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A KIND OF 220kV HARMONIC ISOLATION TRANSFORMER WITH FOUR WINDING

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In order to solve the problem of harmonic content exceeding normal standard in some transformer substations, this paper puts forward a four-winding transformer with the function of harmonic suppression. The filter winding will isolate 220kV winding from 110kV and 35kV windings, and to constitute two sets of inductive filter transformer structure. Respectively, to meet the inductive filtering requirements of 110kV and 35kV sides, realizing harmonic isolation. Then, to establish the simulation model of four-winding transformer in the software of PSCAD. Compared to the 220kV three windings transformer and filter system, simulation results show that the new transformer with the filter system can achieve harmonic suppression and reactive power compensation on 110kV and 35kV sides, and with the good effect.

Keywords: 220kV substation, three windings transformer, four windings transformer, equivalent impedance, harmonic suppression, inductive filtering technology

1. Introduction

The smelting, electric railway, new energy grid-connected and flexible transmission can cause abundant harmonic loads, which results harmonic and reactive power exceeding normal standard in 220kV grid [1][2].

Currently, the main method to solve the problem of harmonic in 220kV substation is to design reactive power compensation device into passive filter on 35kV sides, which makes the device combine harmonic filter and capacitive reactive power compensation [3]. However, when waveform distortion is serious,

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this method will be unable to meet harmonics and reactive power compensation requirements of national standards [4] [5].

In this paper, a kind of 220kV harmonic isolation transformer has been proposed basing on the principle of inductive filtering technology [6-9], which will figure out the harmonic and reactive power compensation in 110kV and 35kV with the corresponding filter atone devices [10-15].

2. Topology and Working Mechanism of Transformer

2.1 Traditional Power Transformers

Fig 1 shows the topological graph of the traditional three-winding power transformer and its filter atone system, the single-phase equivalent model of the transformer is given by Fig. 2. In Fig. 2, W_1, W_2 and W_3 is the winding turns on 220kV, 110kV and 35kV sides, respectively. Winding current is $\dot{I}_1$, $\dot{I}_2$ and $\dot{I}_3$, respectively. The voltage is $\dot{U}_1$, $\dot{U}_2$ and $\dot{U}_3$, correspondingly, $\dot{I}_x$ and $\dot{I}_y$ is the load current on 110kV and 35kV sides, $\dot{I}_f$ is the current of filtering device. Introducing turns of each winding of transformer into basis turns W_1, we get:

$$\begin{cases} K_1 = W_1 / W_1 \\ K_2 = W_1 / W_2 \\ K_3 = W_1 / W_3 \end{cases} \quad [1]$$

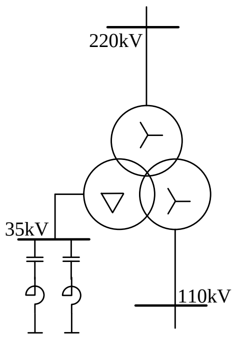


Fig.1 Topological graph of power transformer

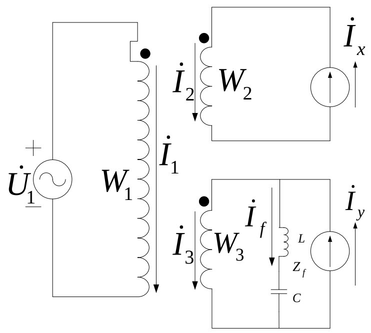


Fig. 2 Transformer single-phase equivalent mode

According to the harmonic equivalent model shown in Fig. 2, we obtain

$$\dot{I}_y = \dot{I}_3 + \dot{I}_f \quad (2)$$

$$\dot{U}_3 = \dot{I}_f Z_f \quad (3)$$

where Z_f is equivalent impedance of specific times filter (converted to single-phase).

$$Z_f = j2\pi f_n L_n + R_{Ln} + \frac{1}{j2\pi f_n C_{fn}} + R_{Cn} \quad [4]$$

Using the equivalent model on 110kV side in Figs.2, we get

$$\dot{I}_2 = \dot{I}_x$$

Neglecting excitation current, we get magnetic potential balance equation

$$\frac{\dot{I}_1}{K_1} + \frac{\dot{I}_2}{K_2} + \frac{\dot{I}_3}{K_3} = 0 \qquad [5]$$

According to the theory of multi-winding transformer, we obtain

$$\begin{cases} K_1\dot{U}_1 - K_2\dot{U}_2 = \dfrac{\dot{I}_1}{K_1} Z'_{K12} + \dfrac{\dot{I}_3}{K_3} Z'_{213} \\ K_1\dot{U}_1 - K_3\dot{U}_3 = \dfrac{\dot{I}_1}{K_1} Z'_{K13} + \dfrac{\dot{I}_2}{K_2} Z'_{312} \end{cases} \qquad [6]$$

In the formula above, each impedance parameter has been converted to actual value of turns. The impedance of the formula can be divided into two categories: one is short-circuit impedance between two windings, specific impedance values can be achieved through appropriate arrangement of windings, ie Z'_{K12} and Z'_{K13}; the other impedance parameter has the properties of leakage impedance, which can be calculated by short-circuit impedance indirectly, ie Z'_{K213} and Z'_{K312}.

$$\begin{aligned} Z'_{K213} &= (Z'_{K12} + Z'_{K23} - Z'_{K13})/2 \\ Z'_{K312} &= (Z'_{K13} + Z'_{K23} - Z'_{K12})/2 \end{aligned} \qquad [7]$$

Using the equations we get above, the wingdings current relationship between 220kV side and 35kV side can be given by the following form

$$\dot{I}_1 = \frac{K_1^2 K_2 K_3 \dot{U}_1 - K_1 K_3 (Z'_f + Z'_{312})\dot{I}_x}{K_2 K_3 (Z'_{K13} + Z'_f)} - \frac{Z'_f K_1 K_2 \dot{I}_y}{K_2 K_3 (Z'_{K13} + Z'_f)} \qquad [8]$$

by turning each parametric in above formula into harmonic parametric, we get the wingdings current relationship between 220kV side and 35kV side.

$$\dot{I}_{1n} = \frac{K_1^2 K_2 K_3 \dot{U}_{1n} - K_1 K_3 (Z'_{fn} + Z'_{312n})\dot{I}_{xn}}{K_2 K_3 (Z'_{K13n} + Z'_{fn})} - \frac{Z'_{fn} K_1 K_2 \dot{I}_{yn}}{K_2 K_3 (Z'_{K13n} + Z'_{fn})} \qquad [9]$$

where n represents for specific times harmonics.

Under the ideal conditions, assuming there is no harmonics on 220kV side, ie $\dot{U}_{1n} = 0$, the filter method of power transformers in ordinary substation is given below: putting in multiple filters, the harmonic has been controlled in the required range [11-12], for the filter is equal to full tuning, the harmonic impedance value Z'_{fn} is zero in the specific times harmonics.

We get the harmonic formula on 220kV side

$$\dot{I}_{1n} = -\frac{Z'_{312n} K_1 \dot{I}_{xn}}{K_2 Z'_{K13n}} \qquad [10]$$

Using Eq. (10), we can know that the current on 220kV side will not be affected by harmonic on 35kV side, but will also be affected by the winding harmonic on 110kV side. What' s more, according to the properties of its current, the winding harmonic on 110kV side can be divided into two types below:

NO.1 When the harmonic current on 35kV side and 110kV have been converted to 220kV side, on condition of property of superposition, for 35kV side, a better filtering effect can be achieved. But there will be some general filtering effect on 220kV side when the effect on 110kV side is inadequate.

NO.2 When the harmonic current on 35kV side and 110kV have been converted to 220kV side, on condition of properties of offset, when filter directly link to conventional 35kV, because the filter is only occurred on 35kV side, the filtering effect is not so good on 110kV side in addition, and the original property of harmonic offset has been broken out by inputting filters, there is almost no filtering effect on 220kV side, and the harmonic content of filter will even become larger.

2.2 Inductive Filtering Four-Winding Transformers

Fig. 3 shows the topological graph of the new four-winding transformer. Fig. 4 shows the single-phase equivalent model of four-winding transformer. In Fig.4, W_1, W_3 and W_4 is the winding turns on 220kV, 110kV, 35kV side, respectively. While W_2 is the winding turns of inductive filter on 35kV side. The corresponding wingding current are also shown in the Fig.4. $\dot{I}_f$ is the current in the filter device.

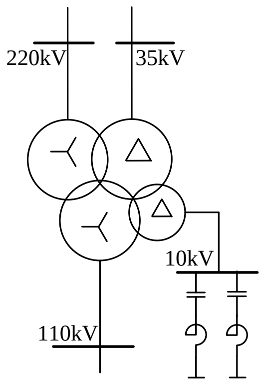


Fig.3 Topological graph of four winding

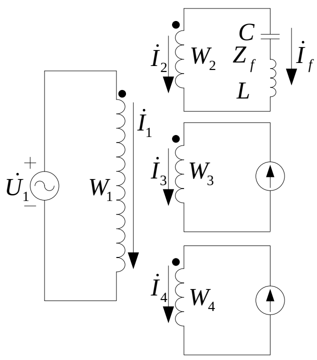


Fig.4 Transformer single-phase equivalent model

Introducing turns of each winding of transformer into basis turns W_1 , we get

$$\begin{cases} K_1 = W_1 / W_1 \\ K_2 = W_1 / W_2 \\ K_3 = W_1 / W_3 \\ K_4 = W_1 / W_4 \end{cases} \quad [11]$$

According to the harmonic equivalent model of single-phase shown in Fig.4, we obtain:

$$\begin{cases} \dot{I}_2 = -\dot{I}_f \\ \dot{U}_2 = \dot{I}_f Z_f \end{cases} \quad [12]$$

where Z_f is equivalent impedance of specific times filter (converted to single-phase).

$$Z_f = j2\pi f_n L_n + R_{Ln} + \frac{1}{j2\pi f_n C_{fn}} + R_{Cn} \quad [13]$$

Neglecting excitation current, we get magnetic potential balance equation

$$\frac{\dot{I}_1}{K_1} + \frac{\dot{I}_2}{K_2} + \frac{\dot{I}_3}{K_3} + \frac{\dot{I}_4}{K_4} = 0 \quad [14]$$

According to the theory of multi-winding transformer, we obtain

$$\begin{cases} K_1\dot{U}_1 - K_2\dot{U}_2 = \frac{\dot{I}_1}{K_1} Z'_{K12} + \frac{\dot{I}_3}{K_3} Z'_{213} + \frac{\dot{I}_4}{K_4} Z'_{214} \\ K_1\dot{U}_1 - K_3\dot{U}_3 = \frac{\dot{I}_1}{K_1} Z'_{K13} + \frac{\dot{I}_2}{K_2} Z'_{312} + \frac{\dot{I}_4}{K_4} Z'_{314} \\ K_1\dot{U}_1 - K_4\dot{U}_4 = \frac{\dot{I}_1}{K_1} Z'_{K14} + \frac{\dot{I}_2}{K_2} Z'_{412} + \frac{\dot{I}_3}{K_3} Z'_{413} \end{cases} \quad [15]$$

In the formula above, every impedance parameter has been converted to actual value of turns, and the calculation method is equal to the method of three-winding transformer.

Using the equations we get above, the wingdings current relationship among 220kV side ,35kV side and 110kV side can be given by the following form.

$$\dot{I}_1 = \frac{K_1^2 K_3 K_4 \dot{U}_1 - (Z'_f + Z'_{213}) K_1 K_4 \dot{I}_3}{(Z'_{K12} + Z'_f) K_3 K_4} - \frac{(Z'_f + Z'_{214}) K_1 K_3 \dot{I}_4}{(Z'_{K12} + Z'_f) K_3 K_4} \quad [16]$$

Assuming there is no harmonics on 220kV side, ie $\dot{U}_{1n} = 0$, by turning each parametric in above formula into harmonic parametric, we get the wingdings current relationship among 220kV side, 35kV side and 110kV side.

$$\dot{I}_{1n} = -\frac{(Z'_{fn} + Z'_{213n})K_1K_4\dot{I}_{3n}}{(Z'_{K12n} + Z'_{fn})K_3K_4} - \frac{(Z'_{fn} + Z'_{214n})K_1K_3\dot{I}_{4n}}{(Z'_{K12n} + Z'_{fn})K_3K_4} \qquad [17]$$

On the ideal condition, the filter design of this kind of four-winding transformer is:

(1) In the design of structure of transformer, the equivalent impedance of filter winding of the transformer can be zero by using the special structure and other factors.ie $Z'_{213} = Z'_{214} = 0$,and we can also get $Z'_{213n} = nZ'_{213} = 0$, and $Z'_{214n} = nZ'_{214n} = 0$.

(2) Induction filter device is designed to specific time all tunable filter, and the specific time harmonic is the most polluted harmonic of the user, thus the harmonic impedance of five-time, seven-time and n-time are zero, we can obtain

$$Z'_{f5} = Z'_{f7} = Z'_{fn} = 0 \qquad [18]$$

We know , Z_{fn} and $\dot{I}_{1n}$ in this time, no matter what value $\dot{I}_{3n}$ and $\dot{I}_{4n}$, we can always get $\dot{I}_{1n}$ = 0 and Z_{fn}=0, which means we can achieve harmonic suppression on 220kV side regardless of the effect of the harmonic on 110kV and 35kV side, a better harmonic filtering has been brought out in addition.

3. The Simulation Results

3.1 Transformer Parameters

The selection of parameters of the four-winding transformer has to meet not only the capacity requirements of substation on 35kV, 110kV, 220kV sides, but also the similarity of the parameters of the two transformers. For the convenience of simulation comparison, we show the transformer parameters on Table.1, 2, and the impedance parameters of transformer on Table 3.

Table.1

Parameter of power transformer

	Capacity(kVA)	Voltage(k)	Connection	Resistance(Ω)
High Voltage Winding	180000	220	Star	0.3656
Medium Voltage Winding	180000	110	Star	0.06729
Low Voltage Winding	90000	35	Corner	0.03472

Table.2

Parameter of four winding transformer

	Capacity(kVA)	Voltage(kV)	Connection	Resistance(Ω)
High Voltage Winding	180000	220	Star	0.3656
Filtering Winding	60000	10	Corner	0.005124
Medium Voltage Winding	180000	110	Star	0.06729
Low Voltage Winding	90000	35	Corner	0.03472

Table.3

Impedance parameter

Impedance	Three-winding	Impedance	Four-winding
U_{13}：	24.38%	U_{14}：	22.29%
U_{12}：	14.24%	U_{13}：	15.52%
U_{23}：	7.75%	U_{34}：	5.54%
		U_{12}：	10.04%
		U_{24}：	12.78%
		U_{23}：	5.57%
		U_{213}：	0.045%
		U_{214}：	0.265%

This transformer is used to an expansion project for a 220kV substation, which requires parallel connection on 110kV side. So, the short-circuit impedance on 220\110kV of this transformer must meet the requirement of parallel connection, the other winding impedance could just meet the requirement of capacity of the short-circuit protection switching.

3.2 Filter Design parameters

Take the test date of harmonic in most engineering examples into consideration [12] [13] [14], the main harmonic components of harmonic source is 3,5,7,9,11,13. The effect of the main times harmonic is the most important in the design of transformer, so we apply the specific-times harmonic 5,7,11,13 of harmonic source, which is the rectifier equipment, to test and verify the simulation of the transformer. Four sets of filter devices have been adopted in this simulation program, and the design principle of the filter devices is given below:

(1) The filter winding parameters of transformer meet the requirements of four-winding transformer whose harmonic impedance is zero on condition of specific-time harmonic, for example: $Z'_{213} = Z'_{214} = 0$

(2) The selection of the rated voltage of the reactor should not only take the increased voltage owing to series reactor into account, but also the harmonic voltage correspondingly. What's more, the compensation capacity should meet the requirements of the design and the level of the devices manufacturing in the same time.

Depends on the discussion above, the parameters of filter devices is given in Table.4.

Table.4

Filtering parameter

		Three-winding	Four-winding
	Inductance（mH）	50.91492	4.15632
Fifth Harmonic	Capacitance（uF）	7.96	97.51
	Inductance（mH）	49.8995	4.07343
Seventh Harmonic	Capacitance（uF）	4.14392	50.763
	Inductance（mH）	49.2976	4.02425
Eleventh Harmonic	Capacitance（uF）	1.6986	20.808
	Inductance（mH）	49.4892	4.01544
Thirteen Harmonic	Capacitance（uF）	1.2189	14.931

4. Research and Analysis of Simulation Results

Under the same situation, the filters have been added to the 10kV filter winding of four-winding transformer and 35kV of existing three-winding transformer, respectively. Using the PSCAD in Fig.5, we get the simulation waveforms of A-phase steady current on 220kV side both of new four-winding transformer and traditional transformer, which has been shown in Fig.6. The waveform from Fig.6[a] to [c] correspond to the condition of unused filter-transformer, used traditional filter-transformer and new four-winding filter-transformer, respectively. It is clear that, there have been serious harmonic owing to unused filter-transformer, and the distortion is also existing when we use traditional transformer, however, which will be improved under the use of new four-winding transformer, and the waveform is almost close to sinusoidal.

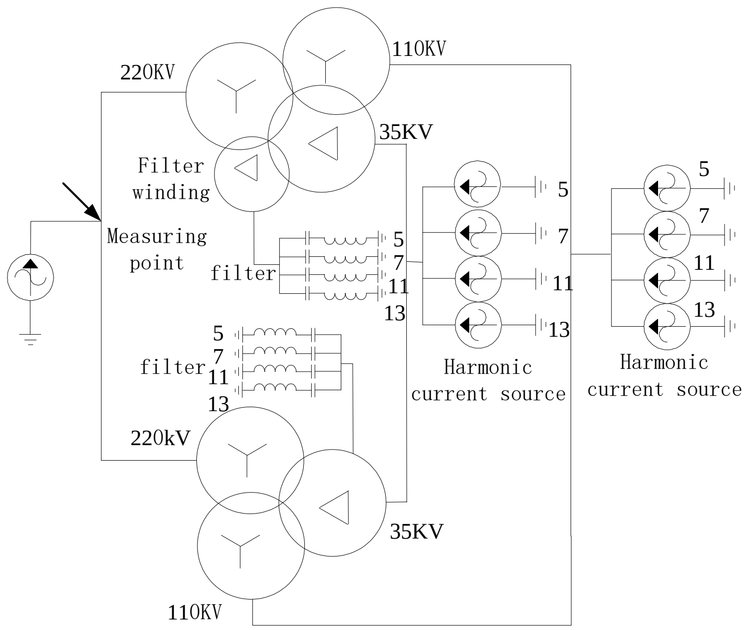
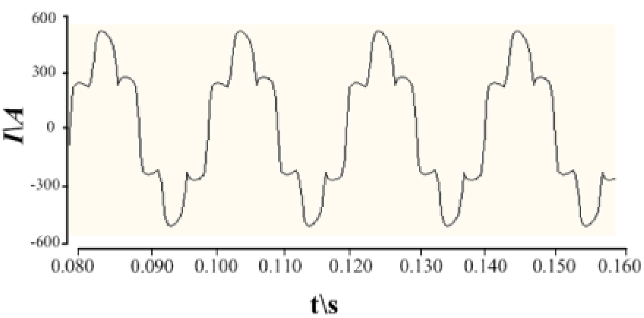
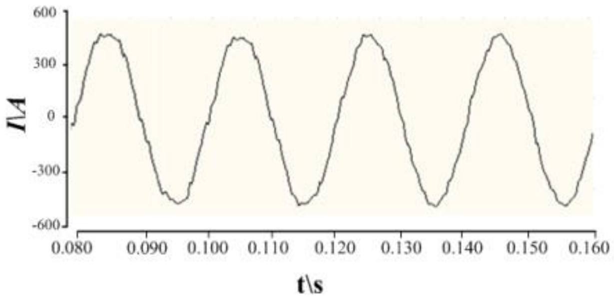


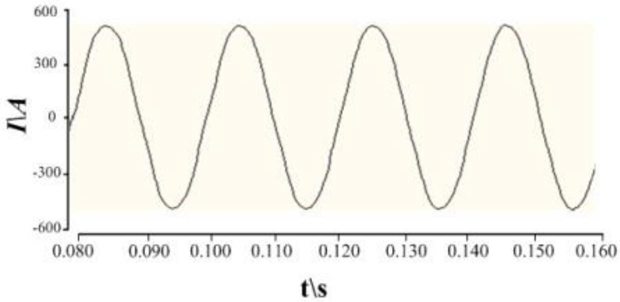
Fig.5 Principle of PSCAD simulation circuit



a unused filter-transformer



b used traditional filter-transformer



c new four-winding filter-transformer

Fig.6 Current simulation curve of 220 kV side

The value of specific-time harmonic current in the harmonic source of transformer on 110kV and 35kV side have been shown on Table.5, and the harmonic content on 220kV side of three-winding transformer and new four-winding transformer after adding filter devices have been given on Table.6. According to the date on Table. 5 and Table. 6, after adding filter devices and simulating assigned-time harmonic on 35kV and 110kV side, the current distortion of three-winding transformer has been decreased from 14.7% to 6.15%.

Table.5

Harmonic current

	Harmonic Content（%）	
Times	Three-winding	Four-winding
1	100	100
5	14.07	14.07
7	5.17	5.17
11	3.45	3.45
13	0.59	0.59
Distortion	14.7	14.7

However, the current distortion of new four-winding transformer has been decreased from 14.7% to 1.54%, which means a better effect of filter.

Table.6

Harmonic current after filtering

	Harmonic Content（%）	
Times	Three-winding	Four-winding
1	100	100
5	6.04	0.85
7	2.23	0.32
11	1.64	0.21
13	0.81	0.35
Distortion	6.15	1.54

Due to the simulation waveform in Fig.6, it is obvious that the new four-winding transformer is good at filtering. The derivation of filter both of the traditional and new four-winding transformer has been verified by the simulation parameters in Tab.5 and Tab.6. When convert the current to 220kV side, no matter there is property of offset or superposition in each other, the new four-winding transformer is better than the traditional transformer in filtering.

5. Conclusion

In summary, we have disclosed a new type of four-winding transformer, which have the function of reactive power compensation and harmonic control in the same time, what’s more, we can design special short-circuit impedance of the filter winding in the transformer. Therefore, when it has been used with the filter, we get a superior effect of filter in order to achieve bilateral shield of the harmonic. Finally, we validate the new four-winding transformer with special design in the result of simulation, which shows that the new transformer is definitely superior to the traditional transformer in the filtering of harmonic.

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