Chapter 13
Harmonic Analysis and Optimum Allocation of Filters in CSCT

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Abstract A new shunt reactive power compensator, CSCT, is presented and introduced in this paper. Mathematical analysis of harmonic content of the current of CSCT is performed and use of a winding with additional circuit has been presented as a solution to suppress these harmonics.

Keywords CSCT · Harmonic filter · Reactive power compensation · Thyristor controlled transformer

13.1 Introduction

CSCT stands for "Controlled Shunt Compensator of Transformer type" [1–3]. A general scheme of this compensator is presented in Fig. 13.1. This configuration is a transformer with three windings. NW is network winding which is connected to the network and is the main winding of the compensator. CW is the second winding to which a thyristor valve and a parallel voltage circuit breaker are connected and is called CW briefly. The third winding is compensating winding which is indicated by ComW in Fig. 13.1. Two highest harmonic filters and a capacitor bank are connected to this winding. It is important to note that CSCT is a three phase compensator. The connection of NWs of three phases is star and the neutral is grounded. Control windings' connection is as same as network windings of three phases. However compensating windings can be delta in connection together.

When the thyristor is opened all the magnetic flux passes through the magnetic core leading to a minimum reluctance, maximum inductance and a capacitive current in NW according to the value of capacitor bank and eventually generate reactive power to the network. On contrary, when the thyristor is closed the flux is subjected to pass through air gap including all of the windings. Hence the reluctance, inductance and the current of NW will be maximal, minimal and maximal inductive (the rated value) respectively.

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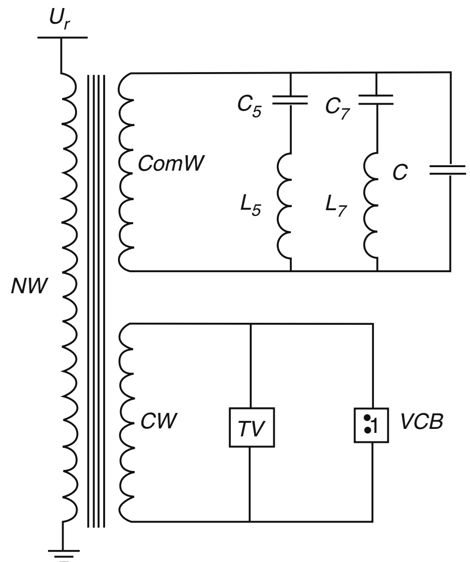

Fig. 13.1 General scheme of a CSCT: TV-thyristors valve, VCB-vacuum circuit breaker, C5-L5 and C7-L7 filters of fifth and seventh harmonics, C-additional capacitor bank

Since there is a reactive power flow control by a thyristor type switch, there will be different order harmonics in the current of NW whose magnitudes depend on the firing angle of the thyristor or generally the closure moment of the switch. Harmonic filters are engaged due to suppress principally the harmonics with the highest degrees since the bigger is the degree of the harmonic, the bigger is the amplitude of the harmonic and correspondingly the harder is elimination of that harmonic. Not only is the harmonic filters design difficult in many cases, but also the cost of them is usually significant. In many cases there may be different solutions to design the filter. However there is certainly the best way to compromise between efficiency of the filters and the costs. It is endeavored in this paper to find the best allocation and design of the harmonic filters to remove harmonic components so that both high efficiency and low costs to be satisfied in the best way. This called for some mathematical analysis and equivalent circuits for the windings of the transformer.

Figure 13.2 represents one phase of the transformer with mentioned three windings. The winding close to the main core is CW, the outer winding is NW and interlayed winding is ComW.

13.2 Mathematical Analysis to Calculate Harmonic Components of the Current

Applying thyristors to control the current of the compensator brings highest harmonics in the current. Highest harmonics are formed during incomplete combustion angle of thyristors when current flows intermittently through thyristor block. With angles $0 \leq \omega t \leq \psi$ and $\pi - \psi \leq \omega t \leq \pi$ the current equals zero, and with angles $\psi < \omega t < \pi - \psi$,

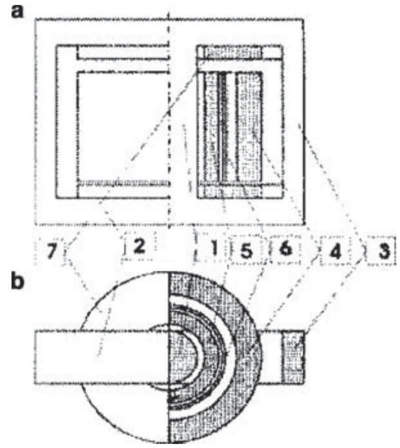

Fig. 13.2 Mono phase diagram of CSCT: (**a**) view form side; (**b**) view form above: 1 – a main core, 2 – yokes, 3 – lateral yokes, 4 – NW, 5 – CW, 6 – ComW, 7 – magnetic shunts

$$i(t) = I_m \cdot (\sin \omega t - \sin \psi) \tag{13.1}$$

Where the firing angle ψ can change in the range of $0 < \psi < \pi/2$.

$$I(\psi) = I_m \cdot \sqrt{\frac{1}{\pi} \int_{\psi}^{\pi-\psi} (\sin wt - \sin \psi)^2 dwt} = \\ = I_m \cdot \sqrt{\frac{1}{\pi} \cdot [(\pi - 2\psi) \cdot (0,5 + \sin^2 \psi) - 1,5 \sin 2\psi]} \tag{13.2}$$

of the root-mean-square current through the thyristor at arbitrary firing angle ψ to the root-mean-square of rated current $I = I_m/\sqrt{2}$ (corresponding with angle $\psi = 0$) equals to:

$$\frac{I(\psi)}{I} = \sqrt{\frac{1}{\pi} \cdot [(\pi - 2\psi) \cdot (1 + 2\sin^2 \psi) - 3 \sin 2\psi]} = \\ = \sqrt{\left(1 - \frac{2\psi}{\pi}\right) \cdot (1 + 2\sin^2 \psi) - \frac{3}{\pi} \cdot \sin 2\psi]} \tag{13.3}$$

The current through the thyristor block decreases fast with increase in ignition angle (see Fig. 13.3). Thus the content of the higher harmonics strongly changes with change in ignition angle and can be calculated by the formula

$$k_{h.k.} = \frac{I_k}{I_1} = \frac{2}{k} \cdot \frac{\frac{\sin(k-1)\cdot\psi}{k-1} + \frac{\sin(k+1)\cdot\psi}{k+1}}{\pi - 2\psi - \sin 2\psi} \tag{13.4}$$

Where I_k and I_1 are amplitudes of k-th and fundamental harmony.

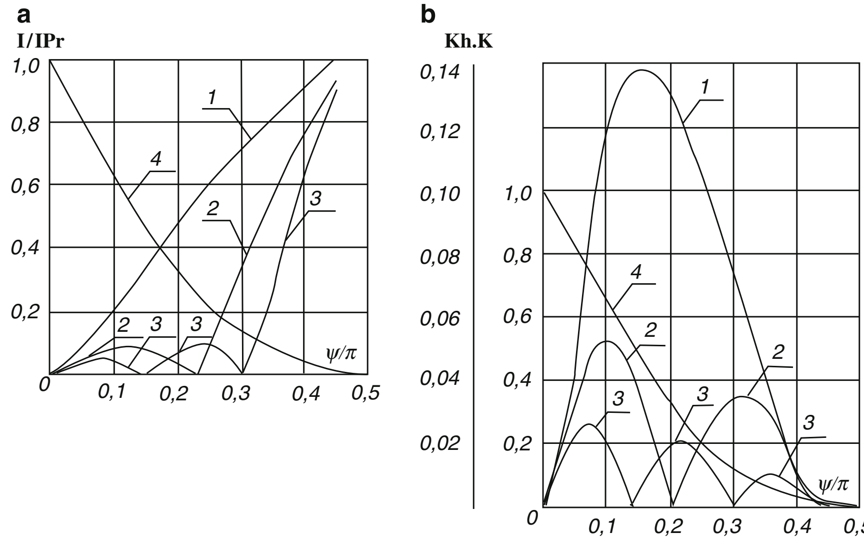

Fig. 13.3 The ratio of currents of highest harmonics: third (1). fifth (2), seventh (3) to the current of the basic frequency with dependence on ignition angle of thyristors $0 < \psi < 90°$: (**a**) in relation to present current of basic frequency; –(**b**) in relation to rated current (when thyristors are completely closed); four-ratio of root-mean-square value of full current to rated current

Results of calculations with this formula are shown in Fig. 13.3. As seen, increase in number of harmonics leads to decrease in its content. Thus the content of the third harmonic in the current continuously increases with reduction in combustion time of thyristors (increase in firing angle of thyristors). With small firing angles of thyristors (greater combustion angles), the increase in the content of the fifth harmonic is replaced by a reduction down to zero when firing angle $\psi = 0.22\pi$ and then increases again approaching 100% under a very small reactor current. The content of the seventh harmonic passes through the minimum (zero) twice and then sharply increases approaching 100% (Fig. 13.3).

The ratio of current corresponding to the highest harmonics to that of rated reactor current (to current when thyristors are completely opened) has entirely different character. For the third harmonic this attitude reaches a maximum when the reactor current is $I = 0.42I_{nom}$ (see curves 1 and 4 of Fig. 13.3b). For the fifth harmonic the maximum is reached at the current $I = 0.63I_{nom}$ (see curves 2 and 4 of Fig. 13.3b). For the seventh harmonic it is reached when reactor current $I = 0.72I_{nom}$. The second maximum of the fifth harmonic is much less than the first. The second and third maximum of the seventh harmonic is also much less than the first.

Value of the first maximum in relation to amplitude of rated current, are resulted in Table 13.1 (designated by the letter β_k).

Special winding in delta connection (compensating winding) is usually used for the compensation of the highest harmonics (third). In this case for the third harmonic this compensatory winding is short-circuit, that excludes the possibility of third harmonics in magnetic flux enveloping the compensation winding.

Table 13.1 Reactive powers of capacitors and inductors related to each harmonic

k	β_k	α_k	$\frac{Q_k}{Q_{nom}}$	$\frac{Q_{c.k}}{Q_{nom}}$	$\frac{Q_{L.k}}{Q_{nom}}$
3	0.138	0.102	0.28	0.19	0.087
5	0.05	0.030	0.068	0.049	0.019
7	0.026	0.013	0.028	0.020	0.0073
11	0.0105	0.0044	0.0090	0.0067	0.0023
13	0.0075	0.0030	0.006	0.0045	0.0015

There are circuit designs for fifth and seventh harmonics suppression. But they are very complex and expensive. The most simple, cheap and reliable enough design is the application of filters of higher harmonics, connected to compensating windings of each of the phases. Each of such filters consists series-connected reactor (with stable inductance) and capacitors selected in such a way that they provide compensating winding short-circuit for each of the harmonics. Thus the corresponding harmonic cannot be hold in the magnetic flux engulfing compensating winding. The filter can also provide compensation of the third harmonic component of a single phase reactor.

Since the source of highest harmonics in reactor current is the control winding with thyristors, the compensating windings should cover it to exclude the possibility of keeping higher harmonics in magnetic flux and by that in the current of the network winding covering the control winding and compensating winding.

Thus for the compensation of the k-th harmonic in the current, CSCT should adhere to the equality

$$k\omega L_k = \frac{1}{k\omega C_k} \tag{13.5}$$

From there

$$\omega C_k = \frac{1}{k^2 \omega L_k} \tag{13.6}$$

Thus under no-load conditions when control block thyristors are shut (Fig. 13.4), compensating winding (ComW) of CSCT is loaded by impedance

$$X_{1,k} = \omega L_k - \frac{1}{\omega C_k} = \omega L_k \cdot (1 - k^2) = \frac{1}{\omega C_k} \frac{1 - k^2}{k^2} \tag{13.7}$$

Conformably the fundamental frequency current in control winding current of CSCT, due to filter of k-th harmonic, equals

$$I_{1,k} = \frac{U_{ph}}{\delta X_{nom} + X_{1,k}} = \frac{U_{ph}}{\delta X_{nom} + \omega L_k \cdot (1 - k^2)} = \frac{U_{ph}}{\delta X_{nom} + \frac{1}{\omega C_k} \cdot \left(\frac{1}{k^2} - 1\right)} \tag{13.8}$$

Where δX_{nom} defines the short-circuit impedance of the basic winding in relation to ComW with filters and X_{nom} also defines the rated short-circuit impedance of the

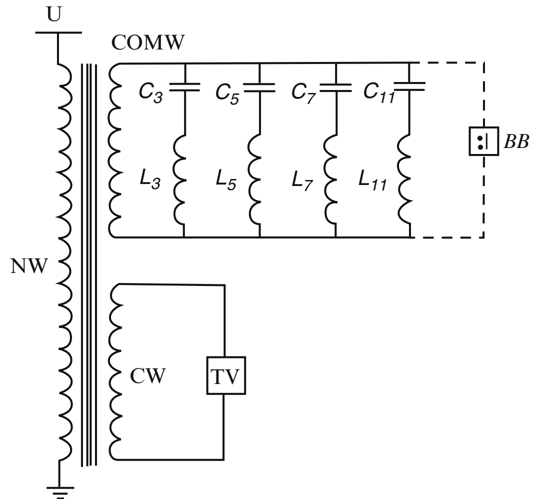

Fig. 13.4 Schematic diagram of CSCT with higher harmonics filters

basic winding in relation to control winding (CW). Since the optimal impedance value X1.k is greater than impedance δX_{nom} (see below), the current through the filter has capacitive character and the ratio of current I1.k to rated current has a negative sign.

$$\frac{I_{1,k}}{I_{nom}} = \frac{X_{nom}}{\delta X_{nom} + \omega L_k \cdot (1 - k^2)} = \frac{X_{nom}}{\delta X_{nom} + \frac{1}{\omega C_k} \cdot \left(\frac{1}{k^2} - 1\right)}$$
$$= -\alpha_k \approx \frac{X_{nom}}{\delta X_{nom} - \frac{1}{\omega C_k}} \tag{13.9}$$

Where α_k is the absolute value of the ratio of basic frequency current through the k-th harmonic filter to rated reactor current.

Resolving Equation (13.9) in relation to ωL_k, we get

$$\omega L_k = X_{nom} \cdot \frac{1 + \alpha_k \delta}{\alpha_k \cdot (k^2 - 1)} \tag{13.10}$$

Capacitor impedance of the k-th harmonic filter to power current according to (13.6), (13.10) equals to:

$$\frac{1}{\omega C_k} = X_{nom} \cdot \frac{k^2 \cdot (1 + \alpha_k \delta)}{\alpha_k \cdot (k^2 - 1)} \tag{13.11}$$

Power of the k-th harmonic filter chokes, due to basic frequency current is:

$$Q_{L_k} = I_{1.k}^2 \cdot \omega \cdot L_k = {\alpha_k}^2 \cdot I_{nom}^2 \cdot X_{nom} \cdot \frac{1 + \alpha_k \delta}{\alpha_k \cdot (k^2 - 1)} \tag{13.12}$$

Capacitor power of the same filter is:

$$Q_{C_k} = I_{1.k}^2 \cdot \frac{1}{\omega \cdot C_k} = {\alpha_k}^2 \cdot I_{nom}^2 \cdot X_{nom} \cdot \frac{k^2(1 + \alpha_k \delta)}{\alpha_k \cdot (k^2 - 1)} \tag{13.13}$$

Total absolute k-th harmonic filter power due to basic frequency current

$$Q_{\sum .k} = Q_{L_k} + Q_{C_k} = {\alpha_k}^2 \cdot Q_{nom} \cdot \frac{(1 + k^2)(1 + \alpha_k \delta)}{k^2 - 1} \tag{13.14}$$

Where the rated power of one phase of the reactor equals

$$Q_{nom} = I_{nom}^2 \cdot X_{nom} \tag{13.15}$$

The maximum current of the k-th harmonic through the filter of that harmonic can be calculated analytically and defined according to (13.4) by

$$I_k = \beta_k \cdot I_{nom} \tag{13.16}$$

Accordingly total absolute power of k-th harmonic filter, due to current of k-th harmonic

$$\begin{aligned} Q_{k.k.} &= I_k^2 \cdot \left(k \cdot \omega \cdot L_k + \frac{1}{k \cdot \omega \cdot C_k} \right) = 2 I_k^2 \cdot k \cdot \omega \cdot L_k = \\ &= 2\beta_k^2 \cdot I_{nom}^2 \cdot X_{nom} \frac{k \cdot (1 + \alpha_k \cdot \delta)}{\alpha_k \cdot (k^2 - 1)} = 2\beta_k^2 \cdot Q_{nom} \frac{k \cdot (1 + \alpha_k \cdot \delta)}{\alpha_k \cdot (k^2 - 1)} \end{aligned} \tag{13.17}$$

Total absolute power of k-th harmonic filter, due to currents of basic and k-th harmonics equals to:

$$Q_k = Q_{k.1} + Q_{k.k} = Q_{nom} \cdot \frac{1 + \alpha_k \cdot \delta}{k^2 - 1} \cdot \left[\alpha_k \cdot (1 + k^2) + 2\beta_k^2 \cdot \frac{k}{\alpha_k} \right] \tag{13.18}$$

We shall find the optimum value Q_k by equating zero derivative of Q_k on α_k

$$\frac{\partial Q_k}{\partial \alpha_k} = \frac{1}{k^2 - 1} \cdot \left[1 + k^2 - 2 \cdot \frac{\beta_k^2 \cdot k}{{\alpha^2}_k} + 2\alpha_k \cdot \delta \cdot (1 + k^2) \right] \cdot Q_{nom} = 0 \tag{13.19}$$

From last equation we get the value α_k corresponding to the minimum power of k-th harmonic filter

$$\alpha_k = \beta_k \cdot \sqrt{\frac{2k}{(1 + k^2) \cdot (1 + 2\alpha_k \cdot \delta)}} \tag{13.20}$$

In this solution, α_k also contains a small term under a root. The smallness of this term allows to calculate α_k by method of successive approximation, assuming as a first approximation that $\alpha_k = 0$ or $\alpha_k = \beta_k$. Taking calculation data for highest harmonic according to data of the following table and estimating the value $\delta = 0.5$, we obtain the following values of α_k and corresponding filter capacity according to (13.17), and also relative values of power capacitors ($Q_{c.k}$) and reactors ($Q_{L.k}$) of filters subject to high-frequency current component (see Table 13.1).

It follows from the resulted data, that the capacity of filters contains a small part of CSCT capacity, especially in the case when the third harmonic is compensated by compensating windings in delta connection of the three phases of CSCT. In this case total capacity of filters does not exceed 10% of reactor power.

To estimate the efficiency of highest harmonics restrictions in reactor current, we shall consider its equivalent circuit in resonance mode in the k-th harmonics (Fig. 13.5). We shall estimate parameters of CSCT equivalent circuit according to Fig. 13.4. In this case the equivalent cross-section of magnetic flux linked with network winding (NW), during short-circuit of control winding (CW) is:

$$F_{eff.1} \approx \pi \cdot d_{12} \cdot \left(a_{12} + \frac{a_1 + a_2}{3} \right) \quad (13.21)$$

Where d12 – mean gap diameter between CW and NW, a12 – gap thickness (radial size), a1 and a2 – thicknesses of CW and NW (radial size).

Equivalent cross-section of magnetic flux linked with CW, during short-circuited ComW, in which filters are connected in parallel,

$$F_{eff.2} \approx \pi \cdot d_{13} \cdot \left(a_{13} + \frac{a_1 + a_3}{3} \right) \quad (13.22)$$

Where d13 – mean gap diameter between ComW and CW, a3 – thickness (radial size) of ComW ($a_3 \approx 0.3a_2$).

If ComW is located in the middle of CW and NW, $d_{13} = d_{12} + a_{13}; a_{13} = 0.5a_{12}$

Equivalent cross-section of magnetic flux linked with ComW during short-circuited CW,

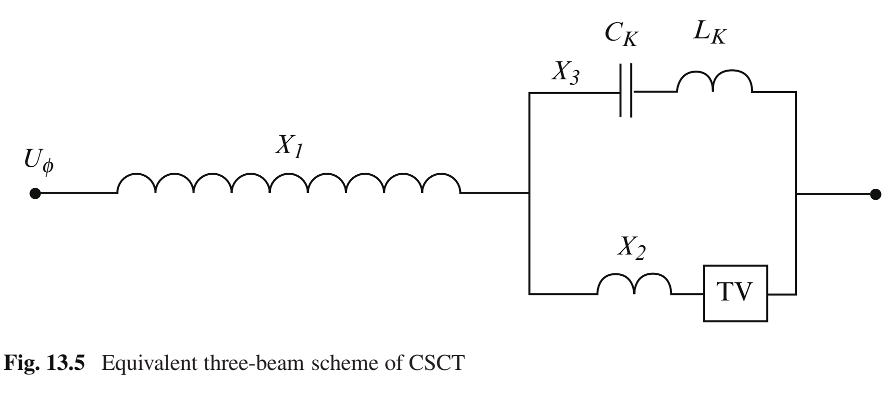

Fig. 13.5 Equivalent three-beam scheme of CSCT

$$F_{eff.3} \approx \pi \cdot d_{23} \cdot \left(a_{23} + \frac{a_2 + a_3}{3} \right) \tag{13.23}$$

Where d23 – mean diameter of a gap between CW and ComW, a23 – thickness of that gap.

In the particular case, where ComW is positioned in the middle of CW and NW, considering that the thickness of ComW is small in comparison with CW and NW, we get $a_{23} = 0.5a_{12},\ d_{23} = d_{12} - a_{23}$.

Correspondingly, the short-circuit impedance of NW in relation to CW equals

$$X_{12} = \frac{8 \cdot 10^{-7} \cdot \pi^2 \cdot f \cdot N_1^2 \cdot F_{eff.1}}{l_0} = X_{\min} \tag{13.24}$$

Where N1 – number of turns of NW, l_0 is height of magnetic conductor window.

Short-circuit impedance of NW in relation to ComW of closed filters,

$$X_{13} = \frac{8 \cdot 10^{-7} \cdot \pi^2 \cdot f \cdot N_1^2 \cdot F_{eff.2}}{l_0} = X_{\min} \cdot \frac{F_{eff.2}}{F_{eff.1}} = \delta \cdot X_{\min} \tag{13.25}$$

For example, it is always possible to choose the position of ComW so that $\delta = 0.5$.

Short-circuit impedance of ComW in relation to CW

$$X_{23} = \frac{8 \cdot 10^{-7} \cdot \pi^2 \cdot f \cdot N_1^2 \cdot F_{eff.3}}{l_0} = (1 - \delta) \cdot X_{\min} \tag{13.26}$$

When $\delta = 0.5$, $X_{23} = 0.5X_{\min}$.

The parameters of k-th harmonics equivalent three-beam scheme of CSCT from the deduced relations equals (see Fig. 13.5).

$$\left.\begin{aligned} X_{1.k} &= \tfrac{k}{2} \cdot (X_{12} + X_{13} - X_{23}) = k\delta \cdot X_{\min}; \\ X_{2.k} &= \tfrac{k}{2} \cdot (X_{12} + X_{23} - X_{13}) = k \cdot (1 - \delta) \cdot X_{\min}; \\ X_{3.k} &= \tfrac{k}{2} \cdot (X_{13} + X_{23} - X_{12}) = 0. \end{aligned}\right\} \tag{13.27}$$

Hence, the equivalent circuit for k-th harmonics looks like represented in Fig. 13.6, where the thyristor block is equivalent to the current generator. Apparently, in this case all the current of k-th harmonic become locked in the filter and does not get in the network winding.

ComW suppresses higher harmonics most effectively when it is positioned in between CW and NW.

Further it is necessary to find out the influence of the presence of highest harmonics filters on CSCT rated current. Nominal condition complies with the complete closing of thyristors when highest harmonics in reactor current are absent.

The equivalent circuit for the first harmonics when the thyristors are completely closed is represented in Fig. 13.7. Equivalent impedance of branch 3 with filter equals to the impedance of the filter (13.7)

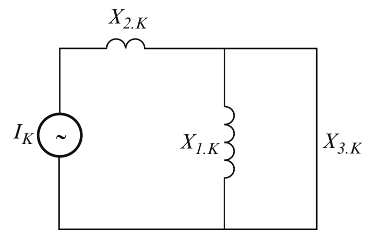

Fig. 13.6 Equivalent three-beam scheme of CSCT for k-th harmonic when ComW is positioned between CW and NW

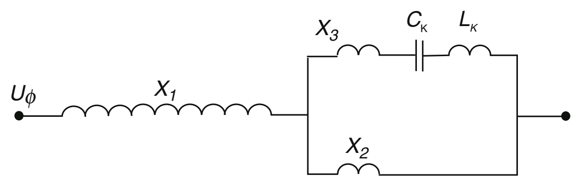

Fig. 13.7 Equivalent circuit of CSCT in normal mode for calculating power current considering k-th harmonic filter

$$X_{3.eq} \cdot \omega \cdot L_k \cdot (1 - k^2) = \\ = X_{\min} \cdot \frac{1 + \delta \cdot \alpha_k}{(k^2 - 1) \cdot \alpha_k} \cdot (1 - k^2) = -X_{\min} \cdot \frac{1 + \delta \cdot \alpha_k}{\alpha_k} \tag{13.28}$$

Equivalent impedance of branch 2 in accordance with (13.25) equals to $X_{2.eq} = (1 - \delta) \cdot X_{\min}$.

Equivalent impedance for the parallel connection of branches 2 and 3

$$X_{2.3.eq} = \frac{X_{2.eq} \cdot X_{3.eq}}{X_{2.eq} + X_{3.eq}} = X_{\min} \cdot \frac{1 - \delta}{1 - \frac{\alpha_k \cdot (1 - \delta)}{1 + \delta \cdot \alpha_k}} \tag{13.29}$$

Total equivalent impedance of CSCT in normal mode considering k-th harmonic filter in accordance with (13.25), (13.27) equals

$$X_{eq.\min} = X_1 + X_{2.3.eq} = \delta \cdot X_{\min} + X_{\min} \frac{1 - \delta}{1 - \frac{\alpha_k \cdot (1 - \delta)}{1 + \delta \cdot \alpha_k}} \\ = X_{\min} \frac{1 + \delta^2 \alpha_k}{[1 + \alpha_k (2\delta - 1)]} \tag{13.30}$$

For example when $\delta = 0.5$ considering the third harmonic filter with the biggest current (see Table 13.1, $\alpha_3 = 0.102$), we shall get

$$X_{eq.\min} = X_{\min} \cdot \frac{1 + 0.102 \cdot 0.5^2}{(1 + 0.102 \cdot 0)} = 1.025 \cdot X_{\min} \tag{13.31}$$

In that case, the presence of filters greatly reduces the rated current of CSCT (approximately by 3%) in comparison with CSCT without filters.

It is necessary to note that the presence of compensation winding with filters between CW and NW allows the provision of short-term forced capacity of the reactor which is necessary for drastic restriction of switching overvoltages. In as much as the inductive impedance of CSCT at short circuit ComW is less than at short circuit CW ($\delta < 1$), short-term short-circuit of ComW, for example, with vacuum switch (VCB on Fig. 13.4), will lead to forced capacity of CSCT about $1/\delta$ times. When $\delta = 0.5$ the forced reactor capacity will exceed nominal two times.

The cross-section of compensation winding (ComW) accordingly as stated above should be chosen the course of all currents. During delta connection of ComW it is necessary to consider the current of the third harmonic in the triangle according to Table 13.1.

$$I_3 = 0.138 I_{1.\max} \cdot k_{tr}$$

Where k_{tr} is ratio of turns in NW and ComW.

Power current and fifth harmonic current through fifth harmonic filter

$$I_5 = (0.03 + 0.05) \cdot I_{1.\max} \cdot k_{tr}$$

Power current and seventh harmonic current through seventh harmonic filter

$$I_7 = (0.013 + 0.025) \cdot I_{1.\max} \cdot k_{tr}$$

As such, total current through ComW equals

$$I_{Com.\Sigma} = 0.256 \cdot I_{1.\max} \cdot k_{tr}$$

Considering the discrepancy of the maximum of all currents components, it is possible to reduce the rated current of ComW, in delta connection and take

$$I_{Com.nom} = 0.2 I_{1.\max} \cdot k_{tr}$$

It is necessary to consider presence of the third harmonic filter when the triangle of ComW is opened (by its star connection) and respectively in addition to consider the power current of the third harmonics filter. As a result, the total current of ComW in this case equals

$$I_{Com.\Sigma} = 0.358 I_{1.\max} \cdot k_{tr}$$

Considering the discrepancy of the maximum of all currents components, it is possible to reduce the rated current of ComW and take

$$I_{Com.nom} = 0.3 I_{1.\max} \cdot k_{tr}$$

The cross-section of conductor ComW equals

$$F_{co.Com} = \frac{I_{Com.nom}}{J_{Com.opt}}$$

The volume of copper of ComW equals

$$V_{co.Com} = \pi \cdot d_{Com.av} \cdot N_{Com} \cdot F_{co.Com}$$

Where NCom $= \frac{N_1}{k_{tr}}$.

It is necessary to add this volume of copper to the total volume of copper of operated reactors. For example, for reactor with ComW in star connection:

$$V_{co.Com} = \pi \cdot d_{Com.av} \cdot \frac{N_1}{k_{tr}} \cdot \frac{0.3 \cdot I_{1.\max} k_{tr}}{J_{Com.opt}} = \pi \cdot d_{Com.av} \cdot \frac{0.3 N_1 \cdot I_{1.\max}}{J_{Com.opt}} \quad (13.32)$$

13.3 Conclusion

CSCT as a new device to compensate reactive power in power systems was introduced in the paper. The main scheme of this device was also presented and illustrated.

Using a thyristor to control the current of the compensator leads to appearance of harmonics in the current. Basic equations of highest harmonics in the current of the compensator are presented. Moreover adding a third winding with highest harmonic filters in less voltage and more current levels than NW is presented as a solution to suppress the harmonics. It is demonstrated in this paper that the optimum place to emplace this winding is between NW and CW.

Obtained results prove that the content of harmonics in the current of CSCT is less than 2% and this fact denotes a successful design of damping surplus harmonics in the current of CSCT.

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