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Thyristor Controlled Phase Shifter: A Comprehensive Survey

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Abstract: Thyristor control phase shifter (TCPS) is one of the new facilities implemented in power network, leading to the development of economically efficient and technically reliable system. This paper introduces the function of TCPS in power system, describes its working principle and structure, and suggests some simple models used in its study and briefly presents the comparison between different types of TCPSs and their applications.

Key words: power system, FACTS, TCPS, phase angle regulation

The electric system for transmitting power has entered its changing period due to the application of power electronic and micro electronic devices as well as new communication technology[1]. Where these facilities open up new options for electric power transmission provides approaches to overcome the limitations of present system by using reliable, high-speed power electronic controllers. These new techniques fuel the review of traditional power transmission theory and create new concepts that allow the full utilization of all existing power generation and transmission facilities.

One can make the system more reliable, more controllable and more efficient without compromising its availability and security by controlling the power transmitted and changing the usable capacity of present transmission lines through voltage and current upgrading, impedance modification and phase angle regulation[2-4]. The flexible AC transmission system (FACTS) offers a versatile alternative to these conventional reinforcing methods in which various power electronics based controllers regulate power flow and transmission voltage and, through rapid control action, mitigate dynamic disturbances and hence enhance the system reliability as well as the power quality[5].

The application of FACTS technology started with the static var compensator (SVC) in 1970s followed by thyristor controlled series compensation (TCSC) schemes in years that are more recent. And now the thyristor controlled phase shifter (TCPS) and thyristor controlled breaking resistor (TCBR) followed them.

FACTS technology is being promoted as a means to extend the capacity of existing transmission networks to their limits without the necessity of adding new transmission lines. The other potential advantage of FACTS is its ability to improve the damping and control the power flow through selected corridors in a network. FACTS devices essentially introduce new degree of freedom to the operation of power system and can be differentiated by their controllable parameters as well as the manners in which they are realized electronically. Thus, these devices are so produced that they can control the series or shunt reactance of the transmission line, regulate the magnitudes and phase angles of voltages. However, in order for FACTS to be accepted by the power industry, this extra flexibility must also lead to net increase in economic benefits as compared with the alternative of expanding the existing transmission networks or generation plants[6].

Thyristor controlled phase shifter (TCPS) is a proposed technology effective for continuously regulating steady state power flow, damping inter-area oscillations and enhancing the transient stability limit of the system[7,8]. Hence this rapid phase shift control falls within the general scope of FACTS devices that have stirred much interest recently in power engineering community.

1 Principle and Structure of TCPS

The basic function of a conventional phase-shifting transformer is to provide a means to control active power flow in transmission line, because this active power flow is predominantly proportional to the sine of the phase-angle across the line[3,9].

The phase shift between two bus voltages in Fig.1 is normally achieved by means of a 3-phase shunt or excitation transformer with its secondary windings connected to the primary windings of a series or boosting transformer. The secondary windings of the latter are connected in series with the transmission line. The winding connections of these two transformers are so arranged that a quadrature voltage can be added to each phase. The adjustment of this quadrature voltage can be achieved through the change of the

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turns-ratio of the excitation transformer. In order to overcome the maintenance problems of the mechanical switches and provide smooth control, anti-parallel thyristor pairs are used for different tap settings thus fast and reliable action of such TCPS can be guaranteed[2,10].

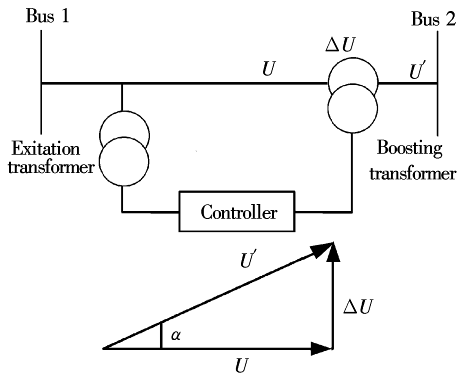

Fig.1 Schematic diagram of TCPS and the fundamental voltage components

Fig.2 shows the schematic diagram of one phase of the TCPS boosting transformer. Voltages at both ends of such TCPS are U_a, U_b, U_c and U_a', U_b', U_c' respectively. Exciting transformer T_1 provides the quadrature voltages and boosting transformer T_2 provides the controlled boosting voltages. The controllers S_1, S_2, S_3, S_4 are back to back thysistor switches. Their functions are merely that of the change-over switches that define the controllable direction and magnitude of the quadrature voltage by connecting their input voltage to the output in one of the following ways:

- Direct (positive quadrature voltage), S_1 and S_2 conducting;
- Reversed (negative quadrature voltage), S_3 and S_4 conducting;
- Prevented from reaching the output (short-circuited), S_1 and S_4 or S_3 and S_2 conducting.

Fig.3 shows the phasor diagram of voltages and currents in circuit shown in Fig.2. From this figure it can be observed that the phase angle between current and voltage at the output (φ) is the same as that at the input (δ), because the quadrature phase regulator is neither a reactive power load nor a generator. This means the function of the quadrature phase shifter is merely to shift the phase angles of the current and voltage of the line to the same extent, i.e., $\delta = \varphi$. Besides, it is worthwhile to mention that no other problems, such as subsynchronous resonance SSR, etc. are to be expected when a phase shifter is installed in a transmission line[13]. This is because SSR is stemmed from the resonance of the series connected capacitance and the inductance of the transmission system and for TCPS, no series connected capacitance is involved[12].

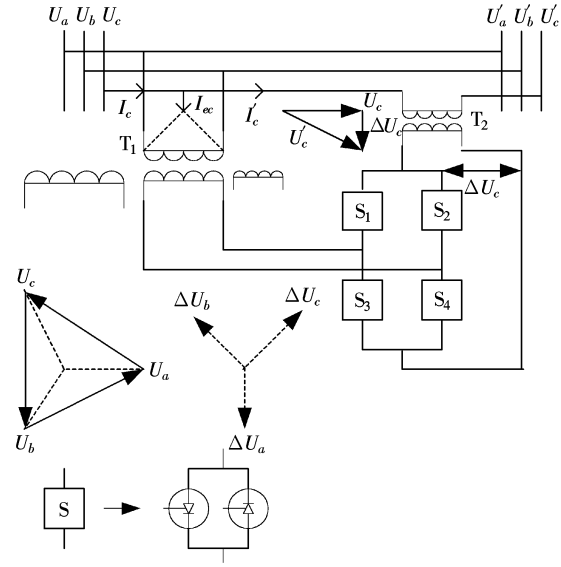

Fig.2 Schematic diagram of one phase of TCPS

2 Functional Models of TCPS

In accordance with the basic functions of TCPS, its functional model can be divided into two categories: static model and dynamic model. The static model is mainly used in the analysis of its function of controlling the steady-state power flow. On the other hand, the dynamic model is mainly used in the analysis of its function of enhancing the transient stability or damping the electromechanical oscillation after large or small disturbances in the system.

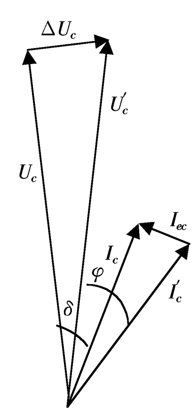

Fig.3 Phasor diagram for phase of TCPS

2.1 Static model

The static model of TCPS can be considered as a conventional phase angle regulator that imposes a series voltage on the transmission line. Since it is expected to exhibit the same leakage reactance and complex turns-ratio exhibited by the conventional phase-angle regulator. Thus, Eq. (1) gives a complex turns-ratio where α is the phase shift in radians and m is the magnitude of the voltage boost[13].

$$\frac{\dot{v}_2}{\dot{v}_1} = \frac{\dot{I}_1}{\dot{I}_2} = m\mathrm{e}^{\mathrm{j}\alpha} = \beta \tag{1}$$

The change in leakage reactance with phase angle α is given by

$$Z = R_{\mathrm{ser}} + \mathrm{j}X_{\mathrm{ser}} + \left|\frac{\sin\alpha}{\sin\alpha_{\max}}\right|^2 (R_{\mathrm{sh}} + \mathrm{j}X_{\mathrm{sht}}) \tag{2}$$

where $m = 1$ for phase shifting transformers; $m = |1 + \mathrm{j}\alpha|$ for quadrature boosters; R_{ser}, X_{ser} are the leakage resistance and reactance of the series winding; R_{sht}, X_{sht} are the leakage resistance and reactance of the shunt winding; α_{max} is the maximum phase angle shift.

According to these two equations, transformer as shown in Fig.4 can implement the TCPS in the network.

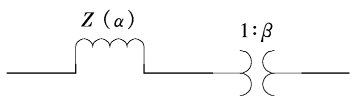

Fig.4 Implementation of TCPS in power network

2.2 Dynamic model

This model captures the basic dynamic functions that might be expected from a TCPS. Each TCPS with its firing control system in the network has been approximately modelled with first order model characterized by a gain and a time constant as shown in Fig.5.

The desired phase-shift (control signal) consisting of a reference angle and feedback signal. This control signal is fed into a lag circuit with a time constant T_s of 15 ms, which represents the delay of the thyristor circuit.

The output is discretized to represent a real TCPS tap changing effect. The descretized signal is the final phase angle imposed on the network $\varphi_{deliver}$[10,13].

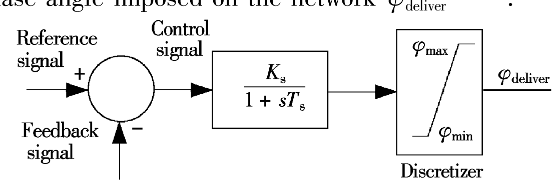

Fig.5 Block diagram of phase shifter with automatic regulator

3 Types and Applications of TCPS

During the last two decades, significant effort has been devoted to overcoming the shortcomings of conventional phase shifting schemes through the utilization of different power electronic circuits. Based on these different circuit configurations, TCPSs can be divided into several categories. Principle of operation, modes of operation, limitations and differences between each other described in Tabs.1 – 3[14]. For example, from Tab.1, it can be observed that one of the main differences between Types A, B, C and Types D, E lies in the switching component used — conventional thyristor or GTO.

In Tab.2, different operation modes corresponding to these different types of TCPSs are given, more concretely, the control ranges over magnitude, phase angle and frequency of their output voltage are listed.

In Tab.3, the feasibility of applying these different types of TCPSs for one or more of the following functions is listed. These functions are:

During steady state operation

- Regulating power flow of transmission line;
- Regulating power sharing among parallel lines;
- Controlling loop flow in power network.

During small signal dynamics

- Preventing torsional oscillations of generator shaft;
- Preventing inter-area low frequency oscillation;
- Mitigating harmonics in power system.

During large signal disturbances

- Enhancing system transient stability;
- Mitigating transient torsional stress of generator shaft.

For ease of clearance, summarize some properties of the four promising types of TCPS[15].

Type-B: Control the magnitude of the injected voltage in discrete steps. The phase of the injected voltage is either + 90 or – 90 and this type does not require harmonic filter.

Type-C: Also based on discrete type control principle. The phase angle of the injection voltage is either + 60 or – 120. Harmonic content is negligible also.

Type-D: It's composed of two GTO based voltage source inverter and DC link. This type provides continuous control over the magnitude and phase angle of the injection voltage. The phase angle can be control from 0 to 360 and requires harmonic filters.

Type-D_2: It's mechanical phase angle regulator, which augmented with static converter. Injected voltage controlled by the electronic converter for rapid phase angle control. For more details can review Ref.[14].

Tab.1 Configurations of different types of TCPSs and the major component of each type

TCPS type	Excitation transformer	Booster transformer	Thyristor	GTO	Filter	Energy storage	Tap winding	H.V. platform
Type-A	✓	✓	✓	×	✓	×	×	✓
Type-B	✓	✓	✓	×	×	×	×	✓
Type-B_1	✓	✓	✓	×	×	×	×	✓
Type-B_2	✓	✓	✓	×	×	×	×	✓
Type-C	×	×	✓	×	×	×	✓	×
Type-C_1	×	×	✓	×	×	×	✓	×
Type-D	✓	✓	×	✓	✓	✓	×	✓
Type-D_1	✓	✓	×	✓	✓	✓	×	✓
Type-D_2	✓	✓	×	✓	✓	✓	×	✓
Type-E	✓	✓	×	✓	✓	✓	×	✓

Tab.2 Operation modes of different types of TCPSs

TCPS type	Injected voltage					
	Magnitude		Phase angle		Frequency	
	Continuous	Discrete	Continuous	Discrete	Fixed	Continuous
Type-A	✓			– 90° or + 90°	✓	
Type-B		✓		– 90° or + 90°	✓	
Type-B_1		✓		0° to 360°	✓	
Type-B_2		✓		0° to 360°	✓	
Type-C		✓		60° or – 120°	✓	
Type-C_1				0° to 360°	✓	
Type-D	✓		0° to 360°			✓
Type-D_1	✓		0° to 360°			✓
Type-D_2	✓		0° to 360°			✓
Type-E	✓		0° to 360°			✓

Tab.3 Application feasibility of different types of TCPSs

TCPS type	Steady state			Small signal dynamics			Large signal dynamics	
	Power flow	Power sharing	Loop flow	Inter-area oscillation	Torsional oscillation	Harmonics	Transient stability	Transient torque
Type-A	√	√	√	×	×	×	×	×
Type-B	√	√	√	√	√	×	√	
Type-B_1	√	√	√	√	√	×	√	√
Type-B_2	√	√	√	√	√	×	√	√
Type-C	√	√	√	√	√	×	√	√
Type-C_1	√	√	√	√	√	×	√	√
Type-D	√	√	√	√	√	√	√	√
Type-D_1	√	√	√	√	√	√	√	√
Type-D_2	√	√	√	√	√	√	√	√
Type-E	√	√	√	√	√	√	√	√

4 Conclusions

1) Varying the angle between the output and the input voltages of the TCPS can control both the magnitude and direction of the power flow.

2) Rapid TCPS control falls within the general scopes of FACTS devices, which has stirred much interest recently in power engineering community.

3) TCPS can provide a practical means of controlling the real power flow in system without affecting the economic generation, conditions and the configurations of the system.

4) Simple static and dynamic models of TCPS have been adopted to analyze its functions in power system.

5) According to the different configurations, different types of TCPSs used in power system can be obtained.

6) This paper provides a brief comparison of various types of TCPSs with respect to their operational modes and application feasibility.

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关于晶闸管控制移相器的综述

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摘　要　晶闸管控制移相器(TCPS)是电力网络中的新设备之一,藉以改善电力系统运行的经济性和可靠性.本文介绍 TCPS 的工作原理、结构和功用,并提出若干不同类型的 TCPS,简单比较了它们的应用.

关键词　电力系统,灵活交流输电系统,晶闸管控制移相器,相位角调节

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