An Introduction to the CSCT as a New Device to Compensate Reactive Power in Electrical Networks

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

Abstract— **A new shunt reactive power compensator, CSCT, is presented and introduced in this paper. Essential requirements of using FACTS devices in power transmission lines are emphasized and advantages of using CSCT are described. Also a general scheme of the CSCT and its operation is illustrated.**

Index Terms—**Compensation, CSCT, Light load, Reactive power.**

I. INTRODUCTION

Capacity of transmission of power in transmission lines will be reduced if a surplus reactive power is distributed in the lines. Moreover there will be a voltage drop if there is reactive power consumption and reactive current is flowed through the lines. In addition to above problems, surplus reactive power in a transmission line over a permissible level will cause a jeopardous problem for synchronous generators. Flexible Alternative Current Transmission Systems, FACTS, can be applied to mitigate such problems in transmission systems. Each of these devices has special characteristics such as construction and care costs, installation convenience, speed of response to any change, harmonic components, rated power, value of voltage and current of filters in relation to controlled voltage and current, power losses and such parameters. CSCT is a shunt compensator with good parameters which are compared with the others in this paper.

A. An introduction to the CSCT

The CSCT stands for "Controlled Shunt Compensator of Transformer type". A general scheme of this compensator is presented in figure (1-1). 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 figure (1-1). 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 are delta in connection together.

VCB in the figure (1-1) is a vacuum circuit breaker which can switch on or off CW while repairing or changing the thyristors without disconnecting CSCT from the network. Figure (1-2) 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.

Now let's consider circumstance of operation of this structure. When CW is open circuit by the thyristor, all the magnetic flux produced by network winding connecting to network passes through the magnetic core of the transformer. Since permeability of the magnetic core is about 3000 times greater than the permeability of the vacuum, the magnetic flux passing through the air gap encompassing three windings is negligible in comparison with the core. So the effective cross-section of magnetic flux path is the area of the core in this mode. As a result, when the thyristor is opened, equivalent reluctance of the transformer is small. So the inductance of CSCT is great. Thus a minimum current, magnetizing current, will pass through network winding. Since all of the windings include the magnetic flux in the core, even if there was not capacitor bank, the induced current in the network winding from ComW is capacitive because of the capacitors of highest harmonic filters connected to ComW. The value of this capacitive current can be increased to an arbitrary value by adding a capacitor with a corresponding value to the ComW circuit.

As a result, in open circuit mode of the thyristor, value of the capacitor bank determines the maximum capacitive current of the compensator however value of the capacitors of the harmonic filters will determine it if any capacitor bank has not been engaged. Now imagine the short circuit condition of the thyristor and consequently the control winding. In such a condition, the magnetic core emplaces a barricade preventing the flux to pass. Hence the magnetic flux produced by network winding is forced to flow through construction elements such as covers and walls of tank or

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M. Tavakoli Bina is with Electrical Engineering Faculty, K. N. Toosi University of Technology, PO Box 16315-1355, Tehran-Iran (phone: +98(21)-8846-9084; fax: +98(21)-8846-2066; e-mail: tavakoli@ kntu.ac.ir).

G.N.Alexandrov is with Electrical Engineering Department, Saint-Petersburg State Technical University, Russia (e-mail: alexandrovgn@rambler.ru).

M.Golkhah is with the Electrical Engineering Faculty, K. N. Toosi University of Technology, Tehran-Iran (e-mail: Goulkhah_elect@yahoo.co.uk).

other metallic parts of the transformer and this phenomenon causes a significant power loss in the transformer approximately equal to copper losses in the coils. In order to avoid occurring this problem, two magnetic shunts are installed above and bottom of all of the windings. The inner diameter of these disks is equal to the inner diameter of CW and correspondingly the outer diameter of them is equal to outer diameter of NW. Six magnetic shunts are used for three phases, two of them for each phase. Magnetic shunts collect the dissipated flux and send it to the yokes tightened to the main core. After using these magnetic shunts, the mentioned additional loss will be reduced up to 10% of the copper losses. In this situation much of the magnetic flux gets out of magnetic shunts to pass through the air gap encompassing all the windings and the remained flux flows in lateral yokes after passing magnetic shunts. In this case permeability of the magnetic flux path is decreased up to the permeability of the vacuum.

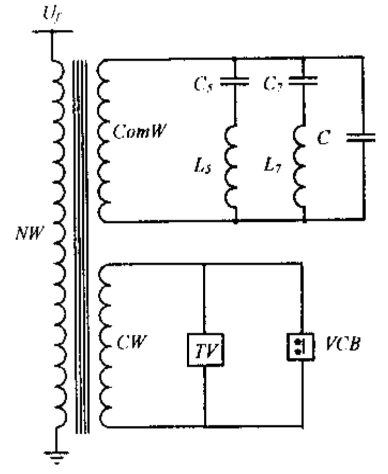

Figure (1-1): General scheme of a CSCT: TV-thyristors valve, VCB-vacuum circuit breaker, C5-L5 and C7-L7 filters of fifth and seventh harmonics, C- additional capacitor bank.

Moreover the cross-section of the magnetic flux path is significantly greater than the short circuit of the thyristor mode. Consequently the reluctance of the magnetic flux path is about 300 times greater than the previous. Hence the equivalent inductance of CSCT will be minimal. In this mode, the maximum inductive current will pass through network windings and accordingly consumption of reactive power will be maximal so called the rated power of the CSCT.

Two modes of operation of CSCT were illustrated. In summarized, in the first mode the thyristor was opened and a reactive power was injected to the network. The other mode was short circuit of the thyristor. In this mode the nominal reactive power was consumed by CSCT from the network. Since in both modes the current of NW has capacitive or inductive characteristic, it has ±90° in relation to phase of the voltage.

Intermediate capacitive or inductive powers can be obtained according to intermediate firing angles of the thyristor. Firing angle of the thyristor can change in range of 90°-180° in relation to the phase of voltage.

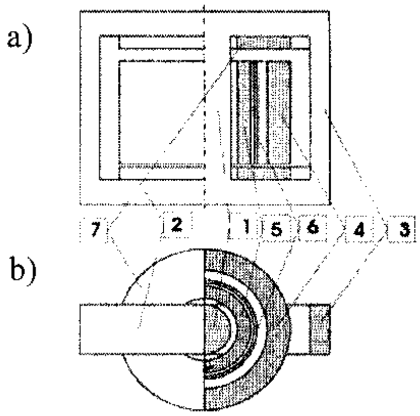

Figure (1-2): Single-phase diagram of CSCT: a- view form side; b- view form above: 1- a main core, 2- yokes, 3- lateral yokes, 4- NW, 5- CW, 6- ComW, 7- magnetic shunts.

The relation of current of NW to the rated value according to different values of firing angle of the thyristor is shown in figure (1-3). It is found from this figure that the current of NW is equal to the rated value corresponding to the firing angle of 90°. As the firing angle increases, the inductive current decreases so that it reaches to zero in a particular firing angle. Six curves have different schemes in relation to different values of the capacitor bank. Increasing the firing angle in greater values causes the current to be capacitive.

II. THE HIGHEST HARMONIC ORDER ON THE CURRENT

Control of compensator with a thyristor will lead to smooth and continuous regulation of current in NW only by changing its firing angle. Cut of the current of CW by the thyristor causes highest harmonics in the induced current of NW. The most harmonic content of the current belongs to the third harmonic which is about 14% of the total current. The contents of fifth and seventh harmonics in relation to the total current are 5% and 2% respectively. Magnitudes of third, fifth and seventh harmonics in relation to the present current and the rated current are presented in figure (2-1).

Compensation windings with a delta connection have been designed to eliminate third harmonic.

In order to damp fifth and seventh harmonics of the current, two adapted filters are used. Each of them is a capacitor serried by an inductor which is in resonant in the corresponding frequency.

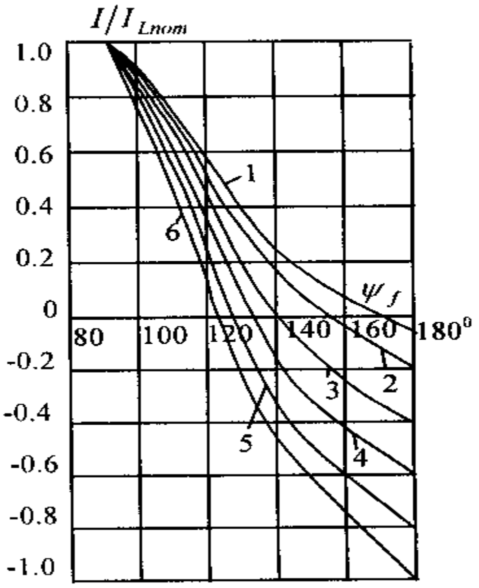

Figure (1-3): The current in NW of CSCT versus the firing angle of thyristors by: C=0 (curve 1), $I_{C,nom} / I_{L,nom} = 0.2$ (curve 2), 0.4 (curve 3), 0.6 (curve 4), 0.8 (curve 5), 1 (curve 6).

It is clear that these filters show a capacitive treatment in the basic frequency.

Total capacitance of filters is about 10% of the rated capacity of the compensator.

Voltage of ComW is less than the voltage of NW and current of Comw is about four times more than current of NW. Thus the content of highest harmonics in the current of NW is less than 2% of the rated current of CSCT.

III. PERFORMANCE OF THE CSCT IN POWER SYSTEMS

Main sources of generating and consuming the reactive power in power systems are:

Electrical machines inductance,
1- Power transmission lines,
2- Transformers,
3- Reactors,
4- Capacitor banks,
5- Capacitors of over head lines and cables.

Overhead lines and cables are the main sources of generating reactive power in power systems. The value of this reactive power changes according to changes of transmitting power through the line. Equation (4-1) presents this relation.

$$Q = P_n.\lambda.\left[1-\left(\frac{P}{P_n}\right)^2\right] \qquad (3-1)$$

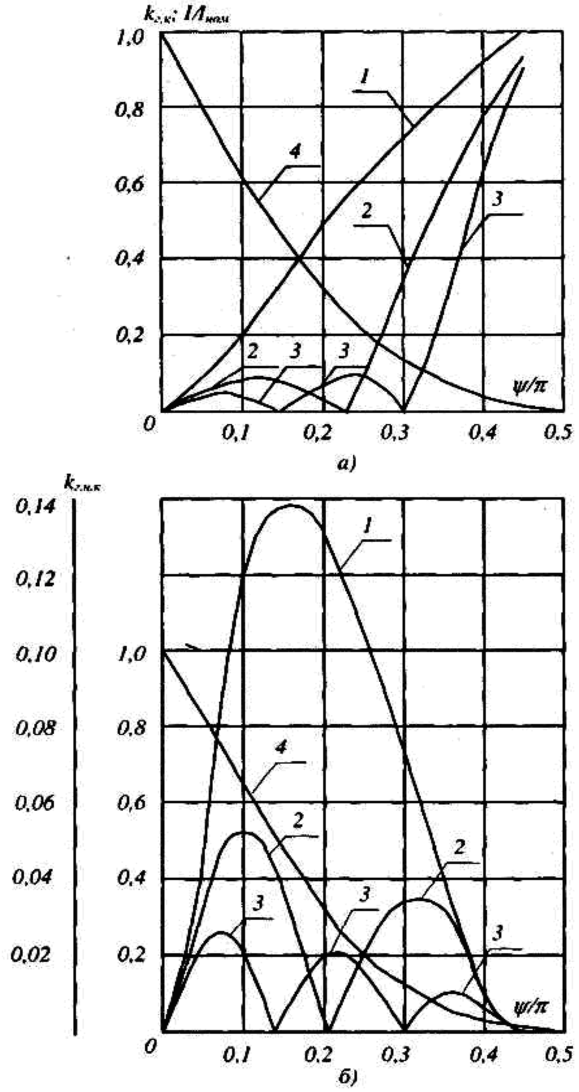

Figure (2-1): The ratio of currents of highest harmonics: third (1), fifth (2), seventh (3) to the current of the basic frequency with dependence on angle og thyristors: a- in relation to present current of basic frequency; b- in relation to rated current; 4- ratio of root-mean-square value of full current to rated current.

Where P_n is the transmission power of the line corresponding to surge impedance loading, and λ is the wave length of the line and P is transmission power of the line. As it is found from equation (3-1), the maximum reactive power will be generated by the line if the transmitted power of that line is equal to zero. Increasing in the transmitted power of the line leads to decrement of generated reactive power by the line so that if the transmitted power of the line was equal to P_n, no reactive power is generated by the line. The transmission line consumes reactive power if $P > P_n$. As we know, the ratio of receiving voltage magnitude to the sending voltage magnitude pertains to the value of the reactive power distributed in the line directly. When $P < P_n$, the line generates reactive power so that the voltage of receiving side has greater amplitude than the voltage of sending side. Correspondingly there is no voltage deviation in the line if the transmitted power through the line was equal to P_n. Eventually there will be a voltage sag in the line if $P > P_n$. This phenomenon is shown in figure (3-1).

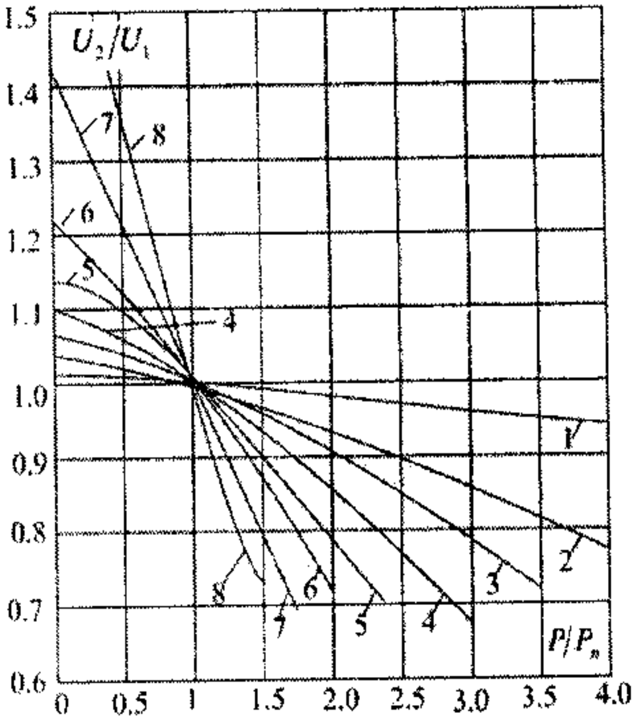

Figure (3-1): The ratio of operating voltages at the output and consuming ends of lines versus the ratio P / P_n by different values $\lambda = 0.1$ rad (curve 1), 0.2 rad (curve 2), 0.3 rad (curve 3), 0.4 rad (curve 4), 0.5 rad (curve 5), 0.6 rad (curve 6), 0.8 rad (curve 7), and 1 rad (curve 8).

When there is surplus reactive power in the line at low load conditions, the voltage of terminals of a synchronous generator can be more than its emf which is a serious problem for that generator because it leads to take place a big dissipation initiating to overheat of frontal parts of generator's winding and accelerate aging of its insulation and also accelerate destruction of frontal parts of generator's stator. To consume this surplus reactive power in the line, shunt reactors should be applied. Since the generated reactive power in the line varies according to changes of transmitted power of the line, reactors should be controlled to obtain different values.

On the contrary, there are usually over loads and voltage drops in long high voltage transmission lines (110-220KV). Hence reactive power generators should be engaged in such conditions. Since this voltage drop is tightly related to transmitted power changes in the line, these reactive power generators should be controlled.

As a result, engaging controlled compensators with the ability of generating and consuming arbitrary value of the reactive power is essentially required.

Using shunt multi level capacitors and inductors changing their levels by power switches, was prevalent in past years. Those had low accuracy in the value of compensated reactive power and the worst problems were low speed of response and high contents of harmonics although their total costs were significantly low.

Electric power networks extension, increasing the sensibility of loads and technological progresses pulled over the traditional instruments and paved the path of a new superhighway, “FACTS devices”.

These devices were deservedly superseded multi level capacitors and reactors. SVC and STATCOM are two well known and drastic shunt bilateral compensators.

Construction and care costs, installation convenience, speed of response to any change, harmonic components, rated power, value of voltage and current of filters in relation to controlled voltage and current, power losses and such parameters are the most important parameters of choosing a compensator to use in a particular application.

CSCT is a shunt compensator with very good parameters such as high speed of response, very low content of harmonics, wide bilateral range of reactive power to generate or consume, low total costs in relation to other FACTS devices, low power losses and etc.

It is important to note that the act of compensator in the mentioned application in the power system should be very fast. Let's consider two examples to demonstrate this claim. Suppose a line which is under an intensive over load. A compensator should operate in the maximum generation of reactive power mode in this condition. Any more over load in this case subject the circuit breakers to cut off the line. Right after cutting off the line since there is no load condition, the surplus reactive power initiated by the line distributes in the line causing it to occur an over voltage.

Hence simultaneously the compensator should alter to maximum reactive power consumption mode to prevent the mentioned problems for the generators. If the act of compensator in changing position is not quick, it exacerbate the over voltage after cutting off the line by remaining in the generating reactive power mode for a while. Next reason is related to the automatic reclosing in single phase short circuit conditions. It is necessary to compensate the capacitive current from phases which are in the operation to the damaged phase. In this case the capacitive of compensator is to change very fast in order to prevent the total switching off this line and to disturb the line conductors.

The CSCT has a very good speed of response to new changes. A micro controller is used in the control system of this compensator and the main reasons to have a delay less than 10 msec are delays of sampling circuits and action of the applied thyristors and changing the magnetic flux and currents in the transformer.

The main control channel of CSCT uses the measured shift angle φ between the operating voltage and the current in the line and. When $\varphi > 0$ microprocessor produces a command for decreasing the firing angle ψ_f (in relation to operating voltage phase) leading to increase the inductive current in NW until the shift angle φ reaches to zero. That means a complete compensation of the reactive power has been achieved. On the contrary when $\varphi < 0$ the microprocessor produces a command to increase the firing angle of thyristors leading to decrease the inductive current in NW up to zero and when it is necessary up to some values of the capacitive current. This channel provides compensation of a surplus reactive power in the normal regime of line operation.

When operating voltage increases above the permissible level, which is indicated by the operator, the first channel is blocked and the operating voltage channel starts to be active. This channel produces a command to increase inductive current of compensator till the nominal value in order to decrease operating voltage up to the maximum permissible level. When the operating voltage is less than the minimum permissible level, the microprocessor produces a command to decrease the inductive current in the NW up to zero and if it is necessary till some value of the capacitive current.

These two control channels provide a strict stabilization of operating voltage in all possible normal regimes of lines operation. By urgent switching off a line, next (third) channel provides increment of the current in NW till the nominal value. Therefore the limitation of power frequency component of switching over voltages is provided by any commutation of power circuit breaker.

Control system of CSCT also provides adequate reaction of the compensator in auto reclosing regimes and also after switching off single phase short circuit faults providing the fast interruption of short circuit arc.

It is very important to note that the ability of CSCT to vary the current in NW without time delay in suitable direction determines the possibility of 100% compensation of the surplus reactive power of lines in all possible regimes of their operation. In this case generators at power stations are released from the consumption of the surplus reactive power of lines which excludes the possibility of an extreme dangerous for generators operating regime, when their e.m.f is less than the voltage at the ends of the generator.

IV. SUMMARIZED CSCT ADVANTAGES

Briefly, the total advantages of using CSCT can be classified as below:

1- Continuous control of reactive power in the range of minimum and maximum capacity of compensating,

2- Direct connection to the power system because of its transformer aspect hence requiring to a little space to install and utilize,

3- Little required devices to install,

4- Low construction and utilization costs,

5- The height speed of response (less than 10msec),

6- Low harmonic components (less than 2%),

7- Low capacitance of harmonic filters in comparison with the same devices,

8- Better efficiency of harmonic filters because of more current level in filters than the current level of NW,

9- Negligible acoustic noises because of eliminating any air gap in the magnetic core of the transformer,

10- Low power losses while consuming reactive power with the rated capacity of CSCT (about 0.6%),

11- Simple and reliable cooling system for the thyristors,

12- Simple protection of the device because of high short circuit impedance in short circuit conditions of low voltage windings of the transformer.

Therefore it can be derived that the CSCT with the above advantages can be widely used in electrical networks in order to improve the power quality.

V. CONCLUSION

The 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.

After interpreting the circumstance of operating the compensator, the useful application of the device and its advantages were remarked.

It can be concluded from the descriptions that CSCT has a very good parameters as a shunt compensator.

Its successful and quick operation in increasing the capability of transmission lines by compensating the surplus or deficient reactive power of the line and preventing the synchronous generators of power system to consume the surplus reactive power of the line leading to heat the frontal parts of their windings and decrease the total longevity of them by consuming the surplus reactive power of the line and holding the ratio of E/U_g greater than 0.85, bears it to mind that it can be widely used in electrical networks.

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