and lower bridges can operate on series or parallel connections of the 12-pulse rectifier. For the high-power rectifier system, the DC current may reach to tens or even hundreds of thousands ampere. Therefore, the load winding's co-phase counter parallel wiring is adopted.

The configuration of the main transformer is Y/Y/Δ/Δ as shown in Fig.2. The load windings are connected to two 6-pulse bridge constituting a 12-pulse rectifier, which can suppress the $6n\pm1(n=1,3,5\ldots\ldots)$ order harmonic currents. The filtering winding is connected to filters, which can suppress 11-th and 13-th harmonic currents and compensate reactive power.

The thyristor phase-controlled rectifier has been the most commonly used rectifier configuration for high power converter applications due to its simplicity, reliability, and high efficiency. The current and voltage for the rectifiers are achieved by controlling the triggering angle of the thyristor. Moreover, the input voltage of the main transformer is adjusted by the voltage regulating transformer with on-load tap changers (OLTC).

According to the Fig.1, the voltage phase relationship of the primary and second winding for I and II bridges can be obtained as follows: 1) The voltage and current phase is the same for I bridge; 2) The second winding voltage phase of I bridge leads II bridges' by 30°; 3) For II bridge, the voltage and current phase of the second winding lag the primary winding by 30°.

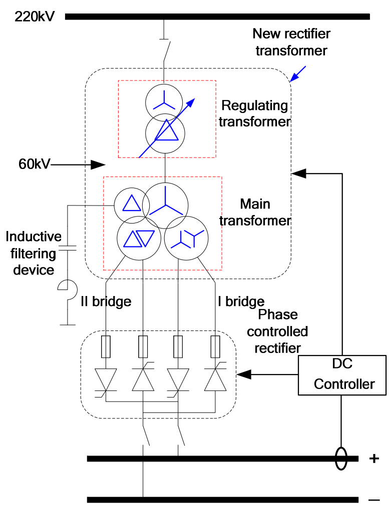


Fig.1. Topology of new 12-pulse industry rectifier system

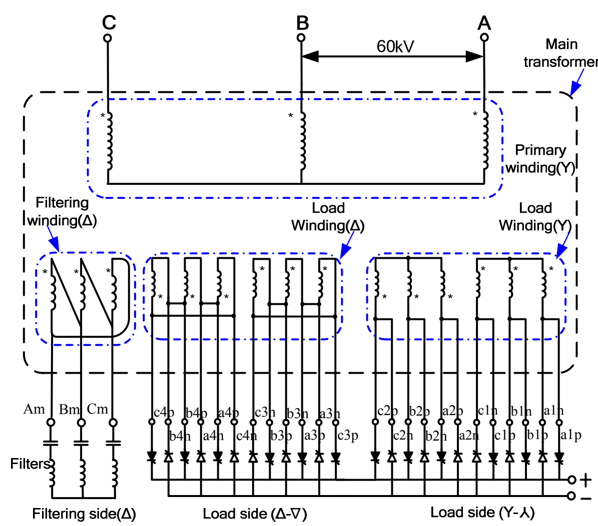


Fig.2: The winding connection scheme of the main transformer

Let's assume that the midpoint between the positive and negative half wave as the time zero, the line current equation for the A-phase current in I bridge is as follows:

$$i_{\mathrm{I}a}=\frac{2\sqrt{3}}{\pi}I_d\left(\sin\omega t-\frac{1}{5}\sin 5\omega t-\frac{1}{7}\sin 7\omega t+\frac{1}{11}\sin 11\omega t+\frac{1}{13}\sin 13\omega t-......\right) \quad (1)$$

The line current equation of II bridge can be obtained:

$$i_{\mathrm{II}a}=\frac{2\sqrt{3}}{\pi}I_d\begin{bmatrix}\sin\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{5}\sin 5\left(\omega t-\frac{\pi}{6}\right)-\frac{1}{7}\sin 7\left(\omega t-\frac{\pi}{6}\right)\\ +\frac{1}{11}\sin 11\left(\omega t-\frac{\pi}{6}\right)+\frac{1}{13}\sin 13\left(\omega t-\frac{\pi}{6}\right)-......\end{bmatrix} \quad (2)$$

For the Y/Δ1 transformer, the following can be obtained: 1) For the fundamental and positive sequence harmonic current, the line-current phase of the primary winding leads the secondary winding by 30°; 2) For the negative sequence harmonic current, the line-current phase of the primary winding lags the secondary winding by 30°. Then, the line current of the primary winding induced by the current in II bridge:

$$\begin{aligned}i_{\mathrm{IIA}}&=\frac{2\sqrt{3}}{\pi}I_d[\sin\omega t-\frac{1}{5}\sin(5\omega t+\pi)-\frac{1}{7}\sin(7\omega t+\pi)\\&\quad+\frac{1}{11}\sin(11\omega t+2\pi)+\frac{1}{13}\sin 13\omega t-......]\\&=\frac{2\sqrt{3}}{\pi}I_d(\sin\omega t+\frac{1}{5}\sin 5\omega t+\frac{1}{7}\sin 7\omega t\\&\quad+\frac{1}{11}\sin 11\omega t+\frac{1}{13}\sin 13\omega t-......)\end{aligned} \quad (3)$$

According to (1) and (3), the line current of the primary winding is□

$$\begin{aligned}i_a&=i_{\mathrm{IA}}+i_{\mathrm{IIA}}\\&=\frac{4\sqrt{3}}{\pi}I_d(\sin\omega t+\frac{1}{11}\sin 11\omega t+\frac{1}{13}\sin 13\omega t-......)\end{aligned} \quad (4)$$

As shown in (4), the 6n±1 (n=1, 3, 5……) order harmonic currents are suppressed in the ac gird side.

3. Theoretical Analyses

3.1 Suppressing Mechanism of Transformer Core Harmonic Magnetic Flux

Fig. 3 shows the flow path of winding's harmonic currents and core's harmonic magnetic flux of the main transformer. When the primary winding, secondary-Y winding and secondary-Δ winding are opened, N2i2n + N3i3n of the harmonic magnetic motive force in secondary Y/Δ winding will be induced by the harmonic current i2n and i3n, which induces the alternate harmonic magnetic flux Φn in the transformer core. Based on the electromagnetic induction principle, the electromotive force e1n, e2n, e3n, e4n of the four windings will be induced by Φn. Then, the e1n of the primary winding will induces the harmonic current i1n, which means that harmonic currents of the valve side are transmitted to the grid side by the transformer core.

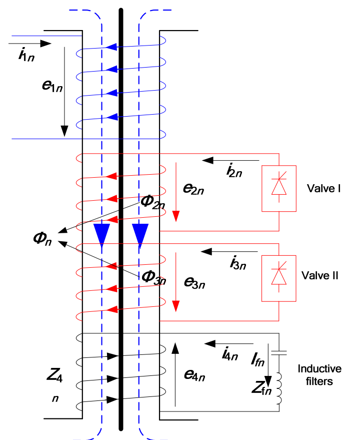


Fig.3. Flow path of harmonic magnetic flux in transformer core

The harmonic magnetic flux of the transformer core can be expressed as follows:

$$\begin{aligned}\phi_{2n} &= \Phi_{2mn}\cos(n\omega t)\\ \phi_{3n} &= \Phi_{3mn}\cos(n\omega t)\\ \phi_n &= \phi_{2n}+\phi_{3n} = \Phi_{mn}\cos(n\omega t)\end{aligned} \tag{5}$$

where: Φ_{mn} is the amplitude of the harmonic magnetic flux of the transformer core.

The harmonic electromotive force e_{4n} which is induced by the main harmonic magnetic flux Φn can be obtained by:

$$e_{4n} = -N_4\frac{d\phi_n}{dt} = n\omega N_4\Phi_{mn}\sin(n\omega t) \tag{6}$$

The equation (6) can be expressed by:

$$e_{4n} = i_{fn}(z_{4n}+z_{fn}) \tag{7}$$

where : z_{4n} and z_{fn} respectively are the harmonic equivalent impedance of the filtering winding and filters.

As mentioned above, the value of harmonic current i_{4n} is finite because it is induced by harmonic current i_{2n} and i_{3n}. If the harmonic equivalent impedances of the filtering winding and filters are equal to zero, the harmonic electromotive force e_{4n} is close to zero. According to (5), ω, N_4 and n are not equal to zero, and $\sin(n\omega t)$ is a time variable, so it can be acquired that Φmn is equal to zero to meet the condition of equality constraints, and it means that the harmonic magnetic flux of the transformer core is suppressed greatly. Therefore, the harmonic currents only flow in the load and filtering windings and can not flow into the grid winding and the public network.

3.2 Inductive Filtering Method and Technology

Since reducing the equivalent impedance of filtering winding and filters, the transformer core harmonic magnetic flux is suppressed, so the harmonic currents only flow in the secondary and filters winding. Inductive filtering technology realizes the condition that harmonic equivalent impedance of filtering circuit is close to zero, that means that the filtering winding equivalent impedance is close to zero and the filters are full-tuned. The differences between the inductive filtering method and the conventional filtering method are as following:

- Inductive filtering method provides zero harmonic equivalent impedance for the harmonic generated by the rectifier to prevent them flowing into the grid side.
- The transformer core harmonic magnetic flux is reduced based on the inductive filtering method so that the loss, vibrate and noise of transformer are reduced.

3.3 Analysis and Design of Synthesis Energy Saving

For the highly energy-consuming industries, such as metallurgy and electro-chemical industries, energy-saving problem is very important. To solve this problem, synthesis energy saving of the new industry rectifier system based on the inductive filtering method are designed with three aspects as follows:

- Energy saving design of the system and key equipments: the suitable trigger angle of the converter-bridge is acquired with OLTC stalls control. The inductive filters realize the full tuned design, and at the same time, the high quality filtering reactor and capacitor should be adopted. The sectional area of all bus bar, including DC bus bar should be increased so that the loss is reduced. In addition, we made the optimization and analysis of regulating transformer and rectifier transformer. Again, other considerations are optimal temperature control based on the principle of minimum power loss of system and choosing the rational topology structure, etc.

- Energy saving of harmonic suppression at the valve side: generally, the harmonics generated by the rectifier will flow into the resistance of the valve side winding, equivalent resistance of transformer core, resistance of the primary winding and resistance of the OLTC. For the inductive filtering method, the overwhelming numbers of harmonics flow into the filtering winding and its LC filtering branch. Thereby, there are few harmonic currents in the primary winding. As mentioned above, the resistance of the filtering circuit and the harmonic magnetic flux in transformer core are reduced greatly. In such a way, the corresponding harmonic loss can be reduced greatly.
- Energy saving of reactive power compensation at the valve side: the new filtering method can compensate reactive power nearest to the harmonic sources so that lots of harmonic currents flow into the filtering circuit, and the total current in the primary winding and voltage-regulating transformer is reduced. Therefore, the new inductive filtering method can reduce the transformer loss more than ac side passive and multi-pulse filtering methods.

It should be pointed out that the conventional filtering method cannot simultaneously realize the good harmonic suppression and energy saving effectiveness because of the larger harmonic impedance of the harmonic circuit.

In addition, the capacity and the inductance of the single fully-tuned circuits can be designed as follows:

$$\begin{cases} C_n = \dfrac{Q_{c(n)}(n^2-1)}{U^2 \omega_1 n^2} \\ L_n = \dfrac{1}{n^2 \omega_1^2 C_n} \end{cases} \tag{8}$$

Where: ω_1 is the fundamental angle frequency; $Q_{C(n)}$ is the capacity of the reactive power compensation for n-order single-tuned filter; U is the voltage of the bus connected to the single-tuned circuit; C_n and L_n are the capacity and inductance values for n-order single-tuned filters.

4.System Simulation Study

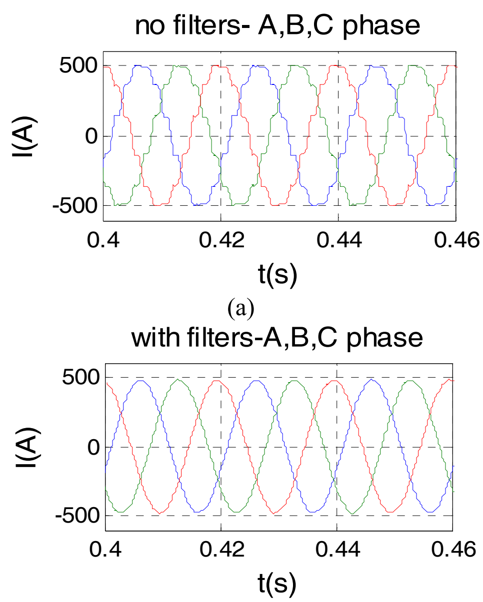
In order to validate the theoretical analysis of the new rectifier transformer and its rectifier, the simulation model is established based on Fig.1 by using MATLAB/SIMULINK. The operational conditions consist of:

Case 1: without inductive filters, OTLC with tap position -1, triggering angle α=7.5°, DC current Id=95995A, DC voltage Ud=1249.93V;

Case 2: with inductive filters, OTLC with tap position -4, triggering angle α=7.8°, DC current Id=95995A, DC voltage Ud=1249.93V.

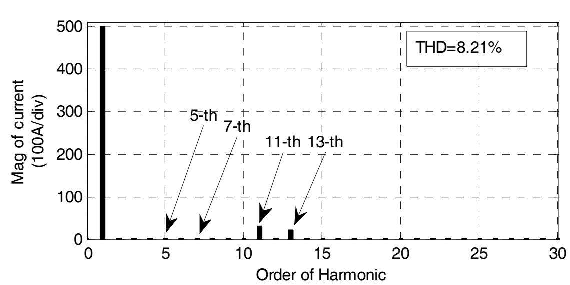
4.1 Harmonic Current Suppression

Fig. 4 shows the waveforms of the currents in the grid side of the new rectifier systems with or without the inductive filters. Fig.5 shows the Fast Fourier Transform respectively. It is obviously shown that the waveforms of the grid side current are improved greatly and approached to sine wave with the filters. The current's Total Harmonic Distortion (THD) is reduced from 8.21% to 1.57%.



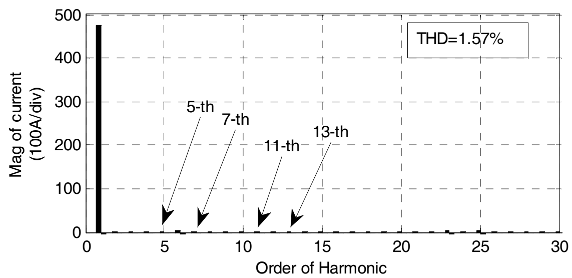
(b)

Fig.4. Waveforms of the currents and characteristic harmonic currents in the grid side, (a) without inductive filtering; (b) with inductive filtering



(a)

Fig.5. Harmonic spectrum of the grid current at the 220kV-Bus side, (a) without inductive filters



(b)

Fig.5. Harmonic spectrum of the grid current at the 220kV-Bus side, (b) with inductive fiters

Tab.1 shows the value of harmonics in the grid side currents of the new rectifier systems with and without inductive filters. It can be shown that the suppressing rates of characteristic-order harmonic currents are more than 98%, which it proves the superiority of the inductive filtering method on harmonic suppression. Please note that the 5-th and 7-th harmonic currents are slightly magnified with inductive filters, but they are not beyond the values of the state limited standards [18].

Table 1

Effectiveness of harmonic suppression

Harmonic orders	Grid side harmonic currents		Filtration rate /%
	Without filters	With filters	
5th/A	0.28	0.62	--
7 th/A	0.14	1.18	--
11 th/A	21.85	0.20	99.08
13 th/A	14.93	0.21	98.59
THD/%	8.21	1.57	--

4.2 Harmonic Magnetic Flux Suppression in Transformer Core

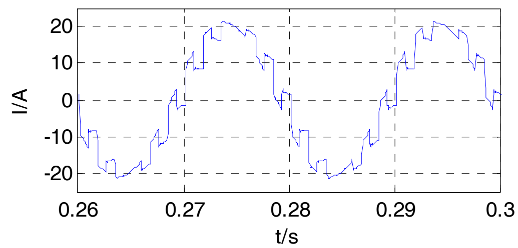
Fig. 6 shows the magnetization current simulation waveforms of the main transformer with and without inductive filters. By comparing the waveforms, it can be shown that the magnetization current waveform is close to the sine wave under effect of the inductive filtering method. Tab. 2 shows the harmonic percentages of the magnetization current.

Table 2

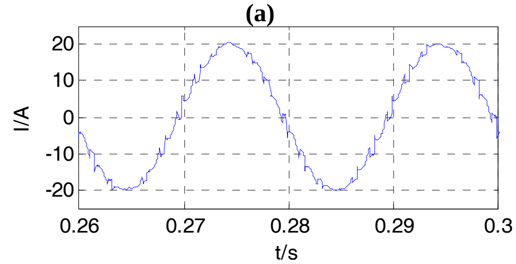
Simulation results of transformer core's harmonic currents with or without inductive filtering method (UNIT: %)

Harmonic order	5th	7th	11th	13th
Without inductive filters	0.24	0.16	13.54	11.34
With inductive filters	0.25	0.79	0.20	0.15

It is shown that the characteristic-order harmonics are reduced to zero, which can prove that the negative effects of the harmonics on the transformer core are greatly reduced.



(a)



(b)

Fig.6. Magnetization current waveforms of the main transformer with and without inductive filters

4.3 Loss and Energy Saving

Tab.3 shows the simulation results of the power, power losses and power factor at the grid side. It can be shown that the power in the grid side is decreased (from 124219kW to 123995kW), the power loss of the main transformer is reduced (from 2611kW to 2464 kW), and the power factor is increased (from 0.92 to 0.97) with inductive filters. So the new industry rectifier system and its inductive filtering method can realize some energy economy, in change of the higher cost of the filters on harmonic suppression.

Table 3

Simulation results on power, loss, and PF

	Power in grid side/kW	Main transformer loss/kW	PF
No filters	124219	2611	0.92
With filters	123995	2464	0.97

5. Conclusions

In the paper, the 12-pulse DC power supply system is presented based on the new rectifier transformer and inductive filtering method. This system can be widely applied in industrial custom power fields needing high-power DC supply source. Its main-circuit topology is different of the conventional industrial DC supply system. The special filtering and harmonic magnetic flux suppression in transformer core mechanism of the new industrial rectifier system is revealed, and the realization condition of inductive filtering method and design of synthesis energy saving are given. All the theoretical and simulation results show the advantages of the new 12-pulse industrial DC supply system on improving the filtering performance, relieving the harmful effect of the harmonic and reactive power currents on the transformer, and realizing energy saving.

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