Deepening Research on State Space Analytical Model of HVDC Transmission System

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***Abstract*—The state-space analytical model can reflect the high voltage direct current (HVDC) transmission system's transient characteristics quickly and accurately. In order to overcome the problems of the traditional state-space model. For example, the inaccuracy of the DC current when the sudden change of current in the snubber circuit. Therefore a state-space analytical algorithm considering the thyristor snubber circuit is proposed. In this paper, the snubber current is added as the state variable to the state equation of the converter. And the coefficient matrix is used to represent the initial value of the state variable under different working conditions. Besides, the implicit trapezoid method is used for calculation, which effectively improves the calculation accuracy of the differential equation of the primary equipment. According to the data exchange between the control system and primary equipment, a complete HVDC analytical model consists of the converter, DC line, and control system is established using the state-space theory and solved by the backward Euler method. Furthermore, the simulation results in PSCAD/EMTDC proved the accuracy and validity of the proposed model.**

Keywords—HVDC transmission system; state-space; snubber circuit; implicit trapezoidal integration; electromagnetic transient simulation

I. INTRODUCTION

High voltage direct current (HVDC) has been widely used in China and abroad due to its large transmission capacity, long transmission distance, and low loss [1].

The HVDC system's transient response process is usually simulated by the numerical integration method of small steps [2]. When calculating the action of switching components, the interpolation method can only be used at fixed integer step points or between steps. So the size of the simulation step will directly affect the calculation speed and accuracy [3]. In order to obtain the accurate time-domain response of the HVDC system and take into account the actual state of each converter valve, the integration step should be selected as a microsecond level, which will consume a lot of calculation time and have truncation error. However, there are numerical stability problems near the switching action time [4-5].

Since the relationship between the internal state variables, the external input and output variables can be more accurately described by the state variables [6], the state-space theory is developed in the paper. When establishing the converter's state-space model, the sudden differential change caused by the snubber currents cannot be ignored, and the dynamic behavior of the snubber circuits must be reflected in precision [7] . And the partial differential equations are solved by semi discretization method.

However, the conventional state-space model of the HVDC system has the following problems:

1) Because the existing model does not consider the impact of the snubber circuit, which could result in a large error in the DC current simulation when the thyristor is turned off.

2) The sudden change of valve voltage during the valve closing period will generate multiple snubber current peaks. And the coefficient matrix corresponding to each working condition of the existing model is constant, so it is difficult to account for the impact of the snubber circuit.

3) The state variable is no longer continuous with considering the snubber circuit. Therefore, the initial value of each working condition needs to be updated, based on the accurate calculation of the switching time.

4) There is still a small amount of snubber current in the snubber circuit when the valve is off, which affects the value of the commutation current and causes the switching time of working conditions to be inaccurate.

Above all, this paper proposed an analytical algorithm for solving the transient process of the HVDC system based on the state space method considering the snubber circuit. First, the different operating states of the primary converter system are expressed by differential equations. On this basis, the dynamic response of the snubber circuit is analyzed, the snubber current is implemented as a state variable into the state equation, and the coefficient matrix is used to show the changes of the variables under different operating states. The initial value is calculated using the implicit trapezoidal method as well. Secondly, according to the control logic block diagram, the inverter control system's time domain response model is established, and the solution is solved by the backward Euler method. Finally, standard calculation examples are used to calculate the transient process under different operating states. The algorithm proposed in this article are calculated in Matlab

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and compared with the simulation results of the HVDC electromagnetic transient model in PSCAD/EMTDC. The results have verified the validity and accuracy of the model and algorithm.

II. MATHEMATICAL MODEL OF PRIMARY EQUIPMENT

A. HVDC System Structure

The complete state-space model of the HVDC system includes a rectifier, inverter, DC line, and control system. The primary equipment structure of a two-terminal 12-pulse HVDC system is shown in Fig. 1.

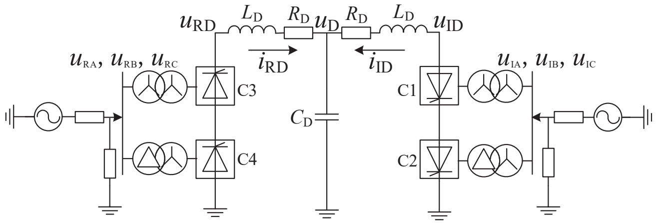

Fig. 1. Structure diagram of two-terminal HVDC primary equipment system

In the figure: L_D, C_D, R_D are the structural parameters in the DC line; u_D, u_{RD}, u_{ID}, i_{RD}, i_{ID} are the voltage and current of the DC line; u_{RA}, u_{RB}, u_{RC}, u_{IA}, u_{IB}, u_{IC} are the AC three-phase voltages on both sides of the system.

In this paper, the rectifier uses a quasi-steady-state model to simplify the series of an ideal voltage source and equivalent resistance [8-9] , which can be used to study the commutation process of the inverter side converter and the dynamic behavior of the snubber circuit.

B. Mathematical Model of Converter

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For the twelve pulse converter, as each thyristor turns on and off, different operating conditions, different circuit connections, and different coefficient matrices will be generated [10]. In typical operation, the inverter side has twelve conduction conditions and twelve commutation conditions, respectively.

Take the S_0 commutation condition as an example: the upper arm *A* phase of the converter corresponding to the Y-Y transformer is turned on, and the lower arm *B* phase commutes to the *C* phase; the Y-Δ transformer corresponding to the converter upper arm A phase is turned on, and the lower bridge arm B is turned on. The equivalent circuit is shown in Fig. 2.

The state-space equation of the converter model is [4]

$$\begin{bmatrix} Tpx \\ 0 \end{bmatrix} = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \begin{bmatrix} y \\ u \end{bmatrix} \tag{1}$$

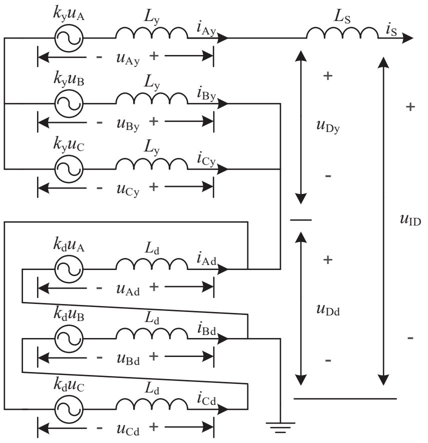

Fig. 2. Equivalent circuit of converter operating condition S0

Where: p=d/dt is the differential operator; state variables $x=[i_{Ay}, i_{By}, i_{Cy}, i_{Ad}, i_{Bd}, i_{Cd}, i_S]^T$; algebraic variables $y=[u_{Ay}, u_{By}, u_{Cy}, u_{Ad}, u_{Bd}, u_{Cd}, u_{Dy}, u_{Dd}]^T$; input variables $u=[u_A, u_B, u_C, u_{ID}]^T$; coefficient matrix $T=\mathrm{diag}(L_y, L_y, L_y, L_d, L_d, L_d, L_S)$.

For the convenience of expression, coefficient matrices *M* and *N* are introduced to replace *C* and *D*. *M* and *N* is the coefficient matrix of the voltage and current relations, respectively, and the state equation is written as

$$\begin{cases} Tpx = Ay + Bu \\ My = 0 \\ Nx = 0 \end{cases} \tag{2}$$

C. Mathematical Model of Snubber Circuit

The converter valve is a converter bridge arm assembled with thyristor components and corresponding electronic circuits, damping circuits, and other devices [11]. The equivalent circuit model of the converter valve is shown in Fig. 3. When the thyristor is turned on, the valve arm resistance is zero, and the valve current is equal to the input AC current, yet the snubber circuit has no effect. When the thyristor is turned off, the valve arm resistance is ∞, and the snubber current is generated during the charging and discharging process of the capacitor, which will flow into the AC circuit and the DC circuit and generate an induced voltage on the inductance of the AC and DC circuit. Especially for the DC circuit, the induced voltage will be superimposed with the cycle, which affects the accuracy of the DC current. In order to solve the above problems, the state equation of the snubber circuit is established.

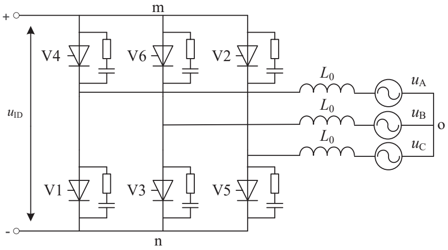

Fig. 3. Six pulse valve with snubber circuit

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For a single thyristor, the snubber circuit is approximately expressed as an RC loop. It can be derived from the component characteristics of the capacitor and Kirchhoff's law:

$$\frac{di_{snub}}{dt}+\frac{1}{RC}i_{snub}=\frac{1}{R}\frac{du_{valve}}{dt} \tag{3}$$

Where: R and C are the resistance and capacitance of the snubber circuit, respectively; i_{snub} is the snubber current; u_{valve} is the valve voltage.

Based on the original state equation, the current relationship equation needs to be revised. The relationship between the snubber current, valve voltage, and the original state variable x and algebraic variable y of all 24 working conditions can be obtained, as shown in Table 1. Moreover, they can be sorted into the current relationship coefficient matrix K and the voltage relationship coefficient matrix Q.

TABLE I. THE CURRENT AND VOLTAGE RELATIONSHIP BETWEEN SNUBBER CURRENT AND VALVE VOLTAGE OF Y-Δ CONNECTION

	i_{xd} Current Relation	**u_{xd} Voltage Relation**	**i_{zd} Current Relation**	**u_{zd} Voltage Relation**
A|B	$i_{Ad}-i_{Cd}=i_S+i_{sd6}+i_{sd1}+i_{sd2}$	$2u_{Dd}-u_{Cd}$	$i_{Cd}-i_{Bd}=i_{sd5}-i_{sd2}$	$u_{Cd}-u_{Bd}$
A|B→C		$3u_{Dd}$		
A|C	$i_{Bd}-i_{Cd}=i_S+i_{sd1}+i_{sd2}+i_{sd3}$	$2u_{Dd}+u_{Bd}$	$i_{Ad}-i_{Bd}=i_{sd6}-i_{sd3}$	$u_{Ad}-u_{Bd}$
A→B|C		$3u_{Dd}$		
B|C	$i_{Bd}-i_{Ad}=i_S+i_{sd2}+i_{sd3}+i_{sd4}$	$2u_{Dd}-u_{Ad}$	$i_{Ad}-i_{Cd}=i_{sd1}-i_{sd4}$	$u_{Ad}-u_{Cd}$
B|C→A		$3u_{Dd}$		
B|A	$i_{Cd}-i_{Ad}=i_S+i_{sd3}+i_{sd4}+i_{sd5}$	$2u_{Dd}+u_{Cd}$	$i_{Bd}-i_{Cd}=i_{sd2}-i_{sd5}$	$u_{Bd}-u_{Cd}$
B→C|A		$3u_{Dd}$		
C|A	$i_{Cd}-i_{Bd}=i_S+i_{sd4}+i_{sd5}+i_{sd6}$	$2u_{Dd}-u_{Bd}$	$i_{Bd}-i_{Ad}=i_{sd3}-i_{sd6}$	$u_{Bd}-u_{Ad}$
C|A→B		$3u_{Dd}$		
C|B	$i_{Ad}-i_{Bd}=i_S+i_{sd5}+i_{sd6}+i_{sd1}$	$2u_{Dd}+u_{Ad}$	$i_{Cd}-i_{Ad}=i_{sd4}-i_{sd1}$	$u_{Cd}-u_{Ad}$
C→A|B		$3u_{Dd}$		

Since the snubber current cannot be expressed by the valve voltage, (3) needs to be added to the existing state equation. Among them, the relationship between the snubber current and the valve voltage can be described in the form of (4):

$$pi_x+\frac{1}{RC}i_x=\frac{Q}{R}py \tag{4}$$

The relationship between valve current, DC current, and snubber current can be represented by (5):

$$Nx=Ki_x \tag{5}$$

The state equation and voltage relationship equation of the converter model remain unchanged, as in (2). Combine (4) and (5) together to obtain the state space equation of the converter model, including the snubber circuit.

III. EXAMPLES AND ANALYSIS

The simulation system in this paper is the CIGRE standard test system under the PSCAD/EMTDC platform [12-15]. The system parameters are: DC system rated voltage 500kV, rated current 2kA. The primary equipment model uses the three-phase AC bus voltage amplitude as input, the AC system frequency is 50Hz, and the rectifier side and inverter side commutation bus voltage reference values are 345kV and 230kV, respectively. The DC line and snubber circuit parameters in Fig. 1 are as follows: R_D=2.5Ω; L_D=0.5968H; C_D=26.0μF; L_S=0.05H; R=5000Ω; C=0.05μF. The PSCAD simulation step is 50μs, and the simulation time is 6s. The validity of the HVDC state-space model is verified by collecting the three-phase voltage values of the AC system on both sides of the DC system rectifier side and the inverter side in the PSCAD simulation model as the input of the state equation.

In order to compare with the traditional state space model, the HVDC CIGRE model with and without the snubber circuit is set up respectively. The waveform comparison of the DC current on the inverter side obtained by simulation is shown in Fig. 4. In the case of no snubber circuit, di/dt is very large, and du/dt is also very large when shutting off, and appear very high overvoltage. The spike-shaped waveform has a great influence on the calculation of state variables. The error of the state space model without considering the snubber circuit is large. Therefore, it is necessary to consider the snubber circuit in the state space analytical model of the HVDC system.

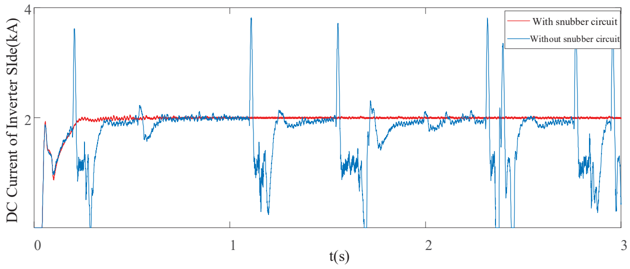
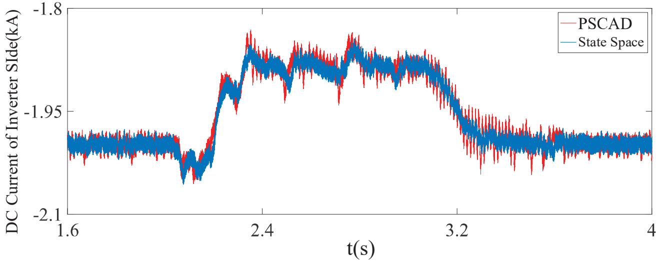


Fig. 4. Simulation comparison chart with or without snubber circuit

The converter bus of the inverter side is grounded in a three-phase short circuit in two seconds, the voltage drops to 0.9 (PU), and the voltage recovers after 1 s. AC voltage and its amplitude at the inverter side and AC voltage amplitude at the rectifier side are collected to generate symmetrical three-phase AC voltage as the input of the symmetrical fault test. The waveforms of electrical quantities related to this method and PSCAD simulation system are shown in Fig. 5. The results of the two methods almost coincide. The numerical results show that the maximum errors of DC voltage and DC current are 5.2kV and 0.027A, respectively. The error percentages are only 1.06% and 1.35%, which proves the accuracy of the proposed model and algorithm.



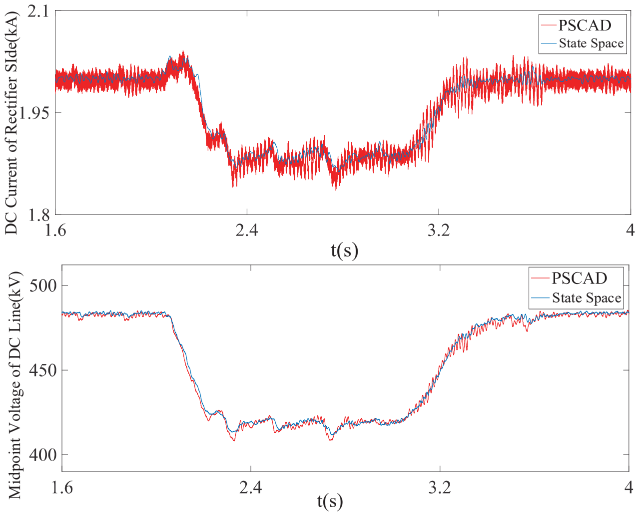


Fig. 5. Simulation comparison chart under symmetrical fault

When the system is running stably, the inverter bus voltage is three-phase symmetrical. The delayed trigger angle α=21.07° calculated by PSCAD simulation, the lead trigger angle β=39.65°, and the arc extinguishing angle γ=15.15°. Calculated by the proposed method are α=20.73°, β=39.39°, and γ=15.00°.

It can be seen that the analytical calculation results using the state-space model are the same as the simulation results of the PSCAD electromagnetic transient model, and the electrical waveforms of the system are relatively similar. However, there will be some errors in the results of some periods. The analysis shows that the main reasons for the difference are:

1) Because the arc extinguishing angle measurement link of the method in this paper cannot be consistent with the measurement method in PSCAD, its fluctuation range increases, and the PI control parameters are on the verge of instability, resulting in apparent fluctuations in DC voltage and current. Therefore, the error of the firing angle is determined by the model and method.

2) The interpolation method and oscillation suppression algorithm adopted by PSCAD have truncation errors, and the calculated state quantity is different from the accurate value.

The above analysis factors will have a particular impact on the control system's adjustment, and in turn, will affect the state of the primary equipment. However, it can be seen from the simulation results that the difference between the two is within the allowable range of error.

IV. CONCLUSION

This paper establishes the state-space model of the HVDC transmission system converter and its snubber circuit, DC line, and control system. Based on the HVDC thyristor converter circuit model, the state equation of the snubber circuit is derived, and the simulation of the HVDC system state-space model is realized. In the process, the calculation accuracy of the state equation is effectively improved after considering the snubber current. It can be seen from the theoretical analysis and simulation results that the state-space model is accurate and effective when solving the transient system response, which verifies the correctness of the model.

With the corresponding interface technology, the models and methods proposed in this paper can be applied in the hybrid simulation of AC/DC hybrid and DC feed-in power systems. The next step is to apply the state space model to the actual engineering example of the double-terminal HVDC transmission system for testing.

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