Study on Operational Tests for FACTS Thyristor Valves

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***Abstract*—Developed synthetic test circuits for thyristor valves of flexible ac transmission systems (FACTS) are established in this paper. By controlling the thyristor valves of synthetic test circuits, it can reproduce test stresses, including, but not limited to, the forward high voltage before the thyristor valve withstanding overcurrent and reverse recovery voltage after thyristor valves withstanding overcurrent, on thyristor valves in FACTS equipment equal to or greater than those that appear in commercial projects. With corresponding test circuits and control strategies, the temperature-rise test, overcurrent test, and the synthetic test for thyristor valves can be performed, respectively. Then, a protection method of synthetic test circuits is presented. Finally, a temperature-rise test platform, overcurrent test platform, and synthetic test platform for thyristor valves have been set up, respectively. The test results show that the developed circuit and proposed control and protect strategies are available to test for thyristor valves used in FACTS.**

***Index Terms*—Break over diode (BOD), controllable high-voltage shunt reactor (CSR), flexible ac transmission systems (FACTS), operational tests, static var compensators (SVC), synthetic test circuits, thyristor valve, thyristor-controlled series compensation (TCSC).**

I. Introduction

THE operation performance of long distance and inter-regional ac transmission system is usually limited by various factors. The power system stability and economy have been improved remarkably over the past 10 years, thanks to the application of flexible ac transmission systems (FACTS) equipment, such as static var compensators (SVC) [1]–[3] and thyristor-controlled series compensation (TCSC) [4]–[7]. FACTS controllers can also effectively mitigate the subsynchronous resonance (SSR) caused by an induction generator. For most FACTS equipment, the thyristor is the most critical semiconductor device. However, the thyristor is sensitive and vulnerable to voltage stress; current stress; $dv/dt, di/dt$; and its junction temperature. To enhance the reliability of FACTS, it is necessary to carry out test research and equipment development for the high-voltage (HV) thyristor valve.

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Since the capacity of FACTS equipment is continuously increasing, a direct test for the HV thyristor valve can hardly be realized. Currently, a synthetic test circuit is the preferred choice to test the valve section, which consists of several series-connected thyristor levels [9]–[12]. In the synthetic test setup, the large current and the high voltage (HV) are generated, respectively, by different power supplies. This method is an economical alternative, since it remarkably decreases the installed capacity of test facilities [11].

In the 1990s, several international companies proposed respective test circuits of various ratings for different test objectives. For example, the HV and large current of the synthetic test setup in ABB Company Switzerland are rated at 50 kV (peak) and 4500 A (rms), respectively [13]. It can be applied to the thyristor valves of SVC. However, its voltage rating is slightly low, and the synthetic test cannot reproduce the forward HV before the thyristor valve withstanding overcurrent. The HV and large current of the synthetic test setup in ABB Company Sweden are 70 kV (peak) and 4000 A (peak), respectively [10]–[12]. However, it can be applied for the HVDC thyristor valve. The HV and large current of the synthetic test setup in Siemens Company are 60 kV (peak) and 2600 A (rms), respectively [9]. Although the test setup is fit for thyristor valves of FACTS and HVDC, its resonance frequency is fixed. What is more, it can't reproduce the reverse recovery voltage of thyristor valves after withstanding overcurrent. In 2004, the China Electric Power Research Institute (CEPRI) developed their synthetic test facility, with voltage and current rating at 80 kV (peak) and ac 4000 A (rms)/dc 5000 A, respectively. The test facility can reproduce the forward HV before the thyristor valve withstanding overcurrent and reverse recovery voltage after thyristor valves withstanding overcurrent. It is fully capable of performing an operational-type test for the thyristor valve of FACTS and HVDC per IEC/IEEE standards [14], [15]. The test facilities had been successfully used for the type test of more than 100 projects, such as the Dunhuang 750 kV controllable HV shunt reactor (CSR) project in 2011, Taoxiang 500 kV SVC project in 2010, and the Yimin-Fengtun 500 kV TCSC project in 2007 in China.

In this paper, the main circuits of the temperature-rise test, overcurrent test, and synthetic test have been improved by referring to the design of synthetic test setup of ABB Company, Siemens Company, and [16], [17]. The low-voltage (LV) continuous trigger for the control of the thyristor valve has been proposed. Then, the overvoltage of the large current test mode and the protection method are analyzed, respectively. Finally, three kinds of test of the thyristor valve have been carried out, respectively.

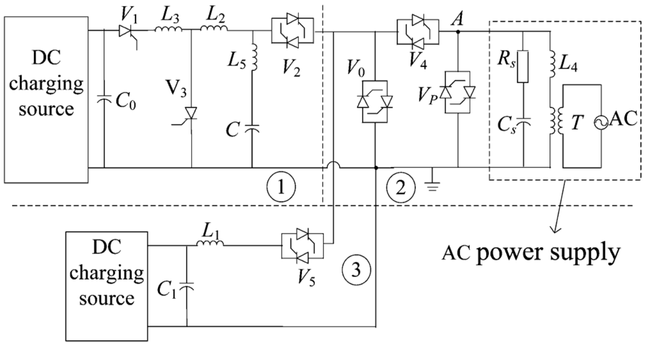

Fig. 1. Schematic diagram of the MIST circuit.

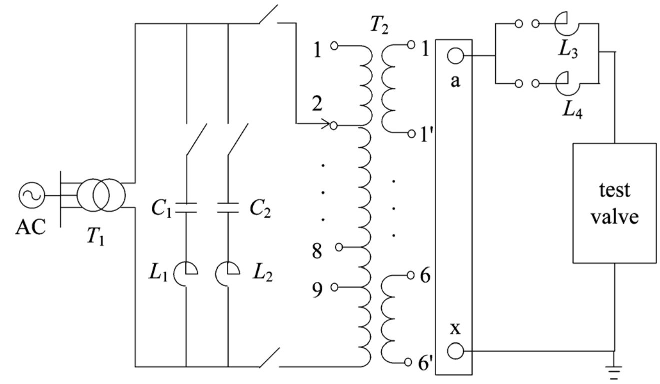

Fig. 2. Schematic diagram of the temperature-rise mode.

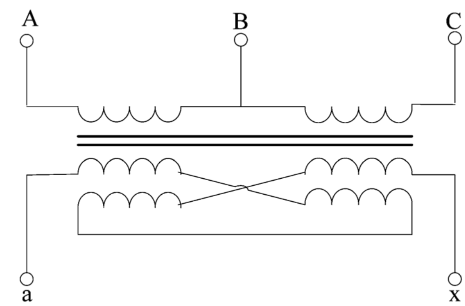

Fig. 3 Wiring of the conversion transformer.

II. Test Circuits

The synthetic test circuit for the operational tests of the FACTS thyristor valve is shown in Fig. 1. It consists of three subsystems, which are the double injection voltage circuit ①, the large ac current injection circuit ②, and the resonance injection circuit ③. The mechanical switches between the circuits can realize the switching of test circuits as well as mechanical isolation. The double injection voltage circuit consists of the LV charging circuit (which comprises the dc charging power supply, the capacitor C_0), auxiliary valve V_1, reactors L_2 and L_3, the oscillatory voltage boost circuit (which includes the resonance reactor L_5 and resonance capacitor C). The large ac current circuit comprises the ac power supply, the charging transformer T, auxiliary valve V_4, snubber circuit R_s and C_s, protection valve V_p, and lead inductance L_4. The resonance injection circuit consists of the capacitor C_1, resonance inductor L_1, auxiliary valve V_5, and dc charging power supply. By controlling thyristor valves V_5, V_2, V_4 and the test object V_0, the temperature-rise test, overcurrent test, and synthetic test of V_0 can be realized. The synthetic test circuit for the operational tests of the HVDC thyristor valve can refer to Fig. 1 (only replace the large ac current injection circuit with the large dc current injection circuit).

III. Operating Principle and Testing Methods

A. Operating Principle of the Temperature-Rise Mode

The circuit of the temperature-rise mode is shown in Fig. 2. Since the load of the conversion transformer T_1 is a single-phase load, the structure of T_1 shown in Fig. 3 can distribute the single-phase load to A phase, B phase and C phase primary windings in the proportion of 25%: 50%: 25%. And the unbalance of the single-phase load for the ac power can be mitigated effectively. Taking into account the requirement for adjusting the voltage and current to the test valve, the secondary winding of the temperature-rise transformer T_2 is designed as 6 windings (mutually isolated) so that the output voltage can be regulated by series and/or parallel windings. Moreover, the output current can be controlled by selecting different limiting reactors, which are adjustable. In Fig. 2, C_1 and L_1, C_2 and L_2 constitute different filtering circuit for the power supply, respectively, and L_3 and L_4 are adjustable reactors which are capable of wide-range regulation for the large current.

B. Operating Principle of Overcurrent Mode

The test circuit mainly comprises subsystems ② and ③ shown as Fig. 1. The test procedures are as follows:

1) Fire the isolating valve V_4 and the test valve V_0 before the instant t_1 so that the test valve carries large current. The procedure simulates the normal current of V_0 in service.
2) Block V_4 and V_0 when the test valve reaches thermal equilibrium and the junction temperature reaches the test requirement.
3) Continuously fire the control valve V_5 at the instant t_2 so that the forward HV applies to the test valve V_0. The procedure simulates the forward HV before the test valve withstands overcurrent.
4) Fire the test valve V_0 at the instant t_3 to keep it under the overcurrent state.
5) When the voltage of capacitor C_1 (Fig. 1) reverses after half a resonance period, block the test valves V_0 to keep V_0 under reverse HV. Then, continuously fire V_5, so that the test valve V_0 is exposed to negative HV. The procedure simulates the reverse recovery voltage after thyristor valves withstand overcurrent. The current and voltage waveforms of the test valve are shown in Fig. 4.

C. Operating Principle of Synthetic Test Mode

The test circuit mainly comprises subsystems ① and ② as shown in Fig. 1. The current circuit verifies the current-carrying and temperature-rise capabilities of SVC and TCSC thyristor valve. Also, the current test is a precondition for the voltage-current synthetic test. The voltage circuit includes the LV charging circuit and the oscillatory voltage boost circuit, which is an actual HV oscillation generator.

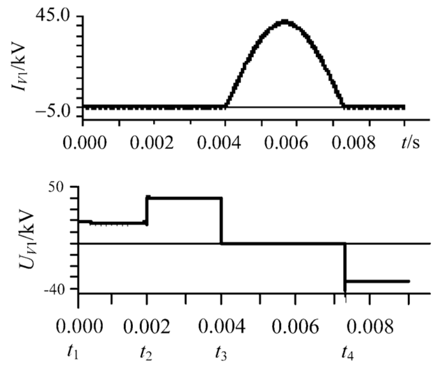

Fig. 4. Waveforms under the overcurrent mode.

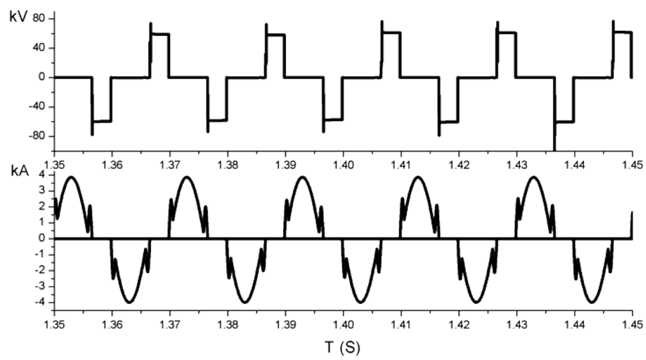

Fig. 5. Current and voltage waveforms of the test valve for double injection test of thyristor controlled reactor (TCR) valves.

On the synthetic test set up, four modes can be carried out by coordinating the current circuit and the voltage circuit, as well as the isolating switch (not shown in Fig. 1). The four modes are, respectively, the single (V or I) injection of the bi-direction test valve, the double (V and I) injection of the bi-direction test valve, the single injection of the single-direction test valve, and the double injection of the single-direction test valve. Each test mode has three operating modes, which are the voltage test mode, current test mode and voltage-current synthetic test mode. As the circuit structure and the sequential circuit of the double injection (both the HV injection and large current injection) test are very complicated, this paper only setup the simulation model for the thyristor valve. The typical simulation waveforms of thyristor-controlled reactor (TCR) valves under the double injection of the bi-direction test, are shown in Fig. 5.

Fig. 5 shows that the synthetic test circuit can adequately represent $di/dt_{on}, di/dt_{off}$, the current strength, the voltage strength, the energy loss and so on.

IV. Continuous Firing Control of the Test Valve

The thyristor is usually used for the current control. However, the work conditions of the thyristor valve V_0 in the test system are different from the actual service conditions. The control valve V_2 with the current control will decrease the HV for the test valve V_0 significantly. The equivalent circuit of the system, including V_2, V_0 and the HV resonance circuit, is shown in Fig. 6.

In Fig. 6, the ideal switches S_0 and S_2 denote the test valve V_0 and control valve V_2, respectively; C_{s0} or C_{s2}, R_{s0} or R_{s2}, and

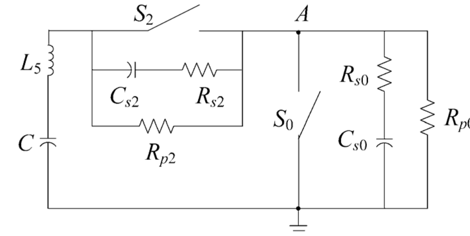

Fig. 6. Equivalent circuit of the control valve and test valve.

R_{p0} or R_{p2}, are corresponding valve of the snubber capacitors, snubber resistors and grading resistors, respectively.

During the overcurrent test of the test valve V_2, three key steps must be followed. The first one is to apply positive HV to the test valve before the thyristor valve withstands overcurrent. The second one is that, after half a period, the test valve shall withstand all the capacitor voltage when the capacitor voltage reverses. The last one is that the voltage of the test valve shall decrease to a low level after keeping the reverse HV for a while.

In the test system, the series connected thyristor levels in V_2 is larger than that in V_0, and R_{p2} larger than R_{p0}. Therefore the HV is not as much as expected by current control of V_2 alone. In order to solve the problem, we have proposed the voltage control for V_2 under the overcurrent test of the thyristor. The control method can keep the voltage close to zero and realize that the HV for the thyristor valve in the overcurrent test.

The voltage control technology can be considered as continuous firing the thyristors. High frequency pulses are sent to the gate units of the thyristors of the resonance valve, if required. And this can spur the carriers redistribute in the thyristors. In addition, positive feedback of two equivalent transistors can be excited at some extent. Consequently, the barrier voltage of the junction J_2 of the thyristors can be greatly reduced. Though they are not carrying currents, terminal voltages of the thyristors can still be fairly low. Test waveforms of the current and voltage are shown in Fig. 4.

As long as continuous firing control of the resonance valve is employed before the commencement of the overcurrent and after half a resonance period of the overcurrent semiwave, the resonance valve can be maintained at the low resistance condition. Apply the required HV to the test valve between the instants t_2 and t_3 as shown in Fig. 4, and cease continuous firing control of the resonance valve at the end of the test, after the instant t_4, the voltage of the test valve will be decreased and the HV will only be withstood by the resonance valve. So, in one sense, the voltage control mode for the equivalent experiment of the thyristor valve is a breakthrough.

V. Analysis and Protection of Fault Overvoltage

A. Analysis of Fault Overvoltage

Under test mode of the large current for test valve, there may occur serious fault. For example, at the instant 0.004 s, the control valve V_2 and isolated valve V_4 are simultaneously turned on and V_0 is blocked. The resonance capacitor C, the resonance reactor L_5 and the transformer T generate resonance. At the instant 0.006 s, the ac circuit breaker of T operates. The simulated waveforms of the voltage and current are shown in Fig. 7.

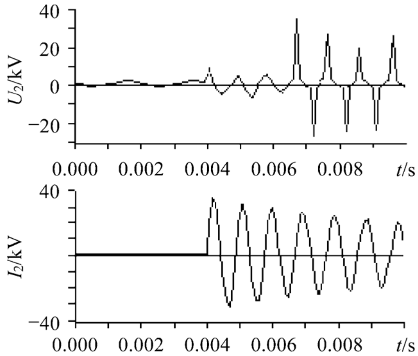

Fig. 7. Simulated voltage and current waveforms without overvoltage protection for the transformer.

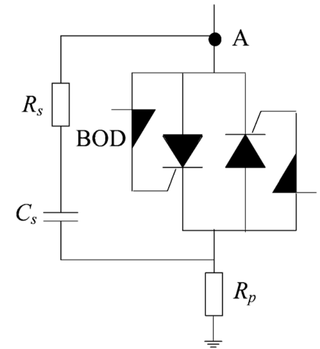

Fig. 8. Schematic diagram of the protection strategy.

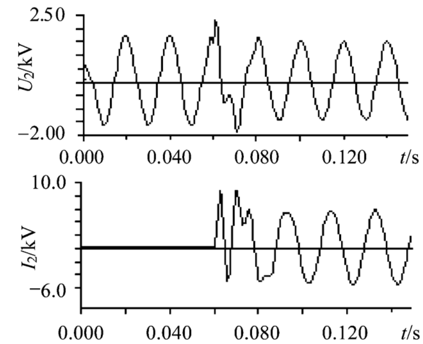

Fig. 9. Simulated voltage and current waveforms of protection valve with BOD.

As shown in Fig. 7, the waveforms of the voltage and current are nearly sine wave before the trip protection of T, and the voltage of T increases greatly following the breaker trip. This may be that the exhibited reactance of the transformer T is its leakage reactance at first, then its magnetizing reactance. So, after the trip protection, the voltage of the transform largely increases. This overvoltage may result in the transformer permanent damage. Besides, due to no current in the primary winding, the transformer tends saturation. It can also be seen from Fig. 7 that the current only slightly decreases after 0.006 s, due to the transformer's saturation. In order to protect the transformer or the equipment in power system, it is necessary to install an overvoltage protection unit at the secondary side of T.

B. Method of Overvoltage Protection

When the control valve V_2 and isolated valve V_4 are simultaneously turned on, the prominent characteristics of the protection unit in the large ac current injection circuit is that the voltage difference between the operating voltage, the protection action voltage and the protective action of residual voltage is very low. Under normal operation, the impulse voltage may be up to 1.59 p.u. due to the reverse recovery charge. However, the maximum allowable voltage is 2 p.u. Accordingly, the protection action voltage and protective action of residual voltage must be limited between 1.59 p.u. and 2 p.u.

There are two conventional methods for overvoltage protection. The first one is to put a metal zinc oxide varistor (MOV) at the secondary side of the transformer for the fault overvoltage. The voltage range of the MOV of the protection action is relatively wide. And the large ac current injection circuit requires a high discharge capacity of the MOV. Depending on the different test modes, the output voltages of the transformer are different. Therefore, the protection system of the current injection circuit needs corresponding voltage level MOV. So, it is difficult to coordinate the MOV under different test modes. Another one is via adjusting spark gap. In transient status, the overvoltage on the transformer increases, which results in the breakdown of the parallel spark gap. However, the protection action voltage is unstable.

In order to suppress overvoltage at the secondary side of the transformer, the following circuit is proposed, including the thyristor self trigger protection, the power-absorbing circuit C_s and R_s, and damping resistor R_p, shown in Fig. 8.

The break over diode (BOD) will breakdown when its forward voltage exceeds a certain value. And the thyristor is triggered due to the gate current pulse. The protection has the advantages of small dispersion and prompt action. The power-absorbing circuit can not only dissipate energy, but also suppress transient overvoltage. The damping resistor can limit the fault current and determine the magnitude of the protective action of the residual voltage. The main parameters in Fig. 8 are: the peak voltage of the protected circuit and the protective action voltage of the BOD are 2.25 kV and 2.6 kV, respectively; C_s is 6 μF; R_s is 30 Ω. Assuming that V_2 and V_4 turn-on simultaneously at the instant 0.06 s, the simulated voltage and current waveforms of the protection valve with BOD are shown in Fig. 9.

Fig. 9 shows that the voltage of point A is clamped by the protection of damping resistance after the fault, and the transformer is not exposed to overvoltage surge.

VI. Parameter Coordination of the MIST Circuit

In the MIST circuit, parameters of all the components can largely affect test waveforms. Parameter coordination for the capacitors, reactors and resistors can bring optimized test waveforms. Major electrical and injection parameters of the circuit are listed in Tables I and II, respectively.

VII. Experimental Validation

In order to verify the effectiveness of the MIST circuit, the temperature-rise test, the overcurrent test and the synthetic test of thyristor valve have been carried out, respectively.

TABLE I
ELECTRICAL RARAMETERS OF THE MIST CIRCUIT

Components	Value	Unit
C	10-50 (5μF constitutes a regulating unit)	
C_1	200/400/700/1100/1300	μF
C_0	5000	
L_1	1.6	
L_2	7/8/9/10/11/12	mH
L_3	1/1.6/1/5.2	
L_5	4/8/16	

The parameters of C_1 and L_1 in the above table is based on resonance frequencies of 356 Hz, 252 Hz, 151 Hz, 150 Hz, and 61 Hz.

TABLE II
INJECTION PARAMETERS OF THE MIST CIRCUIT

Item	Parameter	Value (peak)	Unit
Overcurrent test	I_M	0-40	kA
	U_M	0-45	kV
	ΔU_M	0-45	kV
	di/dt	0-47	A/μs
Synthetic test	I_M	3	kA
	U_M	75	kV
	di/dt	1-10	A/μs
Temperature-rise test	I_M	0.5-3	kA

TABLE III
RELEVANT MEASUREMENTS OF TEMPERATURE RISE

Modes	α	I_{pk} (A)	duration	P_1 (°C)	P_2 (°C)	P_3 (°C)
6kV/ 0.5kA	150°	306	30min.	28	28.6	30
	140°			28	28.6	30
	125°			29.8	30	30
	110°			29.5	30.9	30.3
3kV/ 1kA	145°	358.8	30min.	29.9	30.7	30.1
	130°			30.2	31.6	31.6
2kV/ 1.5kA	140°	557.7	30min.	31.8	33.7	33.2
	135°			31.8	33.7	33.2
	130°			32.6	32.7	32.8

A. Temperature-Rise Test

The circuit of the test platform is shown in Fig. 2. The rated capacity and voltage of the conversion transformer T_1 are 3470 kVA and 10/10 kV (primary/secondary windings), respectively. The nominal capacity of T_2 is 3000 kVA. The primary winding has 9 tap-changers, and the secondary winding consists of six of the same windings. The conversion transformer has four connection modes for voltage/current, which are 6 kV/0.5 kA, 3 kV/1 kA, 1.5 kV/2 kA and 1 kV/3 kA. As the maximum allowable current of the thyristor valve is about 850 A, the temperature-rise test was only carried out under the first three connection modes. An infrared thermometer (TVS-100 series) is used for measuring temperature. Under different trigger angle α for each mode, the peak current of the load is I_{pk}. The ambient temperature of the test site is 30 °C. The measuring point of the temperature rise for the heat-sink is point P_1, the two measuring points of temperature rise for the thyristor are point P_2 and point P_3. The test conditions and corresponding temperature rise are listed in Table III.

B. Overcurrent Test

The resonant frequency of the overcurrent test is adjustable between 50 and 350 Hz. This paper gives the test waveforms of 60 Hz and 350 Hz resonant frequencies. The test waveforms of the two resonant frequencies current and voltage of the thyristor valve, after a half of periodic resonance with thyristor valve blocking, are shown in Fig. 10(a) and (b), respectively.

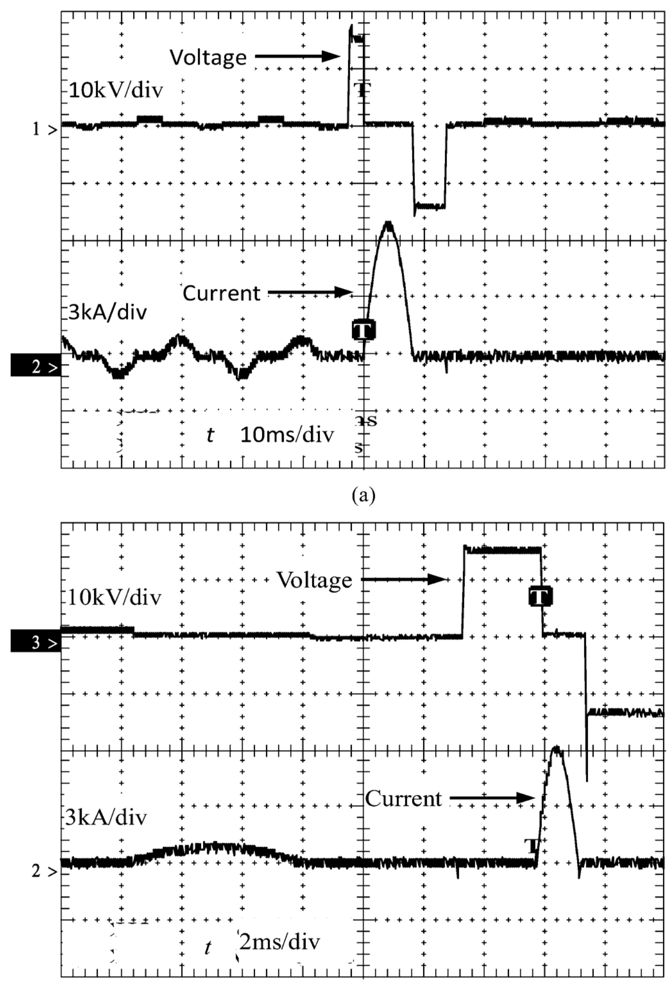

Fig. 10. Test waveforms of the current and voltage with thyristor valve blocking. (a) Overcurrent test of 60 Hz. (b) Overcurrent test of 350 Hz.

From Fig. 10, it can be seen that both the forward HV before the conduction of the thyristor valve, and the reverse recovery voltage after a half of periodic resonance for the thyristor valve can be represented with the proposed voltage control for the thyristor.

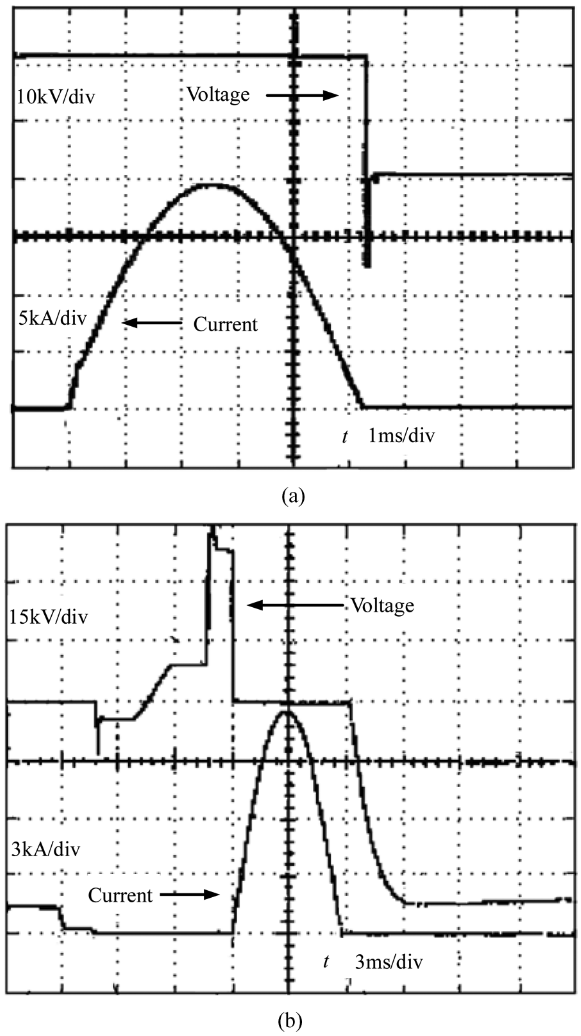

Fig. 11. Test waveforms of the current and voltage with thyristor test valve blocking. (a) Experimental waveforms of ABB Company. (b) Experimental waveforms of Siemens Company.

The test waveforms of TSC thyristor valve by ABB Company and Siemens Company are shown in Fig. 11(a) and (b), respectively. In comparison with the test result of the thyristor test valve in ABB Company and Siemens Company, the test method developed by CEPRI shows the several advantages. First, the test results can reproduce the actual service condition. Second, the resonant frequency of the overcurrent test is adjustable in a wide range. Third, the parameters of the test circuit can be regulated easily.

C. Synthetic Test

Based on the circuit model of the synthetic test, periodic firing and extinction tests are performed on the thyristor valves for two projects (the SVC project in Wanxian, Sichuan, and Yifeng TCSC project) under the synthetic test mode. Wanxian SVC project employed the thyristor controlled reactors (TCR), with a rated voltage 36 kV, rated capacity 180 Mvar and rated current 1666.7 A, whilst Yifeng TCSC project with a rated voltage 46.7 kV and rated capacity 326 Mvar. Basic parameters of the two projects are listed in Table IV. Test waveforms for the SVC and TCSC valve are shown in Figs. 12 and 13, respectively.

TABLE IV
BASIC PARAMETERS OF THE TEST EQUIPMENT

Item	value of TCR	value of TCSC
Number of series valves per phase	24(pair)	46(pair)
Damping capacitance for each thyristor	2.5(μF)	3.8(μF)
Damping resistance for each thyristor	60(Ω)	90(Ω)
Test valve current	1019(A)	425(A)
Test valve voltage	12.5(kV)	80(kV)

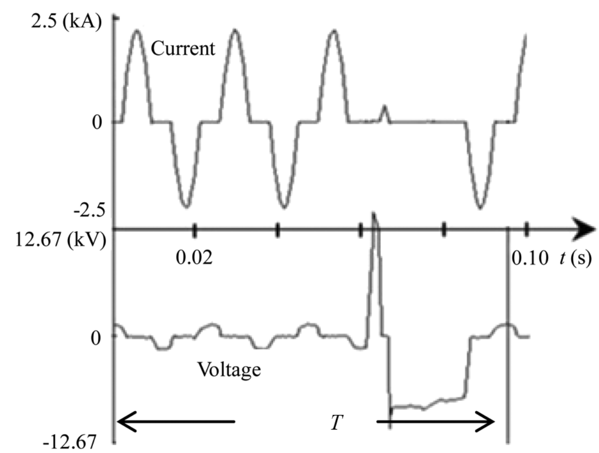

Fig. 12. Waveforms of the operational test on Wanxian TCR valve.

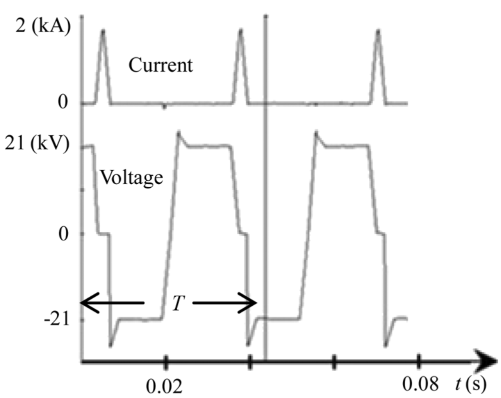

Fig. 13. Test waveforms of the operational test on the Yifeng TCSC valve.

As indicated in the test waveforms of Figs. 12 and 13, the MIST circuit can be used for the thyristor valve of FACTS, which includes the thyristor valve of SVC and TCSC. And the results show that the MIST circuit has the function of the flexible test modes. The MIST circuit is able to satisfy the following different requirements of various thyristor valves:

1) Simulation of di/dt stresses at different instants, such as turn-on and turn-off (by adjusting of injection currents).
2) Reproducing the forward and reverse HV stresses of the thyristor valve (by the HV oscillation generator).
3) Duplicating the large current stresses of the thyristor valve (by the large current circuit).

4) Reproducing the various work conditions of the thyristor valve (by different test modes).
5) Verification of the thyristor valve protection firing (by the control strategy of the test modes).
6) Reproducing dv/dt stress for forward voltage and reverse recovery voltage of the thyristor valve (by the control strategies).

VIII. Conclusion

Operational tests are a key process for verifying the design of the FACTS thyristor valve employed in commercial projects. Considering the high-power rating of modern thyristors, synthetic tests are an effective alternative from the point of economy and practicability. The conventional current control of the thyristor valve cannot reproduce certain characteristics of the thyristor valve in service, such as forward HV before turning on the test valve and reverse recovery voltage after half of a periodic resonance for the thyristor valve. Tests experiences with FACTS thyristor valves have proved that those new synthetic test circuits and new voltage control are a technical feasibility and economy-saving solution in valve design verification.

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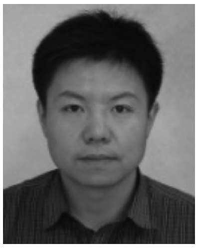

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