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The Open Electrical & Electronic Engineering Journal, 2015, *9*, 591-599 591

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Optimization Design on Power Filter of TCR Under Asymmetrical Voltage

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Abstract: For resolving the problem that power filter cannot work normally because TCR (thyristor controlled reactor) generates extra third harmonic current under asymmetrical voltage, the paper proposes the estimation method of current capacity that TCR generates extra third harmonic current under asymmetrical voltage. Considering extra third harmonic current under asymmetrical voltage, Optimum method based on genetic algorithm is used to design the parameters of power filter. With reactive power compensation and harmonic suppression project of a steel mill as example, the proposed method is simulated by Matlab. Simulation results show optimized power filter can eliminate extra third harmonic current effects under asymmetrical voltage, meet the requirement of reactive power compensation, reduce harmonics current that load injects into system, and guarantee the power filter safe operation under asymmetrical voltage.

Keywords: Asymmetrical voltage, genetic algorithms, power filter, reactive power compensation.

1. INTRODUCTION

Reactive power control is commonly regarded as one of the important contents of power system control [1, 2]. As is known, if reactive power could not be compensated reasonably in time, it will be transported in the power system. Then the electric energy loss of electric equipment will increase. It will affect the economy of power system operation and decrease the utilization of electric devices, and the impulsive reactive load will also lead to voltage fluctuation in power supply nodes, which will affect the power quality. Thus, reactive power balance plays a crucial role in the power system. Due to the advantage of simple structure, large capacity, reliable and high cost performance, TCR (Thyristor Controlled Reactor) is widely used in the field of reactive power compensation and harmonic suppression such as Metallurgical Industry [3, 4].

The structure of PPF (passive power filter) is simple, while it is difficult to design the filter which is with excellent overall properties is very hard. In engineering application, filter parameters are always designed by single technical index on the basis of the engineer's experience, and some more redundancy will be kept in order to ensure the reliability of power filters. It will weaken the performance of filter and increase investment cost.

Filter design should consider economy, technique, safety and other targets, so it is difficult for engineers to design an optimal filter according to the simple engineering experience [5-7]. Thus, some scholars suggest multi-objective optimization algorithm should be used to design the power filter by using the computer. But the existing optimization methods only optimize the PPFs in static VAR compensators (SVCs) and ignore the influence of harmonic current which is caused by TCR. Actually, TCR is a kind of harmonic current source, producing a certain capacity of additional 3^{rd} harmonic current under asymmetrical voltage, and it will affect operation of other power filters. Therefore, it sometimes can be hard to guarantee the reliable operation of filters based on the existing optimization methods [8-10].

To solve the problems as exposed, this paper presents an optimal designing method of power filter based on Genetic Algorithm (GA). The method takes harmonic current produced by TCR under asymmetrical voltage into account, which can guarantee the power filter safe operation when there is TCR in a compensation system under asymmetrical voltage.

2. THE PRINCIPLE OF REACTIVE POWER COMPENSATION SYSTEM WITH TCR

In the power system, usually, TCR and power filters together form a compensation system to compensate the load. Topology is given in Fig. (**1**).

The compensation system consists of TCR and passive power filter. The passive power filter will filter the harmonics current and provide fixed capacitive reactive power at the same time. And TCR will provide inductive reactive power which is controllable and changing with load. By using both of them, the goal of real-time reactive power compensation will be achieved. The thyristors in single-phase TCR, consisting of two anti-parallel thyristors and a reactor in series, will fully turn on when the trigger delay angle $\alpha = 90^\circ$. Meanwhile, the conduction angle $\delta = 180^\circ$ and the reactor in series with thyristors will be equivalent to directly connecting to power grid. If the trigger delay angle α changes be-

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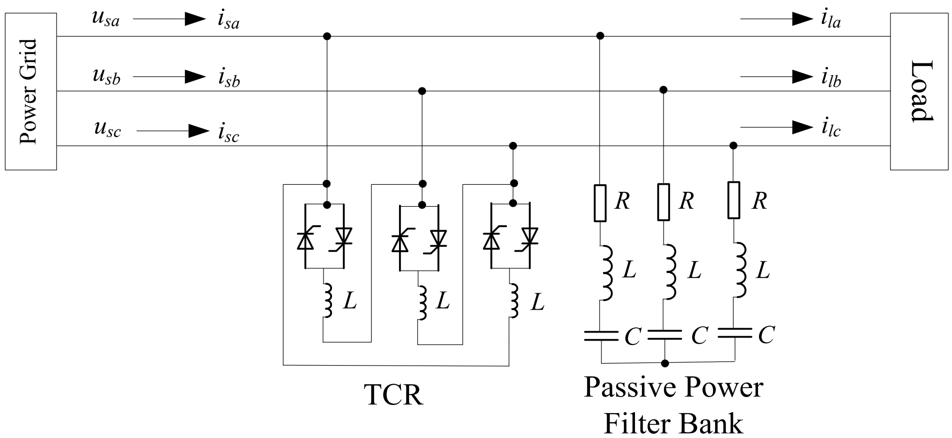

Fig. (1). Topology of TCR compensation system.

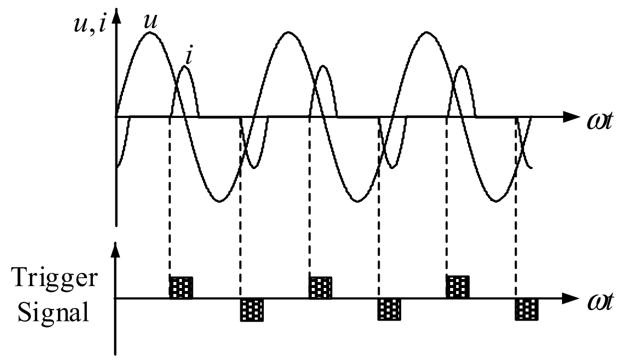

Fig. (2). Waveform of power system voltage and TCR current.

tween $90^\circ \sim 180^\circ$, the thyristors are partly conducting and $\delta \prec 180^\circ$. When $\alpha = 180^\circ$, the thyristors are completely turning off and equivalent to disconnect the reactor from the line. The increase in trigger delay angle will lead to the decrease in current fundamental component, that is, the equivalent inductive reactance of compensator will increase. In contrast, the decrease in trigger delay angle will cause an increase in current fundamental component and is equivalent to decrease the inductive reactance of compensator. Waveform of system voltage and TCR current is shown in Fig. (**2**).

Thus, the RMS of TCR fundamental current is obtained:

$$I_1 = \frac{E}{\pi\omega L}\left(\sin 2\alpha - 2\alpha + 2\pi\right) \quad (1)$$

Also, the fundamental equivalent susceptance of TCR is obtained:

$$B_L(\alpha) = \frac{I_1}{E} = \frac{\sin 2\alpha - 2\alpha + 2\pi}{\pi\omega L} = \frac{\delta - \sin\delta}{\pi\omega L} \quad (2)$$

Single-phase TCR will produce odd characteristic harmonic currents and the RMS of each harmonic current can be calculated by the formula given below:

$$I_n(\alpha) = \frac{U}{\omega L} \times \frac{4}{\pi}\left[\frac{\sin\alpha \times \cos(n\alpha) - n\cos\alpha \times \sin(n\alpha)}{n^2(n^2-1)}\right] \quad (3)$$

$(n = 3,\ 5,\ 7\ \cdots)$

The maximum value of I_n changes with the variation in the trigger delay angle, resulting in a more serious harmonic pollution in power system when using TCR to compensate reactive power. Accordingly, measures should be carried out to eliminate or reduce harmonics.

3. ESTIMATION OF TCR INJECTION THIRD HARMONIC CURRENT UNDER ASYMMETRICAL VOLTAGE

As a matter of fact, the voltage unbalance factor of distribution system is greater than or equal to 3% and yet, and usually reactive power compensatior is used for nonlinear and impulse load, thus the power quality of SVC is even worse. In addition, because TCR has large-capacity reactors, a smaller asymmetric voltage on the SVC bus will lead to a larger positive and negative sequence 3rd harmonic current. Relative to the TCR injection 3rd harmonic current, 5th, 7th or higher order filter bank is capacitive, which will make 3rd harmonic current produce resonance between the system equivalent impedance and high-order filter bank and enlarge 3rd harmonic current, thus it may lead to passive power filter bank overload. That proves the TCR injection 3rd harmonic current may affect the normal operation of power system. Therefore, under certain conditions, when optimizing the filter bank parameters, we should process the TCR injection additional 3rd harmonic current which is caused by asymmetrical voltage even if the load doesn't produce 3rd harmonic current, so as to ensure the reliable operation of filter bank.

TCR current of each phase will form zero sequence current in the triangle reactor and not inject into the power grid when three-phase voltage is symmetrical. On the contrast, when three-phase line voltage is asymmetrical, leading to unequal three-phase voltage amplitudes and phase angle difference, TCR will inject a certain capacity of positive, negative sequence 3rd harmonic current to the power system. Due to the sum of three-phase line voltage is zero, there are only components of negative and zero sequence voltage in three-phase line voltage. When three-phase line voltage is asymmetrical, the capacity of the 3rd harmonic current which TCR injects into the power system is only associated with the amplitudes of negative sequence, phase angle difference between negative sequence and positive sequence in three-phase line voltage, and the trigger delay angle of TCR. To ensure the reliability of filter bank, this paper estimates the capacity of TCR injection additional 3rd harmonic current under more adverse circumstances when system voltage is asymmetrical. Generally, the negative sequence of line voltage can be measured actually, and by National Standard, short-time voltage asymmetry should not exceed 4%, so we do estimation as National Standard regulated, that is, we use 4% as voltage unbalance factor. Fourier analysis shows that the relationship between each harmonic amplitude of TCR phase current and trigger delay angle α just as formula (4) shows:

$$I_{n(a)} = \frac{4}{\pi} \times \frac{U_m}{X_l} \times \left(\frac{\sin\alpha\cos(n\alpha) - n\cos\alpha\sin(n\alpha)}{n(n^2-1)}\right)$$
$$n = 2k+1 \; k=1,2,3 \; \ldots\ldots \tag{4}$$

After analysis, it shows that 3rd harmonic current which is produced by each phase of TCR is maximum when $\alpha = 30^{o}$. Trigger delay angle $\alpha = 30^{o}$ is chosen to do the estimation in this chapter. The 3rd harmonic current which TCR inject to phase-c is:

$$\dot{I}_{c3} = \dot{I}_{ca3} - \dot{I}_{bc3} \tag{5}$$

Where $\dot{I}_{c3}$ is TCR injection line current of phase-c, $\dot{I}_{ca3}$ represents the 3rd harmonic current produced by line voltage $\dot{U}_{ca}$ while $\dot{I}_{bc3}$ is the 3rd harmonic current produced by line voltage $\dot{U}_{bc}$. Each phase of line voltage is synthesized by positive and negative sequence components and since voltage unbalance factor often is smaller, which means that the amplitude of negative sequence voltage is smaller than that of positive sequence voltage's, negative sequence voltage has little effect on practical voltage amplitude. Due to this, the 3rd harmonic current injecting into phase-c only depends on the phase angle difference between $\dot{I}_{ca3}$ and $\dot{I}_{bc3}$. It is seen by the law of cosines that when α changes between 0^{o} $\sim 180^{o}$, the greater the absolute value of phase angle difference between $\dot{I}_{ca3}$ and $\dot{I}_{bc3}$ is, the greater the amplitude of $\dot{I}_{c3}$ is. Under the circumstance of asymmetrical voltage, the additional 3rd harmonic current that TCR injects into the power system is also asymmetrical current. However, if the injection 3rd harmonic current of one phase is greater, the SVC system may not work properly. As a result of that, a greater injection 3rd harmonic current of one phase should be chosen to estimate the capacity of TCR injection 3rd harmonic, so as to ensure the reliability of filter bank. Confirmative analysis shows that when U_{ab}^{+} and U_{ab}^{-} are in phase, the 3rd harmonic phase angle difference between $\dot{I}_{ab3}$ and $\dot{I}_{bc3}$ is larger, which meets the demand of estimation requirements and convenience of calculation. So when U_{ab}^{+} and U_{ab}^{-} are in phase, we use the 3rd harmonic current which TCR injects into phase-c to do the estimation.

Taking the reactive compensation data of one rolling mill as example, we estimate the capacity of TCR injection 3rd harmonic current when system voltage is asymmetrical. The transformer model of this rolling mill is SFZ9-31500/110, the capacity is 31500kVA, the transformation voltage ratio is 121/6kV, capacity of TCR is 20MVAR, the reactance of TCR is $X_L = 5.4\Omega$, and the short-time voltage unbalance factor is up to 4%. According to the estimation method is proposed in this chapter, considering a system whose trigger delay angle $\alpha = 30^{o}$, voltage asymmetry is 4%, and U_{ab}^{+}, U_{ab}^{+} are in phase. Under these conditions, estimate the capacity of 3rd harmonic current which TCR inject to phase-c. When $\dot{U}_{bc} = \dot{U}_{bc1} + \dot{U}_{bc2}$, according to the law of cosines, the line voltage U_{bc} is:

$$U_{bc} = \sqrt{U^2{}_{bc1} + U^2{}_{bc2} - 2\times U_{bc1} \times U_{bc2} \times \cos(60^{o})} \tag{6}$$

For $U_{bc1} = 6000\text{V}$, $U_{bc2} = 240\text{V}$, we obtain: U_{bc}=5883.67V, according to the formula (7), the angle between $\dot{U}_{bc}$ and $\dot{U}_{bc1}$ is θ_1=2.0244°.

$$\theta_1 = \arccos\left(\left(U^2{}_{bc} + U^2{}_{bc1} - U^2{}_{bc2}\right) / \left(2\times U_{bc} \times U_{bc1}\right)\right) \tag{7}$$

Similarly, we can obtain U_{ca}=5883.67V, the angle between $\dot{U}_{ca}$ and $\dot{U}_{ca1}$ is $\theta_2 = 2.0244^\circ$. Thus, the phase angle between $\dot{U}_{ca}$ and $\dot{U}_{bc}$ is $\phi = 115.9512^\circ$. From the preceding analysis, the phase angle between fundamental current $\dot{I}_{ca1}$ and $\dot{I}_{bc1}$ is also $\phi = 115.9512^\circ$ while the phase angle between 3rd harmonic current $\dot{I}_{ca3}$ and $\dot{I}_{bc3}$ is $\phi_3 = 3\times\phi_1$=12.1464°. By formula (4-4), we acquire that the RMS of 3rd harmonic current $\dot{I}_{ca3}$ and $\dot{I}_{bc3}$ are I_{ca3}=150.25A and I_{bc3}=150.25A when the trigger delay angle $\alpha = 30^\circ$. As the law of cosines, because of $\dot{I}_{c3} = \dot{I}_{ca3} - \dot{I}_{bc3}$, the effective value of 3rd harmonic current which TCR injects into phase-c is $\dot{I}_{c3} = 31.7931$A.

As seen from the analysis above, TCR will inject a larger 3rd harmonic current to power system when system voltage is asymmetrical. In order to ensure the reliability of system, we need to process the harmonics current when designing the filter bank.

4. SIMULATION ANALYSIS OF POWER FILTER OF TCR BASED ON GA UNDER ASYMMETRICAL VOLTAGE

In this chapter, The power filter designing method considers additional 3rd harmonics produced by TCR under asymmetrical voltage. The method makes each harmonic current and voltage meet the requirement of national standard, compensation capacity to satisfy the demand of design specification which means that there is no overcompensation and undercompensation, and power filters and system impedance fulfill the desire of no series-parallel resonant. Also, we set up goals of minimum total investment of filters as our optimization objectives to design the parameters. The genetic algorithm (GA) is adopted to solve this parameter optimization problem under multi-restrictions.

According to filter design principles, we follow the steps below to accomplish the specific optimization design based on the genetic algorithm.

We initialize all the constants and determine the type and sets of the passive power filter bank. For the filter system with TCR, estimation is needed even if there is no 3rd harmonic current when the voltage unbalance factor is larger. The initial crossover probability p_{c1} and mutation probability p_{v1} are identified.

Calculate the function value of individual fitness degree and obtain the function ratio of fitness degree *k*. Compare it with the given constant g. When $k > g$, taking crossover probability p_{c2} and mutation probability p_{v2} to do M-generation local search, while if $k < g$, adjust the crossover probability and mutation probability to search the optimal solution within a large space.

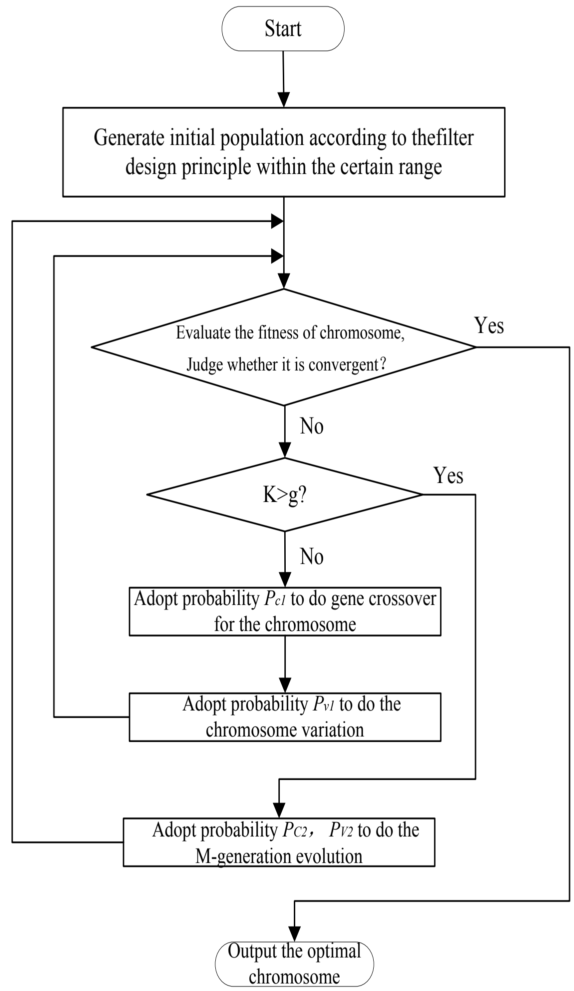

Fig. (3). Flow chart of GA.

Adopt the traditional method of roulette to select the individual and adopt elites to keep the tactics in order to improve the algorithm evolvability.

Adopt the traditional method of Allele-cross method to generate new individuals.

Make individual variability under corresponding probabilities and enhance the local search capability of our algorithm.

Check whether the individual fitness meets the convergence condition. If so, evolution is over. If not, return to condition and continue searching the optimal solution.

The flow chart of this algorithm is shown in Fig. (**3**).

We simulate the filter optimization algorithm presented in this chapter on the basis of the reactive compensation and harmonic suppression data collected from one rolling mill by Matlab. The transformer model of this rolling mill is SFZ9-31500/110, capacity is 31500kVA, the voltage transformation ratio is 121/6kV, required reactive power compensation is 20M VAR, the capacity of TCR is 20M VAR, and the short-time voltage asymmetry is up to 4%. Load in this case is 4 rectifier transformer powering to 17 mill. Harmonics in the side of 6kV system is given in Table **1**. As shown, since the load are phase control rectifiers, 5th, 7th and 11th har-

Table 1. Harmonic current of steel rolling mill.

Harmonic Order	1	5	7	11	13	17
Roughing Mill	263.51	65.88	23.72	15.81	9.22	5.27
Foil Mill	439.19	15.81	11.42	32.94	22.84	5.27
Finishing Mill	351.35	12.65	9.14	26.35	18.27	4.22
Reducing Sizing Mill	187.39	46.85	16.86	11.24	6.56	3.75
Total	1241.44	121.07	43.2	50.25	32.45	9.35

Table 2. Filter parameters calculated by optimal genetic algorithm.

	C (uF)	L (mH)	R (Ω)
3rd Single Tuned Filter	256.55	4.6686	0.2443
5th Single Tuned Filter	660.69	0.6526	0.0342
7th Single Tuned Filter	294.25	0.7476	0.0391
11th Single Tuned Filter	517.63	0.1619	5.1525

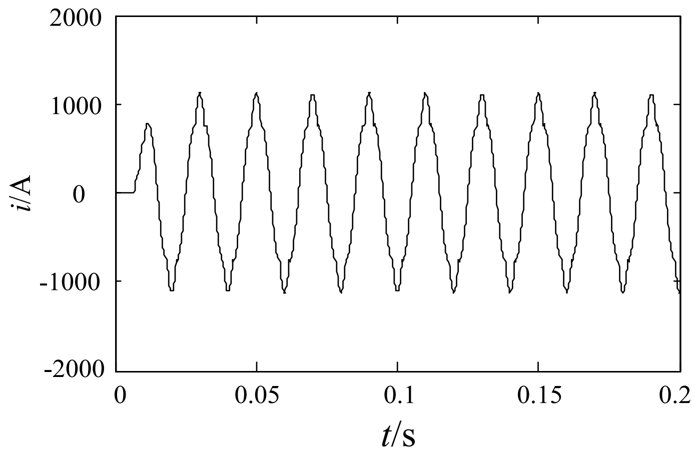

Fig. (4). Waveform of the current which TCR injecting into phase c under symmetrical voltage.

monic current is larger while there is no 3rd harmonic producing by load. However, in this case, the short-time voltage unbalance factor is up to 4% and as a result of that, because there is TCR static VAR compensation in the system, we need to take the influence caused by additional 3rd harmonic current on power system into consideration when system voltage is asymmetrical. Based on the analysis in previous chapter, we adopt an estimation of 31.79 amps as the additional 3rd harmonic current injected into phase-c in our optimization algorithm, and according to the analysis above, we install 3rd, 5th, 7th single tuned filter and 11th second order high-pass filter here. In Genetic algorithm, the initial population was set as 100, crossover probability as 0.7, mutation probability as 0.02. Also, $p_{c\max} = 0.96$, $p_{c\min} = 0.96$, $p_{c\max} = 0.1$, $p_{c\min} = 0.01$, $p_{c2} = 0.1$, $p_{c2} = 0.4$, $g = 1.001$. In this paper, the resonant frequency is 3% lower than the characteristic frequency of harmonic current source, and 10% background harmonic in this system is taken into consideration in order to ensure a better filtering and compensation effect of the PPF under the condition of fluctuating power grid frequency and error in manufacturing precision.

Filter parameters calculated by the optimization algorithm are shown in Table **2**.

Waveform of the current which TCR injecting into phase c under symmetrical voltage is shown in Fig. (**4**).

Frequency spectrum of the current which TCR injects into phase c under symmetrical voltage is given in Fig. (**5**).

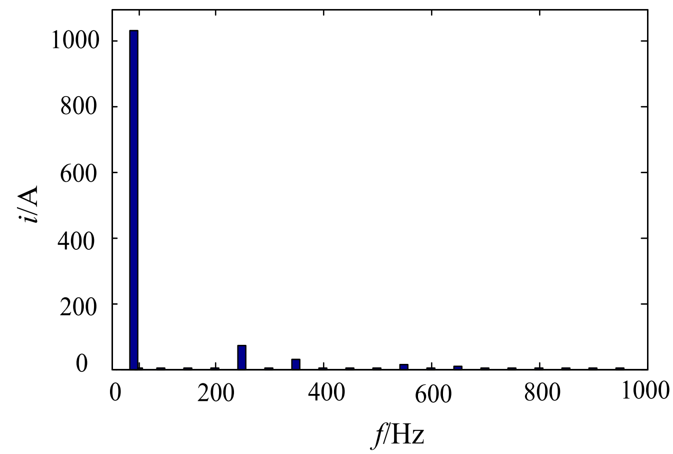

Fig. (5). Frequency spectrum of the current which TCR injecting into phase C under symmetrical voltage.

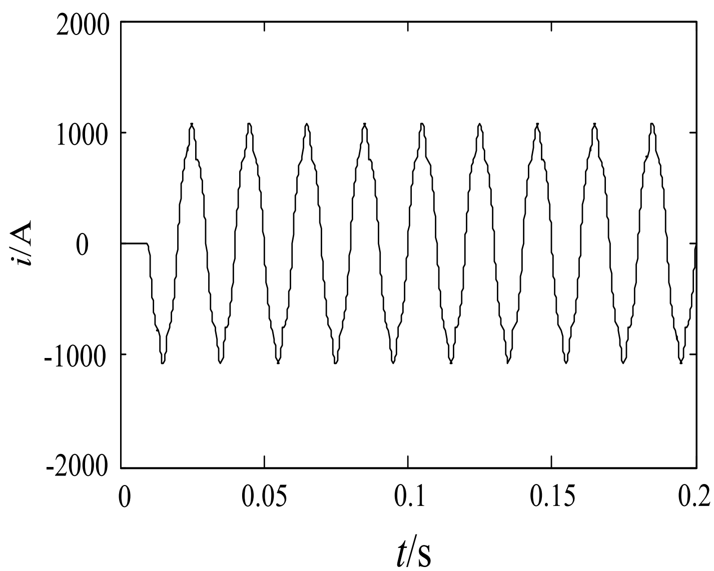

Fig. (6). Waveform of current which TCR injecting into phase C under asymmetrical voltage.

As seen, the 3rd harmonic current produced by TCR under symmetrical voltage is zero sequence current, which does not inject into the power system.

Waveform of the current which TCR injecting into phase-c when trigger delay angle $\alpha = 30^{\circ}$, line voltage asymmetry is 4% and U_{ab1}, U_{ab2} are in-phase, is shown in Fig. (**6**).

Frequency spectrum of the current which TCR injecting into phase c under asymmetrical voltage is given in Fig. (**7**).

As seen from the chart, 3rd harmonic current has increased by 31 amps, which means that the simulation result matches the calculated result in the previous chapter.

Current waveform of power system before PPF operating is shown in Fig. (**8**).

Current frequency spectrum of power system before PPF operating is shown in Fig. (**9**).

As shown, there are larger harmonic components in the system current before compensation devices operating, and after calculation, we obtain the total harmonic factor is 10.51%.

Current waveform of power system after PPF operating is shown in Fig. (**10**).

Current frequency spectrum of power system after PPF operating is shown in Fig. (**11**).

As the figure shows, line current waveform has been obviously improved and the 3rd harmonic current has been filtered after operating the PPF, making the total harmonic factor decrease to 2.13%, which satisfies the national standard. Impedance-frequency characteristics of PPF is shown in Fig. (**12**).

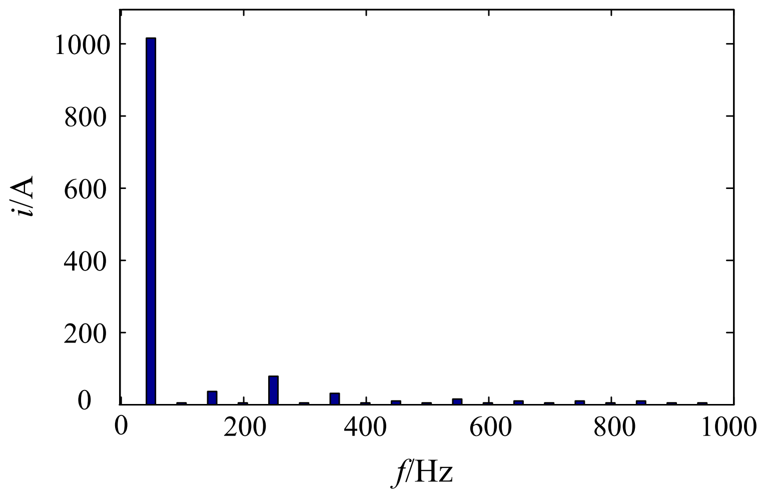

Fig. (7). Frequency spectrum of the current which TCR injecting into phase C under asymmetrical voltage.

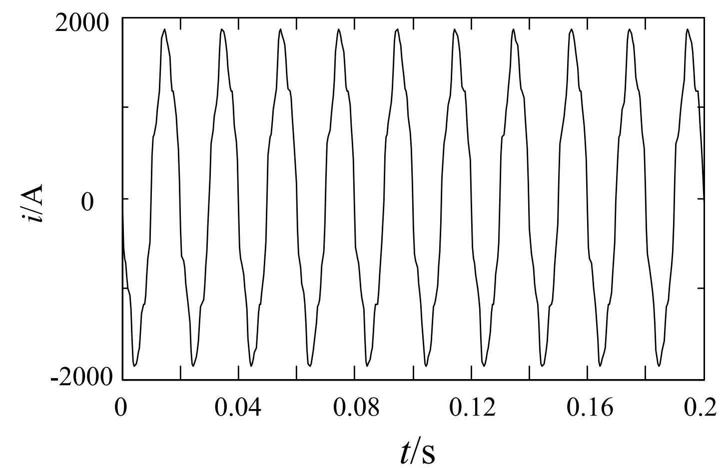

Fig. (8). Current waveform of power system before PPF operating.

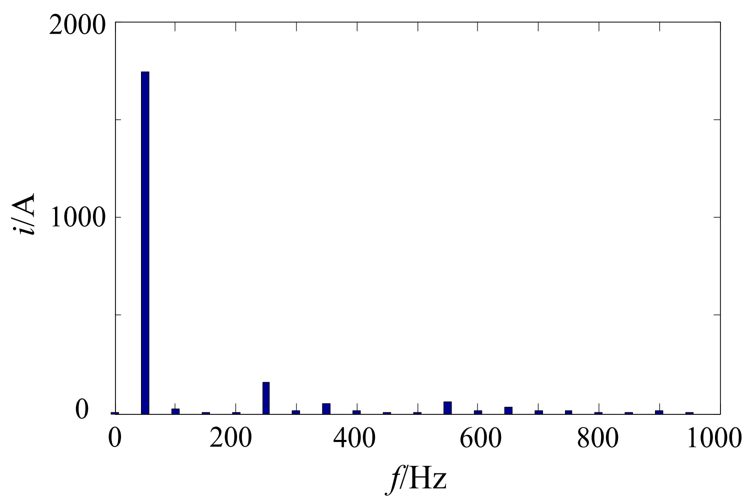

Fig. (9). Current frequency spectrum of power system before PPF operating.

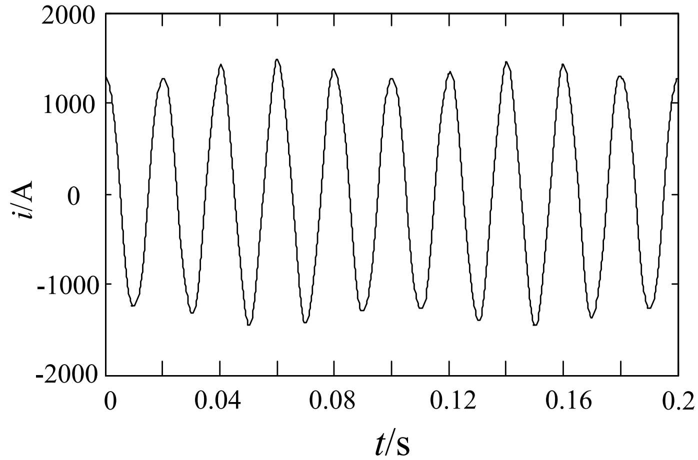

Fig. (10). Current waveform of power system after PPF operating.

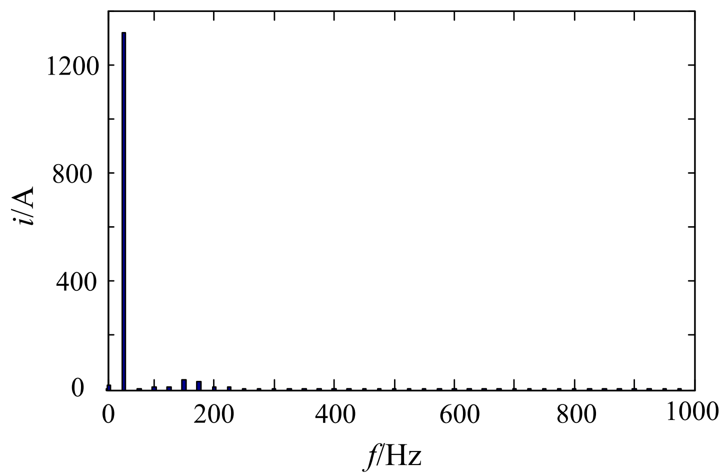

Fig. (11). Current frequency spectrum of power system after PPF operating.

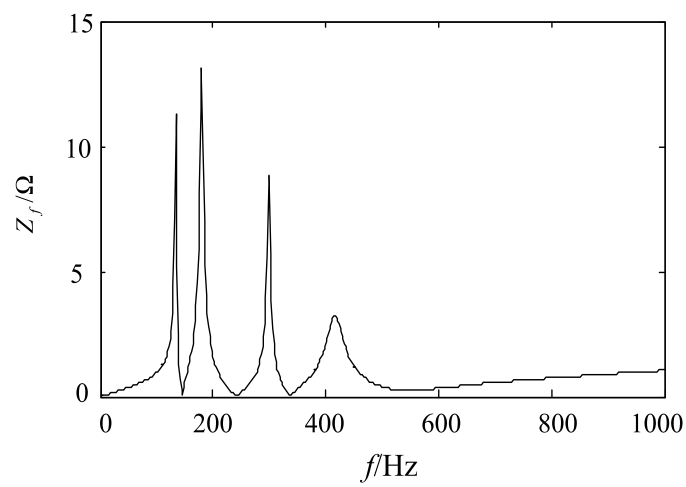

Fig. (12). Impedance-frequency characteristics of PPF.

As the simulation result shows, after optimizing parameters of the filter bank, the effect which is caused by TCR injecting additional 3^{rd} harmonic current on the power system under asymmetrical voltage has been eliminated and we meet the reactive power compensation requirement of the load, while we weaken the harmonic current which load injects into the power system. Above all, the operation effect is excellent.

CONCLUSION

The paper proposes the estimation method of current capacity that TCR generates extra third harmonic current under asymmetrical voltage. Considering extra third harmonic current under asymmetrical voltage, an optimum method based on genetic algorithm is used to design the parameters of power filter. With reactive power compensation and harmonic suppression project of a steel mill as example, the proposed method is simulated by Matlab, simulation results show that the extra third harmonic current generated by TCR under asymmetrical voltage is close to the upper limit of national standard, which must be eliminated. The results proved the necessity of the extra third harmonic current estimation. At the same time, designed power filter achieves predetermined target, reduces harmonics current that load injects into the system, and guarantees the power filter safe operation under asymmetrical voltage.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work is supported by PhD Startup Fund at Northeast Agricultural University (2012RCB16), Postdoctoral Financial Project of Heilongjiang Province and Northeast Agricultural University Innovation Foundation For Postgraduate (yjscx14004).

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Received: June 02, 2015 Revised: August 25, 2015 Accepted: September 11, 2015

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