Harmonic Analysis and Control in 35kV Xin'an substation

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Abstract. In the process of supervision and inspection of Jiangxi power grid, there are some phenomena in 35kV Xin'an substation, such as abnormal sound from transformer and capacitor, and overheating in capacitor. The bus and capacitor power quality test found serious harmonic exceeding. Two methods of harmonic control are proposed, and the comparison of the control effect is carried out. Through the simulation of ETAP, the two methods are able to reduce the harmonic to the national standard and achieve the goal of power quality control. what have done in this paper lay a theoretical foundation for the work in next step.

Introduction

The harmonic generated by various nonlinear loads in power system is an important risk of the safety and stability of power system. Excessive harmonic currents which flow in the power system may result in misoperation of the protection system[1], the increases of measurement error[2-5], over heat and loss of line and equipment[6-9], and so on. Harmonic control of power systems has become the consensus of the power companies, large power users and equipment manufacturers. For the substation, harmonic can increase vibration and heating of the main transformer, misoperation or maloperation of protection。In extreme cases，harmonic currents can cause parallel resonance between the capacitor group and the grid impedance, which may burn equipment, cause widespread power outages and serious social impact. Therefore, it is urgent to control the harmonic of substation.

35kV Xin'an substation and load profile

35kV Xin'an substation electrical wiring diagram as shown in figure 1.

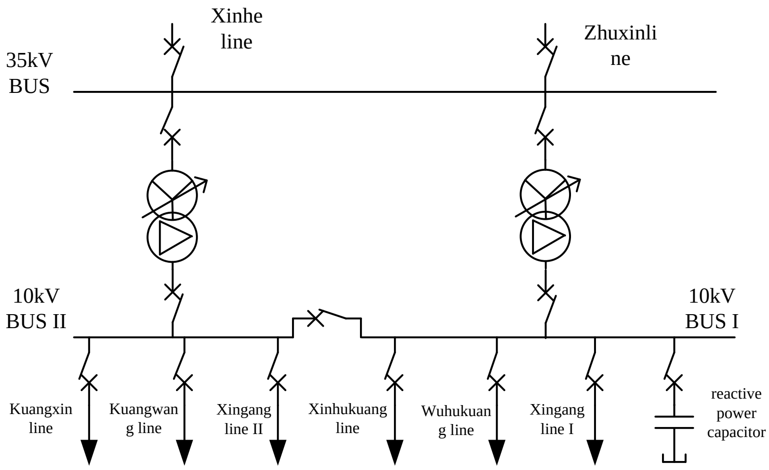

Figure 1 35kV Xin'an substation electrical main wiring diagram

35kV Xin'an substation has two main transformer, the capacity is 8MVA. 35kV bus is not segmented. 10kV Bus are divided into two parts, 10kV Bus I and Bus II running in parallel. 35kV XinHe line and ZhuXin line are power input. The 10kV side has 6 lines, including the beneficiation load line and smelt load line.Kuangxin line,Kuangwang line,Xinhu Kuang line and Wuhu kuang line are beneficiation load line;Xingang line,Xingang II line are smelt load line which supply for

HongXin steel mill; Dashilong line are residential Load line. Beneficiation load is usually Large motor which has little harmonic currents, resident load has the same characteristics. Smelt load generally use thyristor rectifier, which is a typical nonlinear load with serious harmonic output. A reactive power compensation capacitor with a capacity of 2MVar and 5% series reactance rate is installed on the 10kV bus of the substation.

Load measurement and data analysis

The main load in Hongxin steel mill is three medium frequency furnace which supplied by three 630kVA transformers. Transformers have ratio voltage of 10kV:1000V, DYN11 connection. Steel mill installed a 2.1MVar reactive compensation capacitor (series reactance ratio 5%) in 10kV side, but no filtering device. It is found that the harmonic distortion rate increases from 3.9% to 21.3% during the operation of the intermediate frequency furnace, so the harmonic of the substation is mainly produced by the intermediate frequency furnace.

The furnace is essentially a kind of electromagnetic oven, the working process is as follows: first, through an inverter, the three-phase alternating current is rectified into single-phase DC current, then DC current is changed into a 500-1000Hz pulse current by the inverter, and then magnetic field is generated through the copper ring in the internal furnace, finally eddy current generated by magnetic field in steel produce heat which melt steel.

The harmonics produced by the intermediate frequency power supply to the power network are mainly generated by the rectifying device. Based on ideal conditions, the three-phase 6 pulse rectifier AC side current can be approximately represented by square wave. The expression can be launched for AC side current with Fourier analysis method

$$i_a = \frac{2\sqrt{3}}{\pi} I_d [\sin wt - \tfrac{1}{5}\sin 5wt - \tfrac{1}{7}\sin 7wt + \tfrac{1}{11}\sin 11wt + \tfrac{1}{13}\sin 13wt ...] \quad (1)$$

The harmonic current in the AC side of the rectifier is only containing 6K±1th (k is positive integer) harmonic. The ratio of the harmonic current and the fundamental current is equal to the reciprocal of the number of harmonics. In the actual circuit, because of the leakage reactance of rectifier transformer effect, the rectifier valve turn-on and turn off all need to have a transition process. The phase current waveform of the AC side rectifier circuit will become a trapezoidal wave, which is no longer under the ideal conditions, so the Nth harmonic current measurement in practical situations is usually less than 1/n.

Table 1 harmonic voltage of 10kV bus before treatment

Distortion rate /%	THD	5th	7th	11th	13th	17th
measured value	21.25	20.44	5.67	1.83	0.68	0.28
National standard limit	4	3.2	3.2	3.2	3.2	3.2

Table 2 harmonic current of 10kV bus before treatment

Current/A	Fundamental	5th	7th	11th	13th	17th
measured value	500	219.1	49.48	21.51	8.38	2.37
National standard limit	/	34.29	25.72	15.95	13.55	10.29

From table 1 and table 2 measurement data, it can be seen that before treatment 5th, 7th, 11th harmonic current in 10kV Bus exceed the standard, accord with the characteristics of six pulse rectifier. Harmonic voltage distortion rate exceed 5.3 times, 5th harmonic current exceed the standard 6.38 times, accounting for the dominant factor of THDu.

Table 3 harmonic voltage of 10kV capacitor before treatment

Distortion rate /%	THD	5th	7th	11th	13th	17th
measured value	9.13	5.35	4.64	1.13	0.66	0.35
National standard limit	4	3.2	3.2	3.2	3.2	3.2

Table 4 capacitive harmonic current before treatment

Current /A	Irms	Fundamental	5th	7th	11th	13th	17th
measured value	138	94.2	96.3	31.3	5.36	1.39	0.43

With the reactive power compensation capacitors connected to the grid, 10kV capacitor harmonic voltage (same as 10kV Bus voltage) and current are shown in table 3, table 4. Datas shows that the 5th、7th harmonic current and fundamental current flows into capacitors, the 5th harmonic voltage of 10kV bus is greatly reduced; Irms/IN=1.3143 times. The total distortion rate of harmonic voltage exceeds 2.28 times, 5th harmonic voltage exceeding the standard 1.67 times, 7th harmonic voltage exceeding the standard 1.45 times, Urms/UN=1.021 times.

According to the DL / T840-2003 "high voltage shunt capacitor using technical conditions", the capacitor should be able to run under the effective value of 1.3IN. From the test data， the operation condition of Xin'an substation 10kV capacitor is serious, the current exceeded the stable over current, which is easy to cause overheating, expansion, and reduce the life of the capacitor.

Simulation and control measures

In order to reduce the damage to the capacitors, the control of the harmonic can be carried out from two aspects:

Solution one: install the passive filter in the steel plant or substation to eliminate harmonic;

Solution two: reform the transformation of the rectifier to reduce the output of the harmonic current ;

Considering 35kV line as the power supply, This paper build a ETAP model according to the parameters of each element. Comparison of simulation and measured data through table 5 proved the consistency of the simulation model and actual system.

Table 5 Comparison of measured and simulated values of 10kV bus voltage distortion rate

Distortion rate /%	Before capacitors operation		After capacitors operation	
	Simulation value	measured value	Simulation value	measured value
THD	22.42	21.25	9.71	9.13
5th	21.49	20.44	6.02	5.35
7th	5.13	5.67	6.25	4.64
11th	1.74	1.83	1.32	1.13
13th	1.06	0.68	0.84	0.66
17th	0.52	0.28	0.47	0.35

Impedance scanning is an important means of power system analysis, especially harmonic impedance scanning can analyze the effect of filter on harmonic flow.

The part power system is simplified to three components, the power system impedance, the harmonic current source and the filter impedance. Because the harmonic current flows to the grid and the filter, it can be understood as the grid impedance and the filter impedance parallel to the harmonic current source in series, as shown in figure 2.

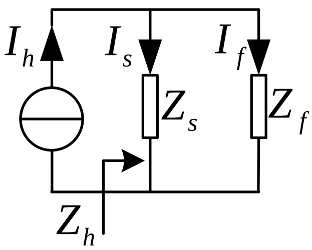

Fig. 2 Schematic diagram of harmonic current flow

Define hth harmonic filtering rate

$$\eta_h = 1 - \frac{I_s}{I_h} = 1 - \left| \frac{Z_h}{Z_s} \right|$$

The ηh can examine the filter on the harmonic control effect, Ih、Is、If respectively represent the harmonic current of source 、harmonic current of power grid and harmonic current of filters, Zh represent system impedance after setting filter branch, Zs and Zf respectively represent the impedance of power grid and impedance of filter.

Because only 5th and 7th harmonic exceed the standard limit, there is only needed to consider the 5th and 7th harmonic impedance, and the resonance risk after the filter connected in power grid. The two aspects of the parameters can describe characteristics of the system.

When the capacitor is not running, the frequency scanned of the 10kV bus as shown in Figure 3. The impedance increases with the increase of frequency. The system has no resonance point. It shows that the local system has no risk of resonance.

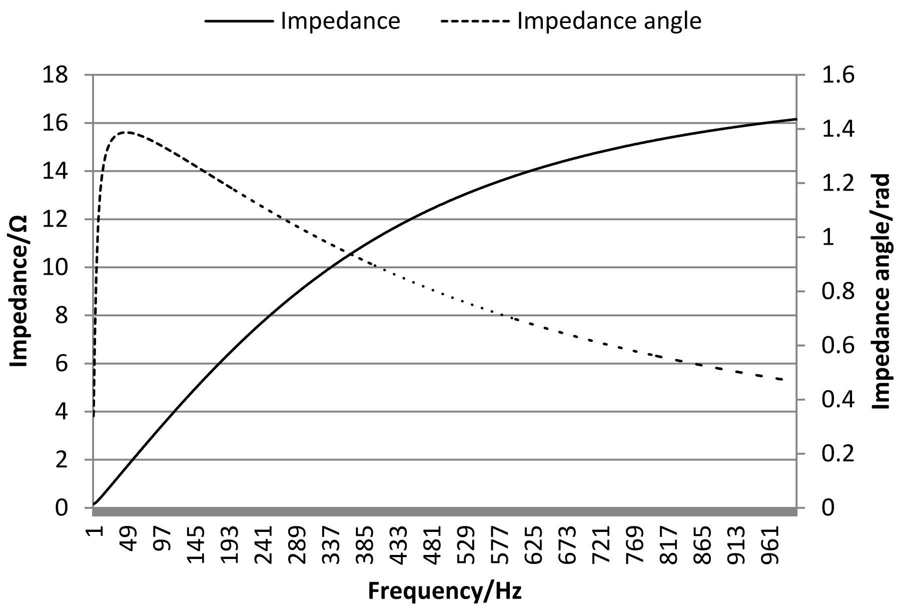

Fig. 3 harmonic impedance curve of 10kV bus before treatment

Table 6 5th and 7th harmonic impedance and impedance angle

frequency/Hz	250	350
harmonic impedance /Ω	7.95	10.23
harmonic impedance angle /rad	1.10	0.96

When the capacitor is put into operation, Xin'an 10kV bus frequency scanning in Figure 4 and table 7 can be seen that 169Hz and 208Hz frequency has a maximum harmonic impedance and a minimum value, and harmonic impedance reduced above 5th harmonic. The data indicate that with the capacitor in power grid,parallel resonance may be triggered at 169Hz, and the series resonance may be triggered at 208Hz. But in this system, the harmonic currents generated by the nonlinear load will not result in series resonance, and the parallel resonant points 169Hz harmonics are not rectification characteristic harmonics, the effect can be ignored. The effect of capacitor is mainly absorption effect on 5th and above harmonics, which are shown in Table 4 and also consistent with the theoretical analysis on resistance rate of 5% [10].

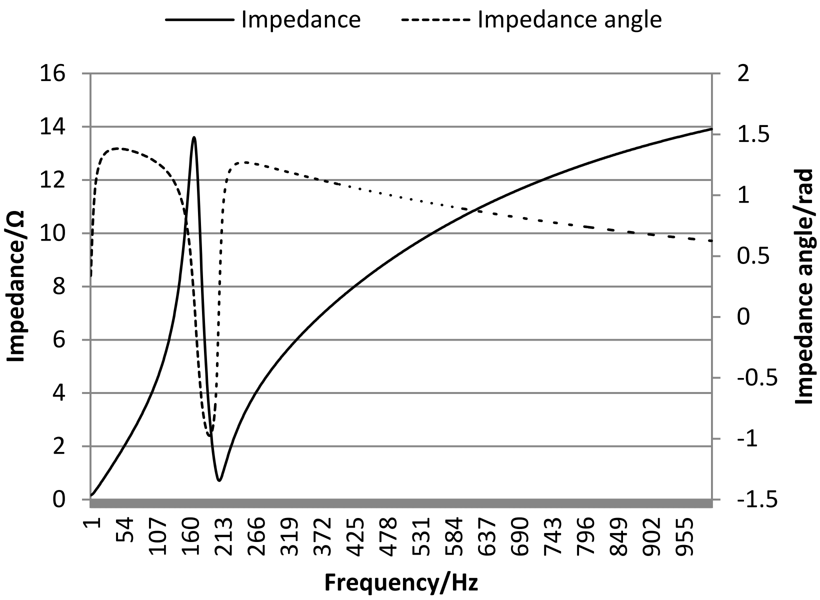

Fig. 4 the variation of the impedance of the 10kV bus after the capacitor input

Table 7 The 5th and 7th harmonic impedance and impedance angle

frequency /Hz	169	208	250	350
harmonic impedance /Ω	13.60	0.71	3.31	6.44
harmonic impedance angle /rad	0	0	1.27	1.15

There is a solution that 5th and 7th single tuned passive filter with reactive power compensation can be installed in steel plant. According to Optimal reactive power allocation for multiple passive filters[11]

$$Q_h = \frac{I_h}{h} \Big/ (\sum \frac{I_h}{h}) * Q \quad (2)$$

Reactive power of 5 and 7 single tuned branches can be distributed, Q5=1800kVar , Q7=300kVar。

According to

$$C_h = Q_h / (w_1 * U^2) \quad (3)$$

Capacitances of single tuned branches can be calculated, C5=19.11uF and C7=3.18uF.

According to

$$L_h = 1/(w_h^2 C_h) \quad (4)$$

Inductances of single tuned branches can be calculated, L5=21.23mH 及 L7=65.09mH. Considering the frequency deviation margin, setting tuning sharpness Q=50.

With

$$Q = X_h / R_h \quad (5)$$

Resistances of single tuned branches can be calculated, R5=0.67Ω,R7=2.86Ω。

Table 8, 5th and 7th single tuned filter branch parameters

Filtering times	Capacitances uF	Inductances mH	Resistances Ω
5th	19.11	21.23	0.67
7th	3.18	65.09	2.86

With impedance scan after 5th and 7th single tuned branches put into operation, it can be seen from the figure 5 and table 9, 5th and 7th harmonic impedance decreases to close to 0, and the rest of the extreme impedance is in 169Hz, 208Hz, 239Hz and 344Hz. From table 6 and table 9, harmonic impedance on 250Hz and 350Hz can be quantitatively calculated. η5 and η7 is 98.36% and 95.70%, which indicate a strong filtering effect of 5th and 7th harmonic current, and the extreme points is not easy to cause resonance because the frequency is not characteristic harmonic frequency.

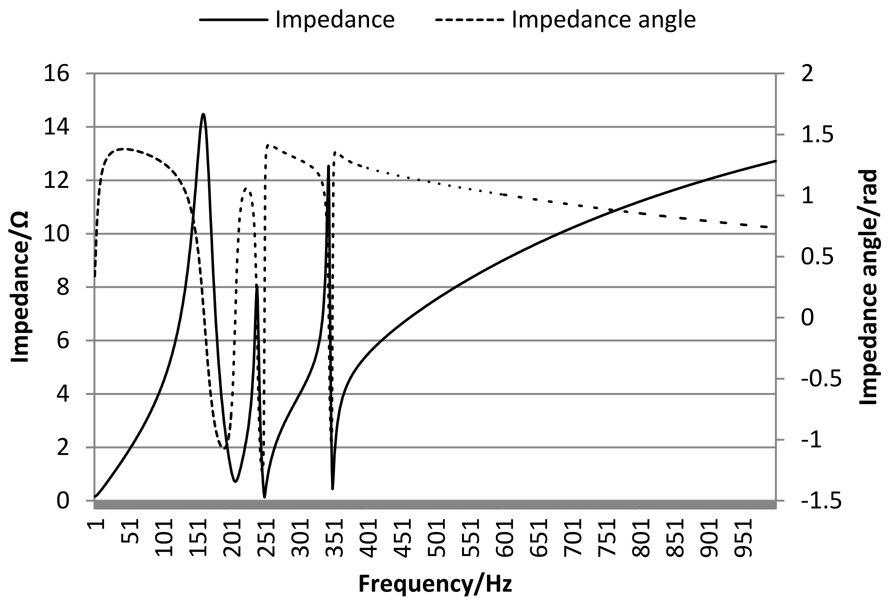

Fig. 5 harmonic impedance curve of 10kV bus after treatment

Table 9 the 5th and 7th harmonic impedance and impedance angle

frequency /Hz	169	208	239	250	344	350
harmonic impedance /Ω	14.48	0.71	8.05	0.13	12.5	0.44
harmonic impedance angle /rad	0	0	0	0	0	0

The capacitor voltage and current data from the table 10 and table 11 after the input of filter branch can verify above conclusion. The capacitor voltage distortion rate and the capacitance current are all in the qualified range, which can optimize the operation environment and reduce the operation risk of the capacitor.

Table 10 harmonic voltage of capacitor after treatment

Distortion rate /%	THD	5th	7th	11th	13th	17th
Simulation value	1.39	0.39	0.24	1.1	0.72	0.83
National standard limit	4	3.2	3.2	3.2	3.2	3.2

Table 11 harmonic current of capacitor after treatment

current/A	fundamental	5th	7th	11th	13th	17th
Simulation value	102	4.1	0.9	1.9	1	1.2

Above analysis shows that the solution of setting single tuned filters can be very good ways to eliminate harmonic current. But the effect of passive filters affected a lot by the impedance of power system, and easy to cause system resonance with different grid impedance caused by different power grid operation mode, so we can reconstruct harmonic current source to reduce harmonic current so as to reduce the impact on the grid.

The original three rectifier transformer can achieve optimal 18 pulse rectification, but with complex winding, 18 pulse rectifier transfomer must be custom-made which can cost a lot. Compromise can be made that one of the transformers turned into YY connected transformer, which can achieve 12 pulse rectification by 6 pulse rectifier. According to this solution, 2/3 of 5th/7th/17th/19th harmonic will be eliminated and the cost is relatively low.

Table 12 Capacitor harmonic voltage after modification of transformer

Distortion rate /%	THD	5th	7th	11th	13th	17th
Simulation value	3.98	3.35	1.18	1.53	0.91	0.82
National standard limit	4	3.2	3.2	3.2	3.2	3.2

Table 13 Capacitor harmonic current after the modification of transformer

current/A	Irms	fundamental	5th	7th	11th	13th	17th
Simulation value	107	101	35	4.2	2.6	1.3	0.9

According to the change of the harmonics, a new harmonic ratio injected to the grid. From Table 14 and table 15 , capacitor voltage and current data after the transformer reformed can be seen. The capacitor current value is in the acceptable range. Capacitance voltage (same as 10kV Bus voltage) is within the qualified scope except 5th harmonic voltage slightly exceed the standard. After setting 5th single tuned filter to eliminate the 5th harmonic, impedance scanning and part of the characteristic frequency points as shown in Figure 6 and table 14.

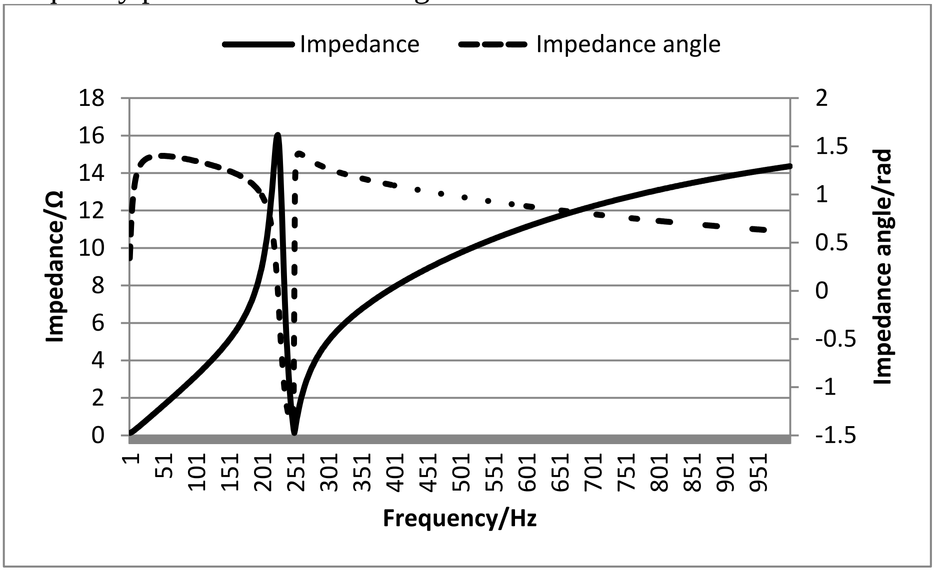

Figure 6 10kV bus harmonic impedance curve after transformer reforming and single tuned filtered setting

Table 14 the harmonic impedance and impedance angle after transformer reforming and single tuned filtered setting

frequency/Hz	224	250	350
impedance /Ω	16.03	0.13	6.69
impedance angle /rad	0	0	1.17

η5 can be quantitatively calculated with data of 250Hz harmonic impedance in tables 6 and 16. The number 98.36% indicate a strong filtering effect of the 5th harmonic. There are also a parallel resonance points in 224Hz, but the effect is not negligible because 224Hz harmonic is not the characteristic harmonics. Capacitor voltage and current data after transformer reforming and single tuned filtered setting from table 15 and table 16 also illustrates the effectiveness of the solution 2.

Table 15 capacitor harmonic voltage after transformer reforming and single tuned filtered setting

Distortion rate /%	THD	5th	7th	11th	13th	17th
Simulation value	1.82	0.13	0.93	1.34	0.82	0.74
National standard limit	4	3.2	3.2	3.2	3.2	3.2

Table 16 capacitor harmonic current after transformer reforming and single tuned filtered setting

current/A	fundamental	5th	7th	11th	13th	17th
Simulation value	102	1.4	3.4	2.3	1.1	0.7

Conclusions

The overheated and the noise in reactive power compensation capacitor in Xin'an substation is caused by the load of the intermediate frequency furnace in the steel plant. The 5% series of reactance can restrain the 5th and above harmonic currents injected into the power grid.

The 5th and 7th single tuned passive filters have obvious effect in solution 1, but many produced resonance points brings great risk when operation mode change in gird; solution 2 with transformer reforming and single tuned filtered setting has less resonant point、ideal effect、low loss and less cost compare to solution 1.

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