Investigation into Equivalency of Synthetic Test Circuit Used for Operational Tests of Thyristor Valves for UHVDC

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Abstract: With the growth of capacity of high voltage direct current (HVDC) transmission lines, the ratings of thyristor valves, which are one of the most critical equipments, are getting higher and higher. Verification of performance of thyristor valves particularly designed for HVDC project plays an important role in the handover of products between the manufacturer and the client. Conventional test facilities based on philosophy of direct test cannot meet the requirements for modern thyristor valves. New test facilities with high ratings are necessarily built based on philosophy of synthetic test. Over the conventional direct test circuit, the later is an economical and feasible solution with less financial investment and higher test capability. However, the equivalency between the synthetic test and the direct test should be analyzed technically in order to make sure that the condition of verification test in a synthetic test circuit should satisfy the actual operation condition of thyristor valves existing in a real HVDC project, just as in a direct test circuit. Equivalency analysis is focused in this paper, covering the scope of thyristor valves' steady state, and transient state. On the basis of the results achieved, a synthetic test circuit of 6 500 A/50 kV for operational tests of thyristor valves used for up to UHVDC project has newly been set up and already put into service in Xi'an High Voltage Apparatus Research Institute Co., Ltd. (XIHARI), China. Some of the results have been adopted also by a new national standard of China.

Key words: equivalency; operational test; synthetic test circuit; thyristor valve; UHVDC
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0 Introduction

Thyristor valves are one of the critical equipments for high voltage direct current (HVDC) transmission. Verification of performance for each HVDC project particularly designed plays an important role[1-3]. At present, direct test cannot meet the requirements for modern thyristor valves, and synthetic test circuit is necessarily built[4-7]. However, the effect produced in synthetic circuit should be equivalent to that in direct test circuit on a test sample[8-11].

Taking a typical test duty specified in Standards[4-5] as an example, waveform generated in a synthetic circuit is compared with that coming from an actual HVDC power system in this paper. Results show that key parameters of waveform applied on test sample can be represented by synthetic circuit, which is proven to be reasonable via a real valve testing for ±800 kV HVDC project.

1 The Waveforms Applied on Thyristor Valve in an Actual HVDC Power System

Fig. 1 shows the current through an arm of an actual 6-pulse converter and the voltage across it during normal operation with firing angle α=20° and periodical time t=20 ms.

Where, I_{vt} is average current through the thyristor valve when it is on; $di/dt|_{on}$ is the rate of the current change when the thyristor valve turns on; $di/dt|_{off}$ is the rate of current change when the thyristor valve turns off; u_{fr} is the forward voltage across it immediately before it turns on; u_{rr} is the reverse recovery voltage across it just after it turns off; du/dt

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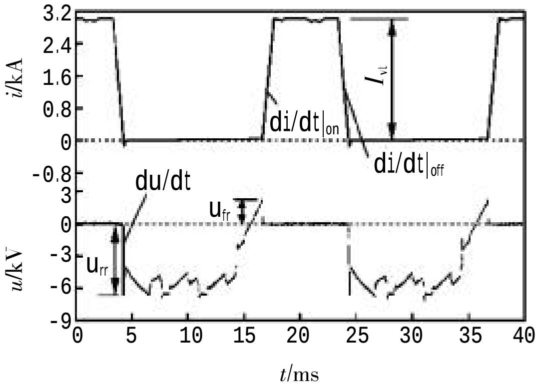


Fig. 1 The voltage and current waveforms of a valve in a 6-pulse converter in actual HVDC power system (α=20°)

is the rate of voltage change.

The thyristor valve operates in four modes, respectively named as "turn-on", "on", "turn-off" and "off". When it is in mode "on", it conducts DC current for 1/3 cycle with a lower voltage drop. When it is in "turn-on" and "turn-off", it bears higher rate of current change. When it is in mode "off", it withstands reverse recovery voltage then forward voltage. Over the reverse recovery voltage, there exist commutation gap and overshoot.

There is no synthetic test circuit that can generate the waveforms as same as those from the actual power system [12-13]. Therefore, those characteristics above should be taken into account seriously to ensure that the waveform generated by synthetic test circuit consists with that existing in the actual power system in the matter of key parameters[14-16].

2 Main Requirements of Operational Tests for Thyristor Valves

2.1 Test sample and its cooling system

Operational tests could be completed on a single valve theoretically. As the converter valves are made of several series sections, and voltage uniformity measures have been taken, operational test can be completed on valve sections, considering limited capacity of test facilities. In general, to ensure test results are representative enough, it is tested on a valve section with 5 series thyristor levels at least.

For all the tests, test samples should be at the most severe cooling conditions, which is to ensure flow, temperature and conductivity of cooling medium must be the same as the worst operating conditions allowed in operation.

These requirements should be met through a set of cooling device specifically designed for the test sample.

2.2 Steady state

There are over 13 items for operational test to check thyristor valve performance, according to Standard[17]. Among these items, maximum continuous operating duty tests can typically check the adequacy of the thyristor levels and associated electrical circuits in a valve with regard to current, voltage and temperature stresses at turn-on and turn-off under the worst repetitive stress conditions. For the purpose of equivalency analysis, this test item is highlighted to introduce the related requirements of operational tests.

Maximum continuous operating duty tests consist of maximum continuous firing voltage test and maximum continuous recovery voltage test. Requirements for test current and test voltage are stated below.

2.2.1 Test current

To check current-carrying capacity of the valve when it is in "on" operation mode, test current (I_{vt}) should be higher than the normal operation current of thyristor valve. It is specified by the standard to be the maximum continuous operating current multiplied by safety factor of 1.05.

2.2.2 Test voltage

This test is to assess the valve section and associated circuit's tolerance ability and adaptability for voltage with the maximum periodic voltage applied. The test can be divided into two parts to complete.

1) Maximum continuous firing voltage test

The peak of the voltage is $U_{tpv1}=U_{vom}\times k_n\times k_{13}$, in which the U_{vom} is maximum steady-state no-load line voltage on the converter transformer valve side; k_{13} is safety test factor, equal to 1.05; k_n is normalization factor, equal to $N_{tut}/(N_t-N_r)$; N_{tut} is the number of series thyristor levels of the test sample; N_t is the total number of series thyristor levels of the single valve; N_r is the redundancy number of thyristor levels of the single valve.

The test voltage is given by bigger one of the formulas between $U_{fr}=U_{tpv1}\times\sqrt{2}\times\sin\alpha_{max}$ and $U_{fi}=U_{tpv1}\times\sqrt{2}\times\sin(\gamma_{max}+\mu_{max})$, in which U_{fr} is the max forward trigger voltage applied to the converter when converter in rectifier operation; U_{fi} is the max forward trigger voltage applied to the converter when converter in inverter operation; α_{max} is the max delay angle of the converter valve when converter in rectifier operation; γ_{max} is the max extinction angle of the converter valve when converter in inverter operation; μ_{max} is the max overlap angle of the converter valve.

2)Maximum continuous recovery voltage test

The test voltage is given by bigger one of the formulas between $U_{rr}=U_{tpv1}\times\sqrt{2}\times k_c\times\sin(\alpha_{max}+\mu_{max})$ and $U_{ri}=U_{tpv1}\times\sqrt{2}\times k_c\times\sin\gamma_{max}$, in which k_c is over-voltage coefficient when commutation in HVDC transmission system, determined by system design.

Test voltage above should keep constant during test period.

2.3 Transient state

2.3.1 $di/dt|_{ON}$

Each thyristor level in a valve is in parallel with a damping circuit comprised of resistor and capacitor. When the thyristor turns on, the capacitor will discharge through the resistor hence to form a transient current flowing through the thyristor. This current appears with a higher changing rate di/dt. Depending on valve design for different HVDC project, it ranges from 1 A/μs up to 10 A/μs. So, the changing rate of current rising at the turn-on instant of thyristor should be represented in a test circuit.

2.3.2 $di/dt|_{OFF}$

A 6-pulse rectifier bridge is a basic unit for a conventional HVDC project. Its AC side is connected with a converter transformer. During commutation process of valves in two adjacent arms of a 6-pulse rectifier bridge, the transformer operates in short circuit. In this case, there is a current going through the thyristor and hence forming the falling slope of DC current. At the instant of current zero, the slope reaches highest. This part of current depends on the short-circuit impedance and the phase-to-phase voltage of converter transformer.

Different HVDC project owns different value of the falling slope of DC current. Therefore, it needs flexibility of test circuit to change parameters of falling slope at current-zero instant especially.

2.3.3 Voltage jump

As shown in Fig.1, there are several commutation gaps existing during reverse recovery period of valve. These will result in heat effect to increase temperature rise of the valve, because voltage jump on the capacitor mainly occurring in the damping circuit leads to producing transient current through the resistor in the damping circuit.

Test circuit should be adapted to simulate these combined losses of thyristors and damping circuit during continuous operation.

3 Equivalency Analysis of Waveform from Synthetic Test Circuit

3.1 Synthetic test circuit and waveform generated by it

See Fig. 2, it illustrates a kind of synthetic test circuit[18-20], which is adopted by thyristor valves for HVDC Transmission Systems, National Standard of China[3]. Here, C_L expresses charging capacitor while C_s main capacitor, L_1 commutation inductance, V_t test sample.

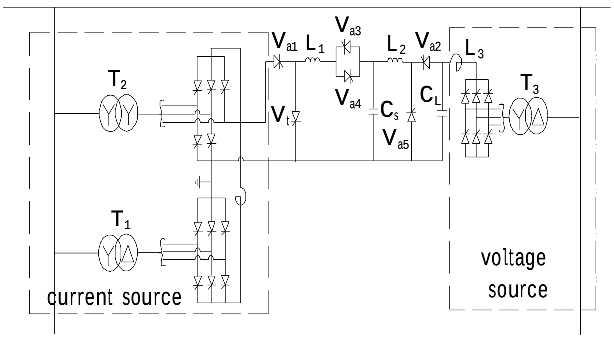


Fig. 2 Schematic diagram of operational test system

Waveforms generated by the synthetic test circuit when operating in maximum continuous operation mode are shown in Fig. 3, where, I_{Vt} is the test current applied in the test sample, u_{fr} is the forward recovery voltage, u_{rr} is the reverse recovery voltage, $di/dt|_{on}$ is the current changing rate at turn-on instant, $di/dt|_{off}$ is the current changing rate at current-zero moment, du/dt is the voltage changing rate, i_{inj} is the current injected by the voltage source.

3.2 Assurance of steady state characteristics

3.2.1 Test current (I_{Vt})

The current I_{Vt} is provided by the current source that is tunable with firing angle. The amplitude of current can fully be reached in terms of requirement for test current[21].

3.2.2 Test voltage

The voltage u_{rr} is provided by the voltage source

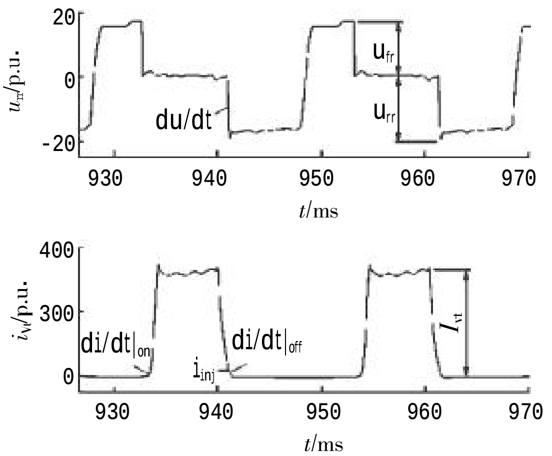


Fig. 3　Waveforms generated by synthetic test

that can be controlled by controlling charging voltage of the capacitor C_L to meet requirement for test voltage.

Difficulty encountered is that voltage attenuation of main capacitor C_s occurs during oscillation in voltage source due to resistance losses. It will cause unstable voltage stress in each cycle across the test sample. Voltage compensation measure should be taken to keep constant in the test voltage during test period.

In this paper, strategy of voltage regulator with closed-loop control is adopted. That is, taking the expected forward voltage across the test sample as objective, and tuning the firing angle α of voltage source to compensate the voltage drop of U_{C_s}. See Fig. 4. When u_{fr} decreased, α is reduced slightly, then U_{C_L} increased, then U_{C_s} increased, thus u_{fr} increased too.

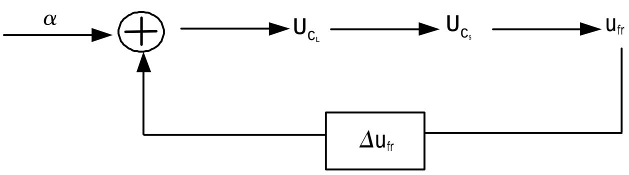


Fig. 4　Schematic diagram of voltage source with closed-loop control strategy

Where, U_{C_L} is voltage across the charging capacitor C_L, U_{C_s} is voltage across the main capacitor C_s, u_{fr} is the peak value of forward voltage across the test sample, $\triangle u_{fr}$ is the difference between the peak value of actual forward voltage and expected voltage across the test sample.

Fig. 5 exhibits the effect of keeping voltage stable with closed-loop control strategy in the voltage source[22]. Where, the first waveform indicates u_{fr}, the second one I_{vt}, the third one counted from the bottom i_{inj}. Prior to work of the current source, the voltage source has functioned with the peak value of voltage u_{fr} compensated per cycle in real time. This realizes the requirement for steady test voltage.

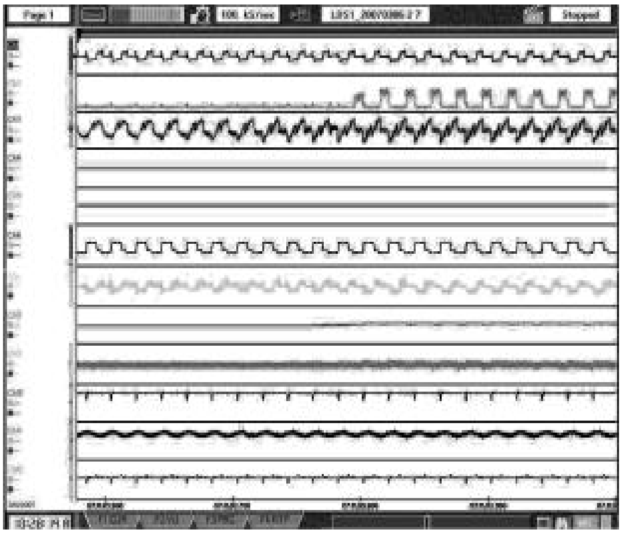


Fig. 5　The panorama of the voltage and current waveform from the synthetic test circuit

3.3　Assurance of transient state characteristics

3.3.1　di/dt|on

di/dt|on of the valve at conducting moment depends on parallel capacitors with the valve[23], in addition to the capacitor embedded in the damping circuit[24]. According to valve design, all the capacitors in parallel with valve should be calculated and scaled to the test sample. When testing, a shunted equivalent capacitor (C_t) with the test sample is needed to simulate the associated impact. In this way, the di/dt|on can be actualized without difficulty.

3.3.2　di/dt|off

Generally, di/dt|off comes from current source with a 6-pulse rectifier bridge, but disadvantage is the value of di/dt|off is fixed and cannot meet requirement for different HVDC project. Take Fig. 2 as an example. The di/dt|off is calculated as follows[25]

$$di/dt|_{off}=di(t)/dt=d\{I_d-I_d[\cos\alpha-\cos(\omega t-120°)]/[\cos\alpha-\cos(\alpha+\mu)]\}/dt=-I_d\times\omega\times\sin(\omega t-120°)/[\cos\alpha-\cos(\alpha+\mu)]$$
$$(120°+\alpha)\leqslant\omega t\leqslant(120°+\alpha+\mu)$$

At current zero when ωt is $120°+\alpha+\mu$, $di/dt|_{off}=-I_d\times\omega\times\sin(\alpha+\mu)/[\cos\alpha-\cos(\alpha+\mu)]$.

In the case of I_d=3.6 kA, α=84.2°, and μ=8.54°, we can get that $di/dt|_{off}$=−7.58 A/μs.

This value isn't adjustable. It relies on the parameters of current source and usually doesn't cover the demands of different HVDC projects.

By using injection current coming from voltage source, the difficulty is overcome reasonably.

See Fig. 2. An oscillation circuit formed by C_S—L_1—V_t produces an inject current i_{inj}, $i_{inj}(t)=I_{m.inj}\sin(\omega_{inj}t)$, in which $I_{m.inj}$ is the peak value of the current, equal to $U_{cs}/(L_1/C_S)^{-1/2}$, ω_{inj} the frequency of the current, equal to $1/(L_1/C_S)^{-1/2}$. Therefore, the change rate at current zero is

$$di_{inj}(t)/dt|_{\omega t=\pi}=-U_{C_s}/L_1=-\omega_{inj}I_{m.inj}.$$

To assure the equivalency at current zero, we should make $di/dt|_{off}=di_{inj}(t)/dt|_{\omega t=\pi}$, i.e., $-I_d\times\omega\times\sin(\alpha+\mu)/[\cos\alpha-\cos(\alpha+\mu)]=-U_{C_s}/L_1$, and $L_1=[\cos\alpha-\cos(\alpha+\mu)]\times U_{C_s}/[I_d\times\omega\times\sin(\alpha+\mu)]$. We can see here that the L_1 depends on α、μ、ω、U_{C_s} and I_d, and the L_1 can be easily adjusted. Thus, choosing different L_1 can realize different requirements of $di/dt|_{off}$ for different HVDC projects.

3.3.3　Voltage jump

As mentioned above, voltage jump can produce additional heat effect. Therefore, IEC 60700-1—2008 specifies the sum of the squares of voltage jumps in the valve voltage waveform, measured over one cycle is not lower than

$$\Sigma\Delta U^2=(1.75+1.5m^2)\times 2\times U^2_{tpv1}[\sin^2\alpha_{max}+\sin^2(\alpha_{max}+\mu_{max})],$$

where m is the electromagnetic notch factor.

During testing in synthetic circuit, the forward voltage and the reverse recovery voltage can be tuned by time sequencer to be equal approximately, so that the losses from voltage jump can be simulated greater than the specified.

3.4　Application of synthetic test circuit in an actual project

Based on the above equivalency analysis, a set of facilities with synthetic test philosophy has been established for operational tests of thyristor valve. Its ratings are 6 500 A/50 kV, being capable of meeting the test requirements up to 5 000 A/±800 kV HVDC project[26]. Operational tests of a real valve for ±800 kV HVDC project have been completed in the synthetic test circuit. Fig. 6 shows one complete module of thyristor valve under test, which consists of a valve reactor and 6 levels of thyristors in series. Its equivalent electric circuit is illustrated in Fig. 7.

Fig. 8 shows a waveform of maximum continuous operating duty test for 1 hour test duration, where test current reaches 4 904 A and test voltage 19.9 kV, $di/dt|_{off}$ 4.5 A/μs, inlet temperature of coolant 43 ℃, outlet temperature going up to 53 ℃, verifying the test sample satisfies related requirements of valve design.

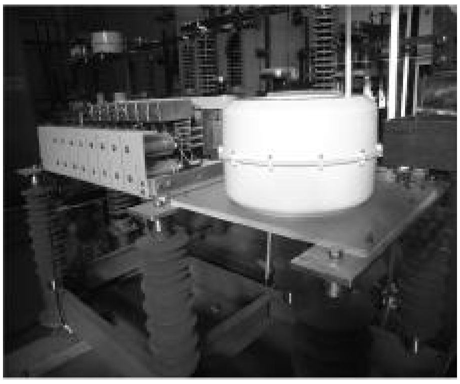
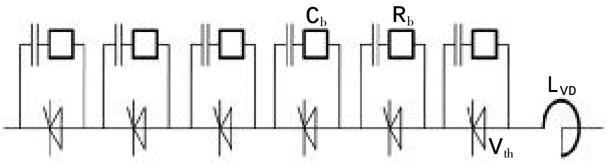


Fig. 6　A real module of thyristor valve under test for a ±800 kV project



R_b=36 Ω; C_b=1.6 μF; V_{th}—thyristor; L_{VD}—valve anode reactor

Fig. 7　Equivalent ciruit of a module of thyristor valve under test

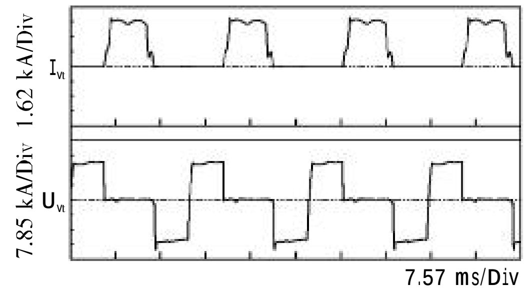


Fig. 8　Maximum continuous operating duty test of thyristor valve

Meanwhile, a waveform of maximum temporary operating duty test is shown in Fig. 9. In this case, the valve modue is stressed with the highest voltage and the highest di/dt, 36.8 kV and 6.6 A/μs respectively.

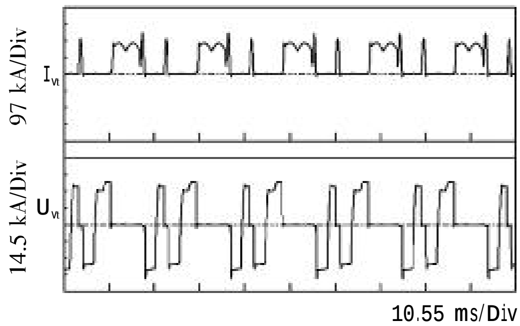


Fig. 9　Maximum temporary operating duty test(α=90°)

4 Conclusion

Through detailed analysis of equivalency in this paper, conclusions can be obtained below:

1)Synthetic test circuit stated in this paper can represent the effect under the four operation modes of valve that are mode "on", "off", "turn-on" and "turn-off". This solves the problem that the test capacity of facilities can't meet the increasing demand of higher ratings of thyristor valve for modern HVDC project.

2)It is better for performance verification of thyristor valve that voltage source with closed-loop control strategy can keep stable the peak value of voltage applied in the test sample per cycle.

3)A synthetic test circuit of 6 500 A/50 kV for operational tests of thyristor valves used for up to ±800 kV HVDC project has newly been set up and already used to complete all the operation tests of a test sample successfully in Xi'an High Voltage Apparatus Research Institute Co., Ltd. (XIHARI). The test results verify that the sample meets the requirements of design for an actual ±800 kV HVDC project.

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