Considering Capacitive Component in the Current of the CSCT Compensator

Mohammad Tavakoli Bina, G.N.Alexandrov and Mohammad Golkhah

Abstract— **The controlled shunt compensator of transformer type (CSCT) provides reactive power using a directly connected transformer to the network. Nominal current of the CSCT is inductive; however, it can be used as a capacitive reactive power compensator if the design of harmonic filters is performed according to the presented relations in this paper. Various equations are demonstrated that describes how to use a capacitor bank for reactive power injection to the power system.**

***Index Terms*—Capacitive control, CSCT, Voltage regulation, Reactive power.**

I. INTRODUCTION

The CSCT is a transformer, composed of three windings; the network winding (NW), the control winding (CW) and the compensating winding (ComW) as shown in Fig. 1 [1]. The principal operation mode of the the CSCT is inherently concentrated on reactive power absorber like a reactor. However, when it is required to inject reactive power to the power system, the CSCT has no capacitor but those included by the tuned LC-filters. As a result, the capability of operation of the CSCT in capacitive mode is limited to the capacitors of the LC-filters.

One solution to increase the capability of the CSCT in capacitive operation mode could be the usage of a capacitor bank. This capacitor bank can be installed across the tertiary winding, the ComW, in parallel with the LC-filters. Theoretically, this is considered as a possible increase of capacitive admittance seen from the NW, while all the three transformer windings combination is taken into account.

Meanwhile, it should be noted that the CSCT has an iron core that is combined with additional yoke in order to present special configuration for high harmonic performance. This also paves the ground for very high short circuit impedance around 100%. In fact, the CSCT operates under nominal current when a fault is occurred at the transformer.

Considering the above facts, the capacitive operation mode using capacitor banks need more attention to be studied for various circumstances. This paper formulates the addition of a capacitor bank to the CSCT, while other characteristics of the CSCT are still strongly appear in the model. Analyzed relationships show that the CSCT can operate in both capacitive and inductive mode when some rating modifications are considered in practice. Hence, it can be claimed that the compensator is bilateral. However, the capacitor can be removed from the compensating winding still having bilateral reactive power compensation if the relationships of designing elements of harmonic filters be correctly performed. These relations are calculated and presented in the following sections.

II. MATHEMATICAL ANALYSIS

Flowing capacitive current in the network winding of CSCT under open circuit condition of CW, which defines the capacitive conductance of harmonic filters of fifth and seventh in the main frequency, has prompted the possibility of bilateral action of the compensator with increased capacitive component of filters of the higher harmonics. (See Fig. 1).

Impedance of the compensator when thyristors are completely closed is defined by (2-1).

$$X_{Leq} = X_1 + \frac{X_2 X_3}{X_2 + X_3} = \delta X_{12} + \frac{(1-\delta) X_{12} X_3}{(1-\delta) X_{12} + X_3} = X_{12}\left[\delta + \frac{(1-\delta)}{1 + \frac{X_{12}}{X_3}(1-\delta)}\right] > X_{12} \tag{2-1}$$

This value is greater than the corresponding impedance of controlled shunt *reactor* of transformer type, CSRT.

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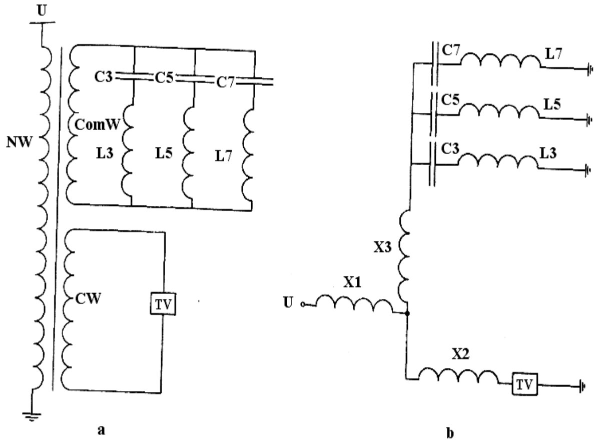

Figure 1: Schematic single-line diagram (a) and equivalent circuit (b) of CSCT without any capacitor bank.

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$$X_{L.eq.CSRT} = X_1 + \frac{X_2 X_{f.eq}}{X_2 + X_{f.eq}} = \delta X_{12} + \frac{(1-\delta)X_{12}X_{f.eq}}{(1-\delta)X_{12} + X_{f.eq}} = X_{12}\left[\delta + \frac{(1-\delta)}{1 + \frac{X_{12}}{X_{f.eq}}(1-\delta)}\right] \approx X_{1\,2} \tag{2-2}$$

To provide the rated current by CSCT as same as CSRT, the impedances X_{12}, X_{13} and X_{23} should be lowered. For instance this objective can be achieved by reducing the number of turns in windings or increasing the height of magnetic window.

In a general view, the solution to this problem can be carried out on the basis of two equations made for locked and opened thyristors. In open thyristors condition, we want the capacitive current flowing through the network winding of CSCT to be equal to its rated current, then

$$I_c = \frac{U_{ph}}{\delta X_{12} + X_c} = -\alpha \frac{U_{ph}}{X_{L.nom}} \tag{2-3}$$

Where X_{Lnom} is the essential rated impedance of compensator in inductive mode of operation and α is required correlation between rated capacitive and inductive currents of the compensator.

The essential value of X_C is obtained from this equation:

$$X_c = \frac{1}{\alpha}\left(X_{L.nom} + \alpha\delta \cdot X_{12}\right) \tag{2-4}$$

Let's now suppose that the inductive current through network winding of the compensator is equal to its rated current with completely closed thyristors:

$$I_L = \frac{U_{ph}}{\delta X_{12} + \frac{(1-\delta)X_{12}X_c}{(1-\delta)X_{12} + X_c}} = \frac{U_{ph}}{X_{L.nom}} \tag{2-5}$$

Then we have from (2-5):

$$X_{L.nom} = \delta X_{12} + \frac{(1-\delta)X_{12}X_c}{(1-\delta)X_{12} + X_c} \tag{2-6}$$

After transposing and substituting Xc from (2-4), we have:

$$\alpha\delta^2 X_{12}^2 + X_{12}X_{Lnom}(1 + \alpha - 2\alpha\delta) - X_{L.nom}^2 = 0 \tag{2-7}$$

The solution of (2-7) specifically when the rated currents in inductive and capacitive modes of operation are equalized (α = 1) obtains:

$$X_{12} = X_{L.nom}\frac{\sqrt{1 - 2\delta + 2\delta^2} + \delta - 1}{\delta^2} = X_{L.nom}\frac{\sqrt{1 - 2\delta \cdot (\delta - 1)} + \delta - 1}{\delta^2} \tag{2-8}$$

$$X_C = -X_{L.nom}\frac{\delta + \sqrt{1 - 2\delta \cdot (\delta - 1)} + \delta - 1}{\delta} = -X_{L.nom}\frac{2\delta - 1 + \sqrt{1 - 2\delta \cdot (\delta - 1)}}{\delta} \tag{2-9}$$

For example when $\delta = 0.6$

$$X_{12} = X_{L.nom}\frac{\sqrt{0.52} - 0.4}{0.36} = 0.891 X_{L.nom}$$

and

$$X_c = -1.535 X_{L.nom} = -1.72 X_{12}$$

Since δ varies between 0.5 – 0.8, the rated inductance $X_{L.nom}$ is greater than X_{12} under any value of α. Hence the compensator's impedance under closed CW condition without filters is less than 100 % unlike from CSRT (see Fig. 2).

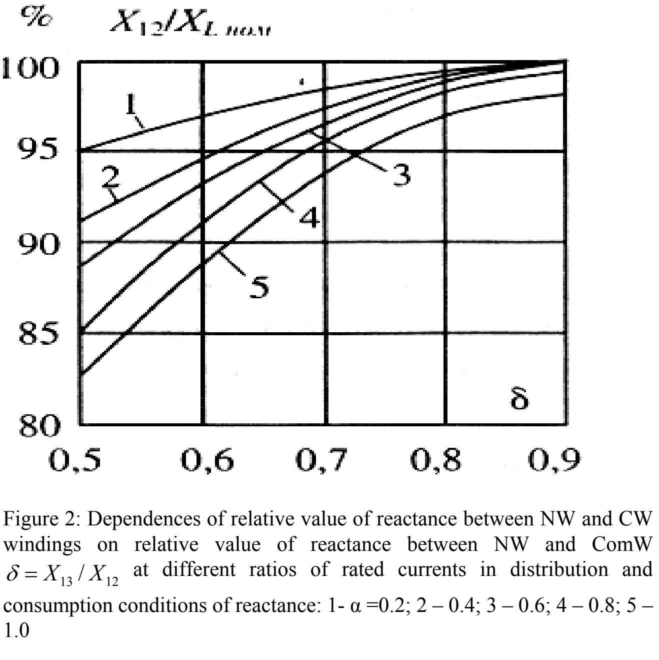

Figure 2: Dependences of relative value of reactance between NW and CW windings on relative value of reactance between NW and ComW $\delta = X_{13}/X_{12}$ at different ratios of rated currents in distribution and consumption conditions of reactance: 1- α =0.2; 2 – 0.4; 3 – 0.6; 4 – 0.8; 5 – 1.0

It means that under the same rated inductive current and equal dimensions, which define X_{12}, the number of turns in windings of the compensator is less than that of CSRT. The ratio $X_{12}/X_{L.nom}$ is increased by increasing δ, and decreased when α is increased. Hence, higher is the value of α, smaller is the number of turns in the windings of CSCT in comparison with CSRT with the same capacity.

Reduction in the number of coils leads to increment in magnetic flux when thyristors are locked and when completely opened. Hence, in CSCT the active cross-section of magnetic conductor steel is greater than that of CSRT with the same capacity.

Further, we shall define the essential capacitance of highest harmonics filters to provide the relation α from the obtained value of Xc and known ratios for filters. The equivalent impedance of filters is defined by the ratio:

$$X_1 + X_{f.eq} = -\frac{X_{L.nom}}{\alpha}$$

So we have:

$$X_{f.eq} = \frac{X_{L.nom}}{\alpha}\left[1 + \frac{\sqrt{(1+\alpha-2\alpha\delta)^2 + 4\alpha\delta} - (1+\alpha-2\alpha\delta)}{2\delta}\right] \tag{2-10}$$

Equivalent impedance of filters on power frequency is defined by the impedance of all installed filters and it will be defined by the ratio:

$$\frac{1}{X_{f.eq}} = \sum_{k=3}^{n} \frac{1}{X_{f.eq}} = \sum_{k=3}^{n} \frac{\omega \cdot C_k k^2}{1-k^2} \tag{2-11}$$

When using the third, fifth and seventh harmonic filters (if for some reason the compensation winding of the three phases is not in delta connection), we obtain:

$$\frac{1}{X_{f.eq}} = \omega\left(C_3\frac{9}{8} + C_5\frac{25}{24} + C_7\frac{49}{48}\right) = \omega C_3\left(1125 + 1.04\frac{C_5}{C_7}\right) = 1.5\omega C_3 \tag{2-12}$$

Whence

$$C_3 = \frac{1}{1.5\omega \cdot X_{f.eq}} = \frac{\alpha}{1.5\omega X_{L.nom}\left(1 + \frac{\alpha\delta \cdot X_{12}}{X_{L.nom}}\right)} \tag{2-13}$$

and C5 = 0.26C3; C7 = 0.105C3.

Voltage of capacitors of filters equals:

$$\Delta U_{c.f} = 1.1U_{ph}\left[1 + \frac{\sqrt{(1+\alpha-2\alpha\delta)^2 + 4\alpha\delta^2} - (1+\alpha-2\alpha\delta)}{2\delta}\right] \tag{2-14}$$

and capacitor power of filters – rated capacitive power of capacitors ratio

$$\frac{Q_{c.f}}{Q_{C.CSCT}} = 1.1\left[1 + \frac{\sqrt{(1+\alpha-2\alpha\delta)^2 + 4\alpha\delta^2} - (1+\alpha-2\alpha\delta)}{2\delta}\right] \tag{2-15}$$

Corresponding dependences of ratios Qc.f/Qc.csct are shown in Fig. 3.

Exceeding the voltage of compensating winding in comparison with the voltage defined by the transformation ratio leads to increment of the magnetic flux in the core. In order to eliminate the saturation of the core, it is essential to increase the active cross-section of the core proportional to the voltage increase.

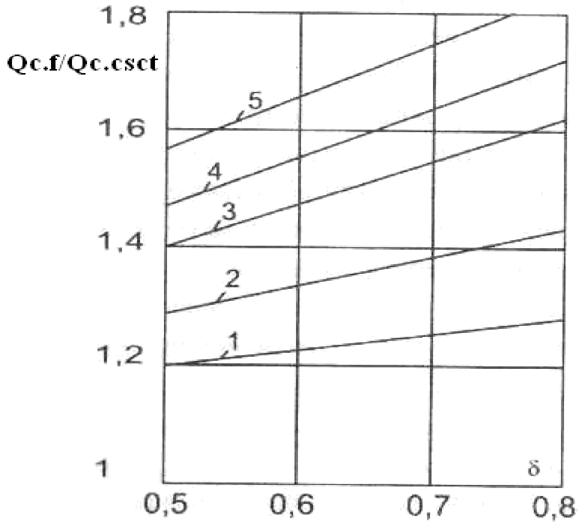

Figure 3: Dependences of amount of third, fifth and seventh harmonics capacitor power – rated capacitive power of CSCT ratio on the relative values of inductive resistance of CSCT between ComW and CW $\delta = X_{13}/X_{12}$ at different values of $\alpha = Q_{C.f}/Q_{L.CSCT}$. All designations are the same as in fig.1. ComW of the three phases are in Y-connection with neutral terminal.

When the thyristors are opened, the current in branch 2 (Fig. 1) equals to zero and the voltage in the thyristors equals to the voltage in ComW (certainly in view of the ratio of the number of turns in CW and ComW ($K_{T.2-3} = K_{T.1-3}/K_{T.1-2}$). Consequently, with equal number of turns in ComW and CW, rated voltage of CW is defined by formula (2-14). With difference in number of turns in ComW and CW, the rated voltage in CW

$$U_{2nom} = \Delta U_{C.f} K_{T.2-3}$$

The rated voltage of CW is chosen based on the appropriate (by technical and economic considerations) current through the thyristors. We shall obtain the relationship between rated current of CW and voltage in NW (see Fig. 1):

$$I_{2.nom} X_2 = U_{ph} - I_{L.nom} X_1$$

or

$$I_{2nom} = \frac{\delta}{1-\delta} I_{Lnom} \cdot \frac{1+\alpha-\sqrt{(1+\alpha-2\alpha\delta)^2 + 4\alpha\delta^2}}{\sqrt{(1+\alpha-2\alpha\delta)^2 + 4\alpha\delta^2} - (1+\alpha-2\alpha\delta)} \tag{2-16}$$

For example when $\delta = 0.5$ according to (2-16)

$$\frac{I_{2nom}}{I_{Lnom}} = \sqrt{1+\alpha}$$

The greater the ratio between rated capacitive and inductive currents α, the more the maximal current in CW increases relative to the rated inductive current in NW (subject to transformation coefficient).

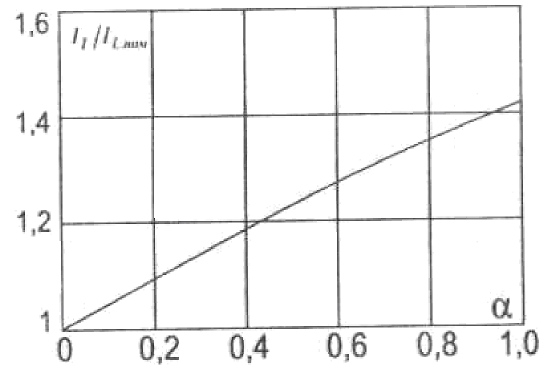

Figure 4: Dependence of maximum current of CW on α when $\delta = 0.5$.

Equating rated current of CW to the chosen rated current of thyristors, IT.nom, we get the necessary transformation coefficient:

$$K_{T.1-2} = \frac{I_{T.nom}}{I_{L.nom}} \cdot \frac{1-\delta}{\delta} \cdot \frac{1+\alpha-\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}}{\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)} \qquad (2\text{-}17)$$

It can be found from (2-17) that the transformation coefficient of CSCT is smaller than that of CSRT with the same capacity and it depends on α and δ.

Thus increase in capacitance of capacitors enables to essentially expand the capacitor current regulation range of the compensator towards inductive current up to ±100 % of rated CSRT current. Hence one thyristors block of CSRT calculated on the maximum current in CW is used. Quick closing of CW in nominal operating mode provides a negligible decrease in the rated current of the CSCT in comparison with the rated current of CSRT without supplementary capacitance. Moreover, CSCT scheme provides high efficient use of capacitance of filters by transforming reactors into static thyristors compensators. It is essential to note that all the regulations and additional instruments are carried out in the low voltage side, CW, which provides a relatively small additional costa in relation to CSRT. Since rated capacitive current flows through the network winding under locked thyristors, it is essential to provide closing conditions of thyristors in some part of the half-period of commercial frequency in order to reduce it. At a particular firing angle, the inductive current is exactly the same as the capacitive current, where the network winding current approaches zero. At further increase in firing angle of thyristors, current becomes inductive and increases right up to the rated value when the firing angle is 180^0 (complete conducting of thyristors). At zero current through the network winding, equivalent impedances of limbs 2 and 3 of the CSCT three-winding schemes are the same. Hence equivalent impedance of thyristors limbs is equal to:

$$X_{2eq} = \frac{X_{Lnom}}{2\delta\alpha}\left[2\delta+\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)\right] \qquad (2\text{-}18)$$

Since at zero current in the network winding of the compensator, voltage loss in inductive impedance $X_1 = \delta X_{12}$ equals to all voltages applied to any other two limbs of Fig. 1. Thus current in the thyristors limb equals to:

$$I_{2.0} = \frac{U_{ph}}{X_{2.eq}} = \frac{2\alpha\delta U_{ph}}{X_{L.nom}} \frac{1}{2\delta+\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)} \qquad (2\text{-}19)$$

And accordingly the relative value of current in thyristor limb under zero current in NW considering (2-16) will be:

$$\frac{I_{2.0}}{I_{2.nom}} = 2\alpha(1-\delta)\frac{2\delta+\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)}{1+\alpha-\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}} \times \\ \times \frac{1}{2\delta+\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)} \qquad (2\text{-}20)$$

As seen, when the current passes through zero, the relative value of current in thyristor limb is defined by only two variables: α and δ. However calculations show that the ratio I2/I2nom does not depend on δ when I1 = 0 and its dependence on α is shown in Fig. 5, which is an approximated function (with inaccuracy not more the 2%)

$$I_2 / I_{2nom} = 0.91\alpha \cdot e^{-0.6\alpha} \qquad (2\text{-}21)$$

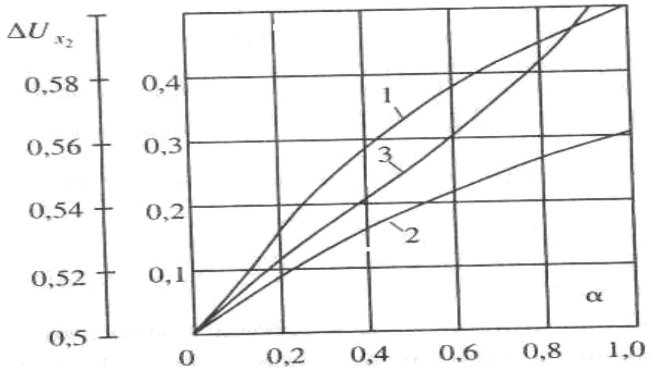

Figure 5: Dependence on α of relative value of current through thyristor block when current in the network winding passes through zero (curves 1,2) at rated phase voltage (curve 1) and at voltage in CW under completely closed thyristors (curve 2), as well as the relative value of that voltage (curve 3).

The ignition angle and correspondingly the firing angle of thyristors when CSCT current passes through zero by the corresponding thyristor characteristic (Fig. 6) can define the relative value of current. However it follows to bear in mind that characteristic Fig. 6 was obtained at constant voltage and constant inductive impedance connected in series with thyristors. In the case of CSCT, inductive impedance $(1-\delta)X_{12}$ remains constant when any current passes through the thyristors and voltage at increased current increases right up to phase voltage at equal reactance of inductive and capacitive limbs.

In nominal inductive operating mode of CSCT, the current through inductance $X_2 = (1-\delta)X_{12}$ is defined by formula (2-16), from where voltage drop in that inductive resistance is:

$$\Delta U_{X_2} = L_{2nom}X_{12}(1-\delta) = \frac{U_{ph}}{2\alpha\delta}\left[1+\alpha-\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}\right] \qquad (2\text{-}22)$$

and consequently the ratio of the voltage drop in the thyristor to the phase voltage changes with change in α (see

Fig. 5), although this change is negligible (in the range of 18%).

In Fig. 5, the dependence of $f(\alpha)$ brought to rated voltage in CW (when thyristors are completely opened) by multiplying the given curve 1 and the corresponding ratio of the voltage drop in the thyristor to the phase voltage (curve 3). This dependence is well approximated by below formula.

$$\frac{I_{2.0}}{I_{2.nom}} = 0.43\alpha \cdot e^{-0.46\alpha} \qquad (2\text{-}23)$$

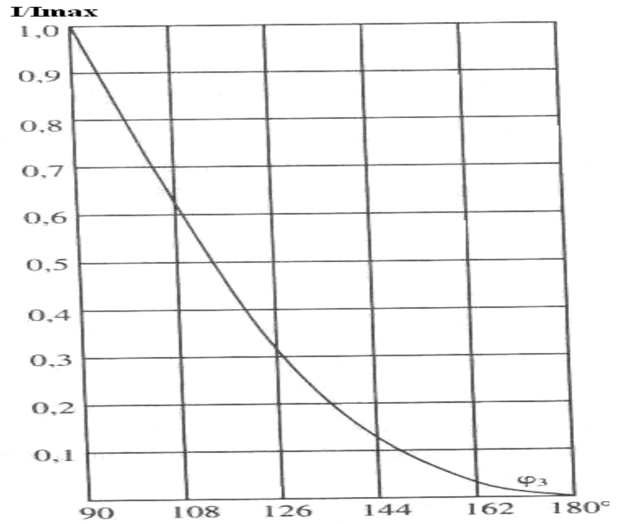

Figure 6: Dependence of relative value of current through thyristor block on ignition angle of thyristors.

This last dependence in conjunction with the curve of Fig. 6 enables us to define the dependence of ignition angle and firing angle of thyristors when network winding current passes through zero on the value of α:

α	0.04 3	0.2	0.4	0.6	0.8	1.0
φ_{ig}	168^0	155 0	143 0	135 0	131.4 0	129 0
φ_{com}	24^0	50^0	74^0	90^0	97.2^0	102 0

Thus with increase in α, the ignition angle of thyristors when CSCT current passes through zero decreases and firing angle of thyristors increases correspondingly.

The obtained result enables us to change the definition of angle characteristics of CSCT: dependence of CSCT current on the ignition angle of thyristors.

Let us bring the relative reactance of thyristor limb K in the earlier stated formulas of CSCT taking the base value of reactance when CSCT current passes through zero:

$$X_{2eq} = -KX_C = \frac{K}{\alpha}\left(X_{Lnom} + \alpha\delta X_{12}\right) \qquad (2\text{-}24)$$

Thus we get the equivalent reaxtance of CSCT at any value of K in the form of:

$$X_{eq} = X_{Lnom}\frac{2K\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)}{2(1-K)\alpha\delta} \qquad (2\text{-}25)$$

Consequently, the ratio of CSCT current to rated inductive current at any value of K

$$\frac{I_{(K)}}{I_{L.nom}} = \frac{X_{Lnom}}{X_{eq}} = \frac{2(1-K)\alpha\delta}{2\delta\cdot K+\sqrt{(1+\alpha-2\alpha\delta)^2+4\alpha\delta^2}-(1+\alpha-2\alpha\delta)} \qquad (2\text{-}26)$$

Considering that the value δ does not influence the relative value of current, we take it to equal its minimal value $\delta = 0.5$.

Then the relation (1.165) is substantially simplified

$$\frac{I_{(K)}}{I_{L.nom}} = \frac{(1-K)\alpha}{K+\sqrt{1+\alpha}-1} \qquad (2\text{-}27)$$

Let's define the relative value of current of thyristors complying with the passing of network winding current through zero by the curve in Fig. 5. For example, when α = 1 according to the above stated φ_{ig} = 129^0 and correspondingly the value I2/Imax=0.3. If the equivalent reactance of thyristor limb at constant voltage is halved (K = 0.5), the relative value of current through the thyristors will equal to 0.3/0.5=0.6. Corresponding ignition angle of thyristors according to curve of Fig. 6 equals 110^0. We define the relative value of CSCT current I/I_{nom} = 0.55 by formula (2-27), therefore when α = 1 that ratio corresponds with the angle φ_{ig} = 110^0. Thus all dependences from I_{Lnom} to I_{Cnom} (see Fig. 7) can be drawn.

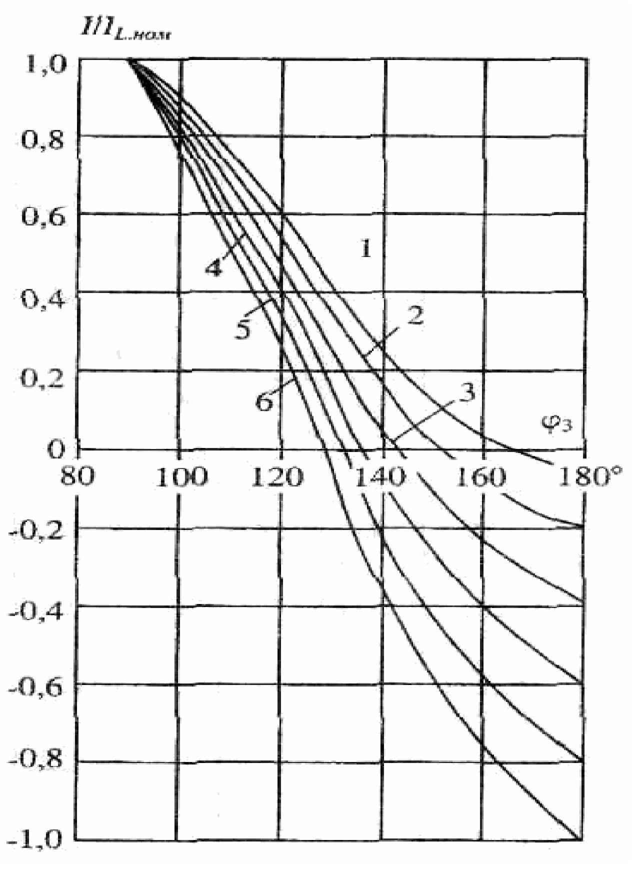

Figure 7: Dependence of the relative value of current of CSCT on ignition angle of thyristors:1- α=0.043; 2 - 0.2; 3 - 0.4; 4 – 0.6; 5 – 0.8; 6 – 1.0.

III. CONCLUSION

This paper introduces the CSCT as a new device to compensate reactive power in power systems. With a glance on the scheme of the CSCT, it seems to be the best way to add an additional capacitor to the ComW to have bilateral reactive power compensation. However, with a mathematical analysis the idea can be changed to correct design of value of the harmonic filter elements in order to achieve a bilateral compensator without essentially needed capacitor bank. In brief, the paper presents vital equations, which are required to design the correct values of harmonic filters' elements to regulate of capacitive reactive power as well as the inductive value. The obtained results show that this purpose is achieved.

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