Optimization of Power Flow in Transmission Line using TCSC Controllers

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Abstract - *The power transfer capacity of long high voltage transmission lines is often limited by the inductive reactance of the transmission line. In some cases, series compensation is used to reduce the inductive reactance of the transmission line, which increases the power transfer capacity of the transmission line. Numerous methods have been used to provide serial compensation of a transmission line. One of these methods is to use a thyristor controlled series capacitor (TCSC). A series controlled thyristor capacitor (TCSC) belongs to the family of flexible devices for alternating current transmission systems (FACTS). It is a variable inductive and capacitive reactance device that can be used to provide series compensation on high voltage transmission lines. One of the significant advantages that a TCSC has over other series compensation devices is that the TCSC reactance is instantaneous and continuously variable. This means that the TCSC can be used not only to provide a series compensation, but also to improve the stability of the power supply system. The literature has shown that there is an acceptable limit for the resolution of the thyristor trigger angle based on the parameters of the components used in the TCSC. If a controller is developed to meet this acceptable level of thyristor trigger angle resolution, the operation of the TCSC will also be acceptable and its operation will not result in unwanted fluctuations in the transmission line variables.*

Key Words: **FACT Controller, TCSC, SSR, TCR.**

1. INTRODUCTION

The Flexible Alternating-Current Transmission Systems (FACTS), incorporating a wide range of possibilities for better utilization. Improvement of voltage and current limits on the power electronics devices leads to a fast development of FACTS in the last decade. FACTS are defined by the IEEE as "AC transmission systems incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability. And among the proposed FACTS devices, possibly the Thyristor Controlled Series Capacitor (TCSC) has given the best results in terms of performance and flexibility. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub-synchronous resonance (SSR); damping the power oscillation; and enhancing transient stability.[11]

FACTS devices are introduced in the transmission line to enhance its power transfer capability; either in series or in shunt. The series compensation is an economic method of improving power transmission capability of the lines. Thyrister-controlled series capacitors (TCSC) is a type of series compensator that can provide many benefits for a power system including controlling power flow in the line, damping power oscillations, and mitigating sub synchronous resonance. The TCSC concept is that it uses an extremely simple main circuit. The capacitor is inserted directly in series with the transmission line and the thyrister-controlled inductor is mounted directly in parallel with the capacitor. Thus no interfacing voltage transformers is required. This makes TCSC much more economic than some other competing FACTS technologies. Thus it makes TCSC simple and easy to understand the operation. Series compensation will:

1) Increase power transmission capability.
2) Improve system stability.
3) Reduce system losses.
4) Improve voltage profile of the lines.
5) Optimize power flow between parallel lines.[3]

Series capacitors offer certain major advantages over shunt capacitors. With series capacitors, the reactive power increases as the square of line current, whereas with shunt capacitors, the reactive power is proportional to the square of bus voltage. For achieving same system benefits as those of series capacitors, shunt capacitors required are three to six times more reactive power rated than series capacitors. Furthermore shunt capacitors typically must be connected at the midpoint, whereas no such requirement exists for series capacitors. [8]

2. CIRCUIT ANALYSIS OF A TCSC

A single-phase TCSC consists of a fixed-reactance capacitor parallel with a variable reactance inductor. This variable reactance inductor is obtained by connecting an inductor in series with back-to-back thyristors. For a three phase TCSC this arrangement is identical for all three phases. The inductor thyristor parallel branch of the circuit is known as a thyristor controlled reactor. This branch of the circuit is the most important part of a TCSC and therefore requires further discussion

3. THYRISTOR CONTROLLED REACTOR

A thyristor controlled reactor consists of back to back thyristors connected in series with an inductor as shown in Figure 3.a. The reactance characteristic of the TCR as a function of the trigger angle of the thyristors is shown in Figure 3.b.

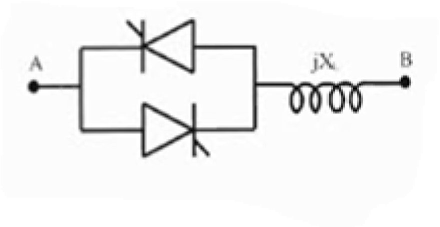

Figure 3.a. Circuit diagram of TCR

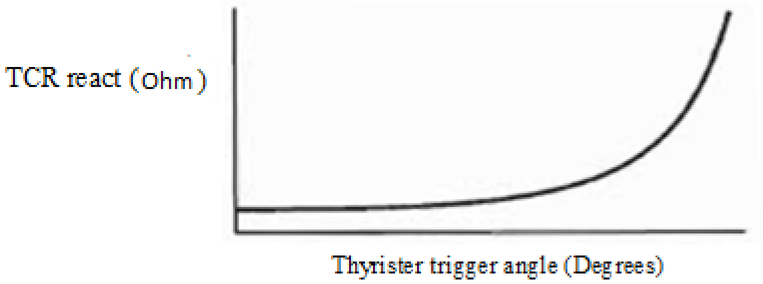

Figure 3.b. Graph of TCR reactance vs. thyristor trigger angle

The characteristic in figure 3.b. shows that the inductive reactance of the TCR increases as the trigger angle of the back to back thyristors is increased from 00. The equation describing the behaviour of the reactance of the TCR as a function of the thyristor trigger angle is given by:[1]

$XTCR= \pi XL / 2(\pi-\alpha) + \sin 2\alpha$---------------- (1)

Where,

XTCR is the net reactance of the TCR at the fundamental frequency

XL is the reactance of the inductor at the fundamental frequency

α is the trigger angle of the thyristors

The circuit of a TCSC is obtained when a fixed reactance capacitor is added in parallel to the TCR. By understanding the operation of the TCR it is now possible to analyze the circuit diagram of a single phase TCSC and obtain insight into the operation and variable reactance characteristic of a TCSC.

4. OPERATION OF THYRISTOR CONTROLLED SERIES CAPACITORS (TCSC)

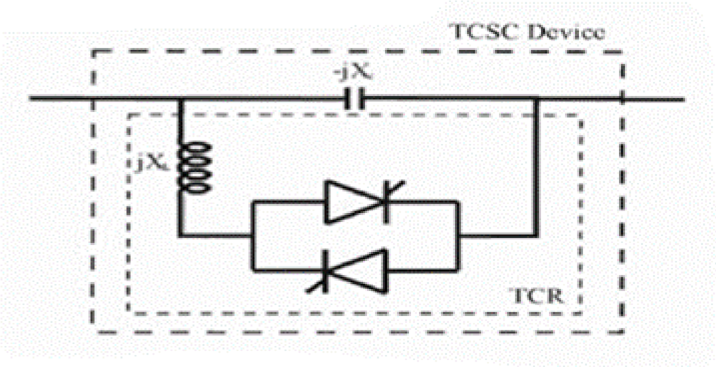

Figure 4.a. Circuit diagram of thyrister controlled series capacitors TCSC.

Having discussed the circuit diagram and operation of a TCR, its now possible to analyze the circuit diagram of a TCSC to understand the operation of a TCSC in greater detail. As shown in Figure 4.a. TCSC consists of two parallel branches one containing a fixed-reactance capacitor and the other a thyristor controlled reactor (TCR).[1] Using this description and equation (1), used to describe the operation of a TCR, it is possible to arrive at the following formula used to describe the operation of a TCSC.

$XTCSC=jXTCR//(-jXc)$-----------------(2)

So, $XTCSC=-jXc/1-Xc/XTCR$--------------(3)

Where,

XTCSC is the net reactance of the TCSC at the fundamental frequency

XTCR is the net reactance of the TCR at the fundamental frequency

Xc is the reactance of the TCSC's internal capacitor at the fundamental frequency

Referring to equation (3) it can be seen that as XTCR is decreased the absolute value of XTcsc will be increased. To illustrate this, two extreme cases will be taken when: XTCR = 00 it can be seen that IXTCSC I = IXC I. The thyristors are not triggered and the TCR branch is open circuit. This is the condition for minimum series compensation. XTCR ~ Xc it can be seen that IXTcscI= 00. The thyristors are being triggered. This is the condition of maximum series compensation and is also the point at which resonance between the inductor and capacitor occurs. However, practically this condition is never realised, for reasons that are explained later on in this section. The corresponding thyristor trigger angle at which resonance occurs is defined as α res.

From the previous discussion it was shown that the minimum reactance of the TCSC is equal to the reactance of the fixed capacitor, therefore the TCSC can be thought of as an 'amplifier' that can, theoretically, boost the reactance of the physical capacitor by a factor of one to infinity. This leads to the definition of a term called the boost factor, KB, which gives an indication of the 'amplification' of the reactance of the TCSC's internal capacitor

$KB=XTCSC/XC$--------------- (4)

Where,

KB is the boost factor of the TCSC at the fundamental frequency

XTCSC is the net reactance of the TCSC at the fundamental frequency

Xc is the reactance of the TCSC's internal capacitor at the fundamental frequency

As stated previously, a decrease in the trigger angle of the thyristors results in an increase in the capacitive reactance of the TCSC, but exactly how this comes about will now be discussed.

Consider the single line diagram of a TCSC shown in Figure 1. If the forward biased thyristor is triggered just before the TCSC capacitor voltage is zero, then a small circulating current, ITCR will flow in the TCR branch as shown in the figure. This circulating current adds to the transmission line current flowing through the capacitor, which results in an increase in the voltage, VCAP, across the capacitor, and an increase in the capacitive reactance of the TCSC

From the discussion above it can be seen that the voltage across the capacitor, and hence the voltage across the TCR, is not constant but is dependent on the trigger angle of the thyristors Therefore equation (3) does not accurately predict the behaviour of the TCSC since equation (1) was developed assuming that the TCR was connected across an ideal voltage source.

The TCSC can operate in one of three modes, depending on the thyristor trigger angle, α. These modes are discussed below [1]:

4.1 MINIMUM COMPENSATION MODE:

-α = 180° - The thyristors are off and the conduction path of the current is only through the capacitor, therefore XTcsc = Xc. The corresponding boost factor is 1. This is known as the blocking mode and is the case of minimum compensation.

4.2 Bypass mode:

- α = 0° - The thyristors are continuously conducting and this allows current to flow through the inductor and through the capacitor. The capacitor and inductor are now in parallel. X TCSC = -I XcII XL I. The corresponding boost factor is negative and the TCSC reactance is inductive. This mode is known as the bypass mode, and this mode of operation is used during fault conditions, when the transmission line current is high, to reduce the stress on the capacitor.

4.3 Capacitive boost mode:

- α = [α res, 180°] - the physical reactance of the capacitor is increased. The reactance of the TCSC is capacitive and is dependent on the value of α. The boost factor, KB, can vary in the range [00, 1]. This mode of operation is referred to as the capacitive eboost mode. However, practically a boost factor of KB = 00 is not possible

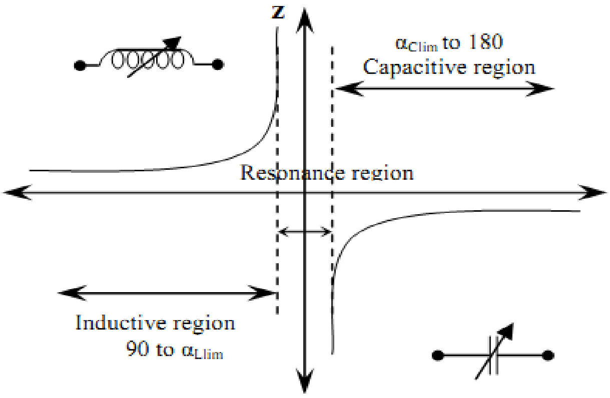

Figure 4.b. Variation of impedance in case of thyrister controlled series capacitors TCSC

Figure 4.b. shows the impedance characteristics curve of a TCSC device. It is drawn between effective reactance of TCSC and firing angle α. Net reactance of TCR, XL (α) is varied from its minimum value XL to maximum value infinity. Likewise effective reactance of TCSC starts increasing from TCR XL value to till occurrence of parallel resonance condition XL(α) = XC, theoretically XTCSC is infinity. This region is inductive region. Further increasing of XL(α) gives capacitive region, Starts decreasing from infinity point to minimum value of capacitive reactance XC. Thus, impedance characteristics of TCSC shows, both capacitive and inductive region are possible though varying firing angle (α). [3]

90 < α < αLlim Inductive region

αLlim< α < αClim Capacitive region

αLlim< α < αClim Resonance region [3]

While selecting inductance, XL should be sufficiently smaller than that of the capacitor XC. Since to get both effective inductive and capacitive reactance across the device. Suppose if XC is smaller than the XL, then only capacitive region is possible in impedance characteristics. In any shunt network, the effective value of reactance follows the lesser reactance present in the branch. So only one capacitive reactance region will appears. Also XL should not be equal to XC value; or else a resonance develops that result in infinite impedance – an unacceptable condition. Note that while varying XL (α), a condition should not allow to occur XL (α) = XC [3] Figure 4.c. shows a simple transmission line represented by its lumped π equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-I and bus-j are Vi and Vj respectively. The real and reactive power flow from bus-i to bus-j can be written.[3]

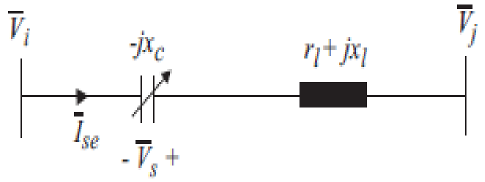

Figure 4.c. Model of transmission line.

The control action of the TCSC is usually expressed in terms of its percentage of the compensation, kc, defined as:

$Kc=xc/xl*100\%$

Where, xl is the line reactance and xc is the effective capacitive reactance provided by TCSC.

$Ise=V i - V j/rl + j(xl - xc)$

The influence of the capacitor is equivalent to a voltage source which depends on voltages V i and Vj. The current injection model of the TCSC is obtained by replacing the voltage across the TCSC by an equivalent current source Is Figure 4.d. In Figure 4.e, VS=−jxcIse, and from Figure 4.e. follows

$IS=V S/rl+jxl=-jxc*Ise/rl+jxl$ Current injections into nodes i and j are

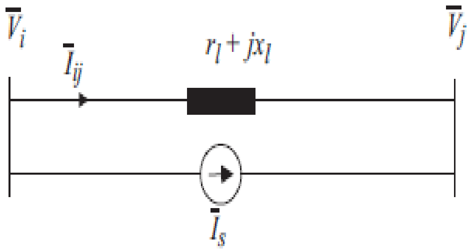

Figure 4.d. Replacement of voltage source by current sourse

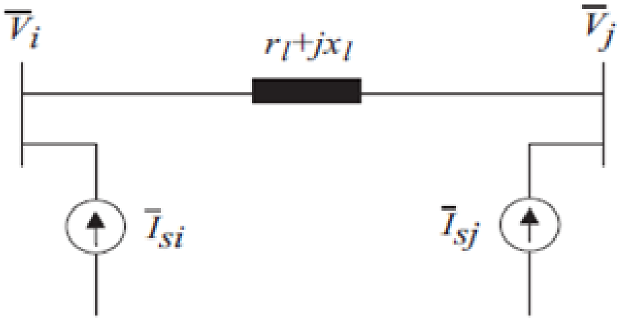

Figure 4.e. Current Injection Model of TCSC

$ISj=-jxc/rl+jxl*V i - V j/rl+j(xl - xc)ISi=-ISj$

and therefore the appropriate current injection model of the TCSC can be presented as shown in Figure 4.f.

The general form of the TCSC control system used is shown in Figure 6, where the Control Strategy block represents the design method for power flow controller based on linearization of power flow equations around an operating point. The output of the block is the change of the compensation degree given by

$\Delta kc = \Delta P\ (rl2+(xl- xc)\ 2)/\ \{2(Vi2-ViVj\cos\theta ij)\ (1 - kc)...$

$-r12(ViVj\cos\theta ij)\ 1/xl+ViVj\sin\theta ij\ (1 - kc)\}$

where $\Delta P = Pref - P$ is the input in the block.

Kcd is the proportional part and Tcd is the integral time constant of the TCSC PI controller. The time constant T approximates delay due to the main circuit characteristics and control systems.

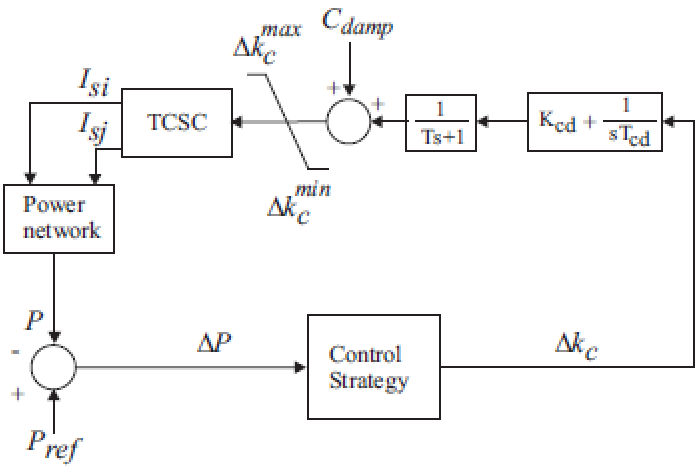

Figure 4.f. General form of TCSC control system.

TCSC line active power and Pref is the line active power to be maintained by TCSC. Kmin and kmax are the limits on the compensation degree changes. [4]

5. CLOSED LOOP CONTROL SCHEMES:

For open loop control of the TCSC impedance, the thyristor trigger angle is set externally and the controller generates the appropriate triggering signal to the thyristors. The trigger angle is chosen depending on the level of compensation required. Alternatively, the level of compensation is set externally and the controller determines the appropriate trigger angle from a look up table or a best fit function.[1]

Numerous low level closed loop control strategies have been proposed to implement a triggering controller for the TCSC. One of the advantages of a closed loop control system is to speed up the slow response time of the TCSC the slow response time of the TCSC is due to the effect of the TCR branch and the capacitor [1] in the TCSC.

The closed loop control strategies that have been proposed are closed loop current control, conduction angle feedback and impedance feedback the feedback signals required for the implementation of these control strategies are the TCSC capacitor voltage and transmission line current for impedance control, and the TCR current for conduction angle feedback control. An advantage of using the TCSC capacitor voltage as a feedback signal is that possible over-voltage conditions of the TCSC can also be avoided [1] by monitoring the TCSC capacitor voltage.

Further advantages of closed loop control of the TCSC include the ability to negotiate the effects of the non linear properties of the TCSC [I], and to reduce the dependency of response on the operating point [1]. It was also proposed [1] that the transmission line current of each phase be used as a feedback signal and a trigger angle be generated for each phase to minimize the effects of the dissimilar [2]

6. CONCLUSIONS

With the history of more than three decades and widespread research and development, FACTS controllers are now considered a proven and mature technology. The recent introduction of TCSC has further widened the scope and added new valuable benefits. This paper reveals an overview of TCSC as one the best proposed devices in FACTS family, its applications and the prospects of TCSC as an effective power system improvement tool.

This paper has addresses a quick overview of thyristor controlled series capacitor as one the best proposed devices in FACTS family and its applications in power transmission system. The performance of TCR was found to be highly dependent on the Firing angle of the TCR. It was found that as the firing angle increases, results in the consequent reduction of the reactor current. TCR has the ability to ensure a continuous and fast reactive power and voltage control which can increase the performance of the system such as control of transients over voltages at power frequency, preventing of voltage collapse, and increase in transient stability and decrease in system. This paper also presented equipment for controllable series compensation of transmission lines.

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