Optimization Study on TSF Based on Dynamic Modeling Combined with Genetic Algorithm for a Steel Mill

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Abstract—Considering the terrible harmonic pollution and rapid variable reactive power due to the furnaces of 35kV bus, the TSF (Thyristor Switched Filters) has been studied in this paper. Due to superior performance of TSF such as high voltage, high capacity and fast response of compensating reactive power, it was applied to suppress harmonic current and compensate reactive power of secondary side of main transformer of a steel mill of Heilongjiang Province in China. An optimization method of TSF that combining dynamics with GA (Genetic Algorithm) is proposed in this paper.

The work conditions of TSF were modeled and analyzed by Thévenin and Norton theorem, respectively. Considering the perturbation of impedance and frequency of the 35kV power system, response of fundamental current injected into every filter of TSF was analyzed based on dynamics analyzing method. Expressions of harmonic current injected into every filter of TSF were given by character calculation. The results of numerical analysis and measuring results show that, by TSF the harmonic currents injected into power system accord with Chinese national standard GB/T-14549-93 and its power factor is increased to 0.95 from before 0.82. In fact, proposed method can apply to suppress harmonics and compensate reactive power of furnace of 35kV bus of the steel mile.

Index Term—Thyristor Switched Filter; dynamics modeling; parameter perturbation; harmonic current; reactive power; GA (Genetic Algorithm)

I. INTRODUCTION

Comparing to Passive Power Filter (PPF), Thyristor Switched Filters (TSF) can compensate dynamic reactive power and prevent over compensation. Comparing to Static Var Compensator (SVC) [1-2] and Static Var Generator (SVG) [3], TSF has the advantages of high voltage, fast compensating dynamic reactive power, suppressing harmonic and eliminating voltage flicker efficiently. Comparing to Hybrid Active Power Filter (HAPF) [4,5], TSF has the advantage of lower cost and better work effect. Therefore, the research on TSF has great practical value on solving the problems of serious harmonic pollution and dynamic compensation of reactive power on electrical distribution network of high voltage. It also has better effect on protecting power system and corresponding electrical equipment [6,7].

The biggest advantage of TSF to PPF is that the switch of PPF was substituted by thyristor of TSF. In fact, TSF can switch tuning filter by thyristor immediately and accurately according to require of actual reactive power. Considering the resonance of the reactance of power system with filter capacitor of TSF due to the harmonic current, selecting a set of appropriate parameters of TSF is one of the main difficulties for designing TSF. Corresponding to the basic coding rules Thyristor Switched Capacitor (TSC) and PPF, TSF must be taken into consideration of both difficulties [8]. Among performance criterion of TSF such as stability, cost, voltage grade, filter effect, compensation capacity, the stability must be first considered due to the potential influence of resonance between TSF and inductance of the power system. Especially the perturbation of frequency and inductance of power system must be considered in order to avoid the resonance of TSF. In fact series and parallel resonance between TSF and power system often decided
by parameters of TSF. Fig.1 gives a resonance photo of TSF with power system of 690V. It shows that the thyristor and the capacitor of TSF are all burned-out due to the resonance. Therefore, when design TSF, accurate parameters that may be avoid resonance and ensure the safety and stability of TSF must be considered [9-10].

![Resonance photo of TSF with power system](image)

**II. GENETIC ALGORITHM**

Based on GA that was proposed by professor Holland of Michigan state university, multi-objective optimization of parameters of TSF was considered. It superiority function consist of some terms discussed as follows [11].

A. Filter effect and total harmonic distortion (THD)

The design principle of TSF is to filter the harmonic current that feedback to the power system. By TSF the harmonic current must be lower than Chinese national standard GB/T-14549-93. THD of the current is the first optimizing criterion when the multi objective optimization method is applied to optimize the TSF. If fundamental current and every order of harmonic current was obtained the THD may be expressed as follows

\[
. T_i = \sum_{i=1}^{N} \left( \frac{I_i}{I_1} \right)^2 \quad (i = 3, 5, 7, 11, 13, 23, 25) \quad (1a)
\]

\[
T_i \leq T_{max} \quad (1b)
\]

There, variable \( T_i \) denotes the THD of studied harmonic current. Variable \( I_1 \) denotes fundamental current. Variable \( I_{hi} \) \( (i = 3, 5, 7, 11, 13, 23, 25) \) denote the harmonic current that was induced by the load of harmonic source such as power rectifier of DC furnace, inverter of the motor with high capacity and etc. Variable \( T_{max} \) is the standard value of THD that is allowed by Chinese national standard GB/T-14549-93. According to optimization criterion of GA \( T_i \) that describes the distortion degree of current must be minimized.

B. Power factor

![Vector analysis of reactive power compensation](image)

Compensating fundamental reactive power is an important function of TSF that including several single tuning filters and a high passing filter. By the power analyzer U900F the maximal and minimal reactive power of the inductive load of a power system may be obtained, which can be denoted by variables \( Q_{max} \) and
$Q_{\text{min}}$ respectively. In Fig.2 variable $P_{\text{max}}$ and $P_{\text{min}}$ correspond to maximal and minimal active power of inductive load that satisfy following expression

$$\text{taga1} = \frac{Q_{\text{min}}}{P_{\text{max}}} \quad (2a)$$

$$\text{taga2} = \frac{Q_{\text{min}}}{P_{\text{min}}} \quad (2b)$$

Suppose TSF consists of 3.th, 5.th, 7.th, 11.th, 13.th and high pass filter, according to multi objective optimization method of GA, following expression must be satisfied

$$Q_{\text{min}} \leq Q = \sum_{i=3,5,7,11,13,h} Q_i \leq Q_{\text{max}} \quad (3)$$

There variable $Q$ denotes the sum of compensating capacity of total filter that one among it may be denoted by variable $Q_i (i = 3, 5, 7, 11, 13, h)$. Trouble of Eq.3 is that if above filter was switched according to reactive power only, the filter effect of TSF can’t be considered. So filter capacity must be regarded as a criterion of multi objective optimization of GA. Suppose there are 3$^{\text{rd}}$, 5$^{\text{th}}$, 7$^{\text{th}}$, 11$^{\text{th}}$, 13$^{\text{th}}$, 23$^{\text{rd}}$ and 25$^{\text{th}}$ harmonics that may be denoted by $I_3, I_5, I_7, I_{11}, I_{13}, I_{23}$ and $I_{25}$ respectively, compensating capacity of every filter may be described as follows

$$Q_i = \left( I_i / i \right) \sum_{i=3,5,7,11,13,23,25} \left( I_i / i \right) Q \quad (4)$$

Based on above discussing a optimization strategy of switching TSF was given which including following two conclusions,

First, the filter with maximum compensating capacity may be divided into several groups that with same capacity in order to avoid overcompensation.

Second, in order to increase filter capacity of every group, a capacitor of TSF may be instead of a group of two series combined with two parallel connection of capacitor.

Fig.3 Phase diagram of measured voltage and current

Fig.3 is the phase diagram of voltage and current that measured by power analyzer. Angle of power factor and degree of unbalancedness of three phases may be analyzed by positive sequence, negative sequence and zero sequence voltage and current. Fig.3 show that, according to the multi objective optimization method of GA, the power factor of studied power system must be closed to 1.0, at least closed to 0.95.

C. The Lowest Cost of TSF

The cost of TSF is decided by the compensating and filter capacity of TSF which was associated with classification of voltage and capacity of capacitor. Moreover, TSF may be described by a topology consists of circuit breaker, thyristor, fuse, reactor and capacitor and etc.. Except breaker, thyristor and fuse which rated voltage and rated current were only calculated by above topology model, the capacity of every reactor and capacitor which parameters may be modified must be considered, in order to decrease the cost of TSF.

According to multi objective optimization method of GA, the cost of TSF was given by following expression

$$F = \sum_{i=3,5,7,11,13} (P_L + P_C C_i) + P_R R_h + P_L L_k + P_C C_k \quad (5)$$

There $P_L, P_C$ and $P_R$ denote the unit price of the resistor, reactor and capacitor of TSF. $L_i (i = 3, 5, 7, 11, 13)$ and $C_i (i = 3, 5, 7, 11, 13)$ denote the reactor and capacitor of $i^{\text{th}}$ single tuning filter respectively. $R_h, L_k$ and $C_k$ denote the resistor, reactor and capacitor of high pass filter of TSF. Variable $F$ that denotes the total cost of TSF must be minimized by above multi objective optimization method of GA.

III. STUDY BACKGROUND OF DC ARC-FURNACE

In order to suppress harmonic current and compensate reactive power, a harmonic current, power factor, total harmonic distortion and etc. of 35kV bus of a steel mill has been studied. The topology of distribution power system is shown as Fig.4. Rating capacity of main transformer 1# is 12.5MVA. The voltage of primary side and secondary side is 35kV and 0.24kV respectively. Short-circuit impedance of main transformer which connection type is $Y/\Delta$ is 6.67%. There is in-phase inverse parallel rectifier with rated current 6kA in order to eliminate 5$^{\text{th}}$ and 7$^{\text{th}}$ harmonic current induced by three Phases Inverse Bridge.

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There are two DC electric arc-furnaces for rough working and two AC arc-furnaces for precision working in steel mill. Due to asymmetric triggering pulse of inverse parallel rectifier there are 5th, 7th, 11th, 13th, 23rd and 25th harmonic current in 35kV bus. Considering AC arc-furnace with 5000kVA the 3rd harmonic current must be analyzed.

As shown in Fig.4 primary side of transformer $T_1$ and $T_2$ was measured by a Power Quality Analyzer U900F. Every harmonic current injected into 35kV distribution feeder was shown as Tab.1. According to Chinese national standard GB/T-14549-93 and base short-circuit capacity of 35kV bus the harmonic standard value was given that was shown by second row of Tab.I.

![Fig. 4. Schematic diagram of electric arc furnace](image)

<table>
<thead>
<tr>
<th>Order n (A)</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>18.0</td>
<td>18.0</td>
<td>13.2</td>
<td>8.4</td>
<td>7.0</td>
<td>4.1</td>
<td>3.8</td>
</tr>
<tr>
<td>5th</td>
<td>20.3</td>
<td>32.0</td>
<td>36.6</td>
<td>20.5</td>
<td>15.2</td>
<td>4.5</td>
<td>3.9</td>
</tr>
<tr>
<td>7th</td>
<td>30</td>
<td>60</td>
<td>52</td>
<td>32</td>
<td>22</td>
<td>8.3</td>
<td>7.2</td>
</tr>
</tbody>
</table>

The Tab.1 and Fig.5 - Fig.10 show that, the 3rd, 5th, 7th, 11th, 13th, 23rd and 25th harmonic currents were greater than national standard of China. In particular maximum values of 5th and 7th harmonic current are especially terrible. Moreover, there are periodic harmonic currents that were induced by work period of arc furnace.

Fig.11 shows that the current THD of power system is greater than 4% that permitted by Chinese national standard. Fig.12 indicates that the power factor of this power system is about 0.82.
There were switchboard tripping, burn-out cable, computer and TV was automatically turned on, lighting flashing, fuse of consumer line blow out and etc in 35kV bus of the steel mile which induced by terrible harmonic current. Considering the high voltage, terrible harmonic current, rapid varying reactive power and big compensation capacity, TSF is applied to suppress harmonic and compensate reactive power of DC furnace of above steel mile.

IV. DYNAMIC MODELING OF TSF

Considering the effect of in-phase inverse parallel rectifiers with asymmetrical 12 pulse triggering signal of DC furnace, a TSF consist of 5th, 7th, 11th and 13th single tuning filter were presented. Third single tuning filter and high pass filter of TSF were given also according to actual measured harmonic current and power factor. The topology of TSF was shown by Fig.13.

When design the TSF, in order to obtain rated voltage and rated current of corresponding reactor and capacitor of TSF which were decided by fundamental current of power system and harmonic current induced by load, the fundamental model and harmonic model of TSF were given and analyzed by Thevenin and Norton theorem, respectively.

Fig.14 shows the fundamental and harmonic model of TSF, respectively. There $L_s = 35.92 \text{mH}$ and $L_d = 15.89 \text{mH}$ denote the fundamental equivalent inductor of power system and load, respectively. Variable $u$ denote the phase voltage of 35kV bus of steel mine. $L_s(i = 3,5,7,11,13,h)$ and $C_s(i = 3,5,7,11,13,h)$ denote the reactor and capacitor of TSF.

In Fig.14 a), suppose $u_{c_k}(k = 3,5,7,11,13,h)$ and $i_{s_k}(k = 3,5,7,11,13,h)$ denote voltage of capacitor and the loop current of every single tuning filter and high pass filter. By analyzing loop circuit, following dynamic
equations were given

\[
\dot{u}_s = i_{s1}/C_k \quad (k = 3,5,7,11,13,h) \quad (6)
\]

\[
i_{sf} = \frac{u - R_s i_{sf} - u_m - L_s (\Delta - i_{sf})}{L_n + L_s} \quad (n = 3,5,7,11,13) \quad (7)
\]

\[
i_{sf} = [u - L_s i_{sf} - u_m - L_s (\Delta - i_{sf})]/L_s \quad (8)
\]

\[
i_{h} = (R_s/L_n)(i_{sf} - i_{h}) \quad (9)
\]

\[
i_{af} = [u - L_s (\Delta - i_{af})]/(L_n + L_f) \quad (10)
\]

There

\[
\Delta = i_{sf} + i_{f} + i_{s} + i_{af} + i_{hf} + i_{df}
\]

In Eq.6 Variable \( u \) denote phase voltage of 35kV bus of power system that satisfied following expression

\[
u = \sqrt{2}(35/\sqrt{3})\cos(2\pi \cdot f \cdot t)
\]

There \( f \) denote fundamental frequency of power system.

In Fig.14 b), \( i_{sf}(k = 3,5,7,11,13,h,s) \) denote the harmonic current injected into \( i_{fh} \) filter and power system respectively. Define following variables

\[
z_1 = j2\pi fC_k
\]

\[
z_2 = jL_2 \pi fC_k + R_k \cdot j2\pi fL_k / (R_k + j2\pi fL_k)
\]

\[
z_3 = R_k + j(2\pi fC_k / (i = 3,5,7,11,13))
\]

There \( z_1, z_2, z_3 \) denote reactance of power system, high pass filter and \( i_{fh} \) single tuning filter respectively. Variable \( n = 1,2,3,\ldots,23,25 \) denote the order of harmonic current. Applying symbolic computation, the harmonic current injected into power system is express as follows

\[
i_{h} = Z_1/z \cdot Z_2/1 + Z_3/1 - I_n
\]

The harmonic injected into \( i_{fh} \) filter may be expressed as follows

\[
i_{h} = Z_1/1 + Z_2/1 + Z_3/1 - I_n
\]

There \( I_n(n = 1,2,3,\ldots,23,25) \) denote every harmonic current induced by the load, i.e. DC furnace in this paper.

Tab. II and Tab. III show the parameters of TSF by classical algorithm and GA respectively. Comparing Tab.III with Tab. II, obtained parameters of TSF by multi objective optimization of GA, especially capacitors, were standardization product of China. It denotes that the cost of TSF may be evidently decreased by GA.

V. PERTURBATION ANALYSIS OF TSF

In order to decrease the cost of reactor and capacitor and avoid overcompensating, its grade of voltage and current of TSF must be considered also. Based on above analysis the influence of surge current, flicker of voltage or perturbation of impedance and frequency of power system to TSF are studied in this paper.

As shown by Eq.6-Eq.12, the differential equations that described dynamic behaviors of TSF were derived according to KCL (Kirchhoff’s Current Law) and KVL (Kirchhoff’s Voltage Law). Considering perturbation of fundamental frequency \( f \) and inductor \( L_s \) of power system is within \( \pm 1\% \) and \( \pm 5\% \) respectively, the influence of perturbation to rated current of capacitor of TSF were analyzed by dynamic numerical iterative method. Corresponding calculation results are illustrated by Fig.15 to Fig.20.

Fig.15a)-Fig.20a) show the response of fundamental current injected into 3\(^{rd}\), 5\(^{th}\), 7\(^{th}\), 11\(^{th}\) and 13\(^{th}\) single tuning and high pass filter when the perturbation of frequency of power system is within \((\pm 1\%) \times 50Hz\). It indicates that the surge current induced by perturbation of frequency is evidently greater than stationary fundamental current.

Fig.15b)-fig.20b) show the response of
fundamental current injected into 3rd, 5th, 7th, 11th and 13th single tuning and high pass filter when the perturbation of inductor $L_i$ of power system is within $(1\pm5\%) \times 35.93\text{mH}$. It indicates that the surge current induced by perturbation of power system is also evidently greater than stationary fundamental current.

More detail data of current are illustrated by Tab.4. Maximum fundamental currents injected into each filter that was described by Fig.15-fig.20 in condition of perturbation of power system are shown by boldface of Tab.4. It must be considered when design the rated current of the capacitor of TSF.
In fact, the rated current of a capacitor is decided by fundamental and harmonic current injected into the capacitor.

For example, according to Tab.1 and Tab.4 the current injected into 5\textsuperscript{th} single tuning filter are satisfy following expressions

\begin{align}
    i_{5\text{max}} &= \sqrt{i_{5f\text{max}}^2 + i_{5h}^2} = 87.830A \\
    i_{5f\text{max}} &= 78.598A \\
    i_{5h} &= 60A
\end{align}

There, \(i_{5f\text{max}}\) and \(i_{5h}\) denote the maximum fundamental and harmonic current injected into 5\textsuperscript{th} single tuning filter respectively.

Above principle of selecting perturbation current accord with multi objective optimization method and transient response of TSF that induced by perturbation of parameters of power system. Maximum rated current injected into each filter of TSF are shown by Tab. V.
Considering the operating current of a capacitor is usually 1.3 times larger than rated current, the rated current of a capacitor of each filter are shown by fifth row of Tab.5. The question is that, rated current of 5th filter is 39.198A which is 1.94 times less than maximum current injected into this filter. A topology of two groups including 16 capacitors first connected in parallel then they are connected in series each other is proposed. Above topology is illustrated by Fig.21.

By fig.21 that consists of 32 capacitors which capacity of every capacitor is 100kVar, the actual rated current of capacitor of 5th single tuning filter was described by following expression

\[ i_{\text{actual}} = 39.198 \times 2 = 78.396A > 76.06A \quad (19) \]

It indicates that proposed topology can bear maximum current injected into 5th single tuning filter.

**VI. FAULT ANALYSES OF TSF**

A unit of 5th single tuning filter consists of 4 capacitors connected in parallel and series is shown by Fig.22. There are total 8 same units in Fig.21.

Suppose \( I \) denote the total current injected into this unit, in work state it satisfies following expression

\[ i_{51} = i_{52} = i_{53} = i_{54} = \frac{U_{0}}{2} \omega C_{5} / 2 = U_{0} C_{5} / 2 \quad (20) \]

In Eq.20, \( C_{51} = C_{52} = C_{53} = C_{54} = C_{5} \quad (21) \)

In Eq.20 variable \( i_{51}, i_{52}, i_{53} \), and \( i_{54} \) denote the current injected into capacitors that marked by C51, C52, C53 and C54 respectively. Fig.22 b) illustrate the fault state of capacitor that induced by surge current, flicker of voltage or perturbation of impedance and frequency of power system.

For example, if the capacitor C51 burn-out, following expression was satisfied

\[ i_{53} = i_{52} + i_{54} = U_{0} (C_{53} + C_{52} // C_{54}) = 2U_{0} C_{5} / 3 \quad (22a) \]

\[ i_{53} = i_{54} = U_{0} C_{5} / 3 \quad (22b) \]

Comparing Eq.20 to Eq.22a show that current injected into capacitor C53 in fault state is 1.333 times greater than that one in work state, it must be considered when designing a TSF.

Supposing the resonance point of the 5th tuning filter in work state is \( n_{w0} \) that satisfy

\[ n_{w0} = \frac{1}{2\pi L_{c_{5}}} = 4.85 \quad (23) \]

There \( L_{c_{5}} \) denote the reactor of 5th filter.

\[ n_{w0}^{'} = \frac{1}{2\pi \sqrt{2/3} L_{c_{5}}} = \frac{3}{2} \sqrt{n_{w0}} = 5.94 \quad (24) \]

It indicates that resonance point of 5th tuning filter in fault state is 1.225 times greater than that one in work state. Eq.24 implies that the 6th harmonic current will inject into the 5th tuning filter when the fault occur.
are the main reasons that influence the stability of response of TSF.

The instability of TSF, i.e. the resonance induced by perturbation of parameters of power system must be avoided. Above discussing may give a reference to designing the parameters of TSF.

VII. EFFECT ANALYSIS OF TSF

In order to predict the effect of TSF the characters calculation method was applied to modeling and simulating the TSF.

Obtained detail data was shown by Fig.24 where the symbol “Δ” denote the standard value of harmonic current accord with national standard GB/T-14549-93 of China. Symbol “○” denotes actual harmonic current injected into the power system, symbol “*”denotes harmonic current by TSF.

Fig.24 indicates that the harmonic current injected into power system by TSF was evidently lower than national standard GB/T-14549-93. As a matter of fact, the effect of TSF may be influenced by the many complex elements of power system such as perturbation of frequency and inductance, load variation and etc..

Fig.25-Fig.29 illustrates the harmonic current injected into second line of 35kV bus by TSF which data are measured by U900F at one time. There “+” and red line denote the $i^{th}$ harmonic current injected into power system by TSF and not respectively.

It indicates that the 3$^{rd}$, 5$^{th}$, 7$^{th}$, 11$^{th}$ and 13$^{th}$ harmonic current injected into second line of 35kV bus by TSF are evidently less than that one when TSF wasn’t applied.

An especially conditions were shown by Fig.26 and Fig.27 there were some 5$^{th}$ or 7$^{th}$ harmonic current wasn’t eliminated. For example, between 19:03:24 and 19:53:24 of Fig.26, there was a peak value of 5$^{th}$ harmonic current that reached to 32A which overrated national standard GB/T-14549-93 of China. This problem for surges current that induced by switching dynamic filter of TSF may solved by taking an ulcerior optimizing control stratagem of crossing zero of voltage.

Fig. 24. Harmonic current injected into power system

Fig. 25. 3$^{th}$ harmonic inject into power system by TSF

Fig. 26. 5$^{th}$ harmonic inject into power system by TSF

Fig. 27. 7$^{th}$ harmonic inject into power system by TSF
In this paper the TSF was applied to suppressing harmonic current and compensating reactive power of the furnaces of a steel mile of China. In order to decrease the cost of TSF the optimization method of GA was applied to normalizing the parameters of TSF. Based on Thevenin and Norton theorem a dynamic model of TSF in condition of fundamental and harmonic current that described the behavior of TSF was given respectively.

Combining the dynamic modeling method with KCL and KVL, the perturbation of impedance and frequency of the 35kV power system was analyzed. Expressions of harmonic current injected into every filter of TSF were derived by character calculation. Based on presented method the maximum rated current of the capacitors and reactors of TSF may be decided.

The results of simulation model and measure practice show that, the harmonic currents injected into power system and power factor accord with national standard GB/T-14549-93 of China. Except the analysis of this paper, the proposed method may used to analyze other similar system, such as suppress drop off voltage and harmonic distortion of wind power system when it was connected with the power system.

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REFERENCES


Comparing Fig.30 with Fig.12 show that, the power factor of 35kV bus increases from 0.82 to 0.95 by TSF. There isn’t any overcompensation of reactive power in Fig.30.

Comparing Fig.31 with Fig.11 show that, the THD of current of 35kV bus decreases from about 20% to 7.8%. It indicates that the harmonic current injected into the power system was evidently suppressed.


Liguang Wang was born in Heilongjiang Province, China, in 1972. He received his Ph.D. in Electrical Engineering from the Harbin Institute of Technology, Harbin, China, in 2002. Since 2003, he has been with the Department of Electrical and Electronics Engineering, Harbin Institute of Technology, where he is currently an Associate Professor. His current research interests include harmonic suppression and reactive power compensation of power system, parameter identification in ac machines, and nonlinear modeling methods.