Application of DSSC in Power Flow Control of Grid-Connected Electric Locomotive System

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Abstract: In recent years, urban rail transit has become one of the most effective ways to solve the problem of urban traffic congestion because of its advantages of fast, efficient, safe and comfortable, energy saving and environmental protection. However, Electric locomotive, as the core vehicle of railway transportation, will bring some negative effects when it is connected to power system, such as reducing power flow of lines, reducing power quality of power grid, etc. Distributed static series compensator (DSSC) is one of the flexible AC transmission system (FACTS) technologies. It can adjust the power flow flexibly and quickly by changing the impedance of transmission lines, so as to improve the stability and reliability of power system and improve the congestion of power transmission. Firstly, in this paper, the structure and principle of DSSC are analyzed. Secondly, taking Shaoshan 4 electric locomotive in China as an example, its simulation model is analyzed and established. Finally, DSSC is connected to the Electric locomotive grid-connected system, and simulation experiments are carried out to verify the practicability of DSSC in power flow control of grid-connected electric locomotive.

1. Introduction

With the widespread existence of urban traffic in modern society, its coverage area is also more and more extensive. The grid-connected operation of electric locomotives poses a severe test to the safety and stability of electric power system. Therefore, it has become an inevitable task to detect, limit and control the harm caused by power quality problems [1].

The concept of Flexible AC Transmission System (FACTS) technology was first proposed by Dr. N.G.Hingorani, deputy director of the Electrical Power Research Department of the Electric Power Research Institute (EPRI), in the Journal of EPRI in 1986 [2]. FACTS is a new technology which integrates power electronics technology, microelectronics technology, communication technology and control technology to control AC transmission, so as to improve the operation efficiency, stability and reliability of the system [3].

The main function of FACTS is to improve the power flow control of transmission lines, to transmit more power to transmission lines within the controllable range and to ensure that the current of transmission lines does not exceed its thermal stability limit, so that the system can operate safely and steadily [4].

DSSC is a controller with excellent economy and function in FACTS device. It can change system parameters and adjust voltage amplitude and phase angle of electric power system. In 2006, the Harrian Working Group completed the development of the first DSSC prototype and applied it to the rated voltage of 69-161kV [5]. The successful application of DSSC not only proves the correctness of its theory and the feasibility of its practice, but also shows that DSSC can bring huge economic benefits to the power system.

DSSC is mainly composed of single-turn transformer (STT), single-phase voltage inverters, DC bus capacitors, filters and control modules [6]. Its structure is shown in Fig. 1.

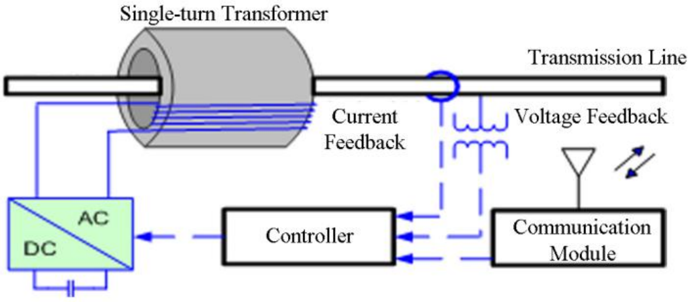


Fig. 1 DSSC structure diagram

The main function of DSSC is to adjust the line impedance and phase angle of the system by superimposing the AC voltage generated by single-phase voltage inverters on the line. The functions of series compensation and phase shift control can be realized through corresponding control strategies, which can effectively control the power flow of power system, improve the transmission capacity of power grid and improve power transmission congestion. At the same time, DSSC also has the advantages of low voltage level, flexible installation and easy maintenance.

2. Principle of DSSC

The DSSC topology is shown in Fig. 2.

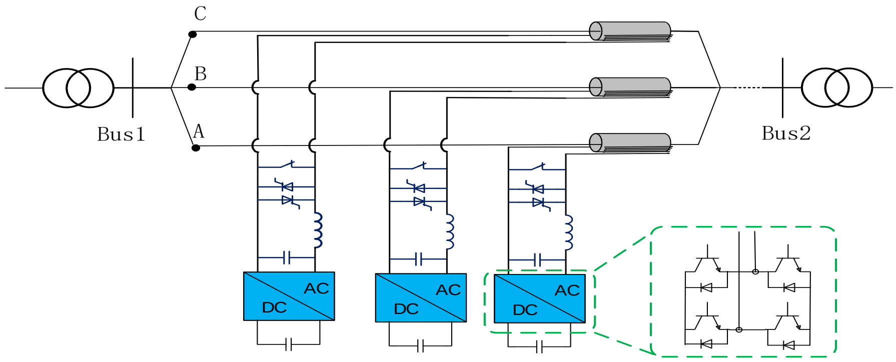


Fig. 2 DSSC topological structure

The basic principle of DSSC is shown as follows: when the power flow of the line does not need to be adjusted, the normally closed mechanical switch is in the state of closing, and the current does not flow through the DSSC device. When the line power flow needs to be adjusted, the mechanical switch opens, the single-phase voltage source converter charges, and injects a controllable voltage into the transmission line. One component of the voltage is perpendicular to the current direction of the line to regulate the line impedance; the other component is consistent with the current direction of the line to compensate the power loss of the converter and maintain the stability of the DC capacitor voltage of the converter.

From the topology diagram, it can be seen that the existence of large capacitors on the DC side ensures that the direction of DC capacitor voltage will not change. With the alternating turn-on and turn-off of the bridge arm of the single-phase converter, the capacitor on the DC side is charged or discharged by energy exchange with the transmission line, and the DC power is exchanged. When the switch is on, the output voltage of the AC side is equal to that of the DC side, and the large capacitor of the DC side conveys energy to the AC side. At this time, the converter is in the inverted state. Conversely, the energy flows from the AC side to the DC side through the channel of the diode, and the converter is in the rectifying state. The energy exchange between the device and the transmission system is realized through the converter.

3. Working Principle of Electric Locomotive

Single-phase AC traction is the most commonly used traction system in the world. The most representative type of locomotive is rectified electric locomotive. In China, the main types are Shaoshan series locomotives such as SS1, SS3, SS4, SS8, etc [7]. In this paper, taking Shaoshan 4 (SS4) electric locomotive as an example, the main circuit diagram is shown in Fig. 3.

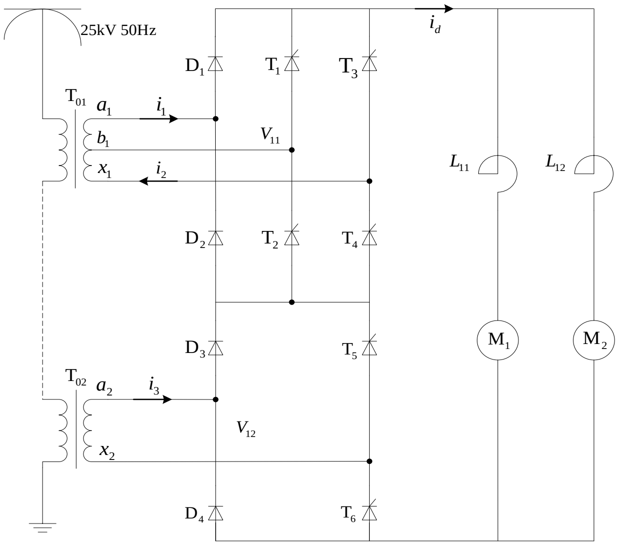


Fig. 3 Main Circuit Diagram of SS4 Electric Locomotive

SS4 electric locomotive is a heavy-duty eight-axle electric locomotive. It consists of two identical four-axle locomotives connected by intermediate coupler and rubber joint windshield. It has internal electrical reconnection control. The cable and air brake system are connected to the air duct, and the roof is equipped with 25kV high voltage cable. Two locomotives can be operated separately as two four-axle locomotives and there are reconnection devices at both ends of the locomotive. It can be connected to another eight-axle electric locomotive for reconnection operation to increase total traction. The main drive system of locomotive adopts AC-DC electric drive mode and DC traction motor [8].

In Fig. 3, rectifier bridge 1 is a three-phase rectifier circuit, rectifier bridge 2 is a single-phase rectifier circuit, T01 and T02 are step-down transformers, D1, D2, D3 and D4 are diodes, and T1, T2, T3, T4, T5 and T6 are thyristors. The output voltage of the rectifier bridge is supplied to two series traction motors M1 and M2 respectively through the flat wave reactor L11 and L12. The figure shows that the output voltage amplitude after rectification is the sum of the output voltage amplitudes of Rectifier Bridge 1 and Rectifier Bridge 2. The superposition of two rectifier bridges can improve the reliability of DC power supply.

SS4 electric locomotive adopts four-section semi-controlled bridge circuit powered by unequal three-winding transformer. The three windings are a1b1, b1x1 and a2x2. The no-load rated voltages of the three windings are 335V, 335V and 670V respectively. Assuming that V11 is the sum of three winding voltages, there are three unequal ratios of Va1b1=Vb1x1=V11/4, Va2x2=V11/2 .The four-section bridge control mode is as follows:

The first stage: thyristor T1, T2 trigger, winding a1b1 put into operation, thyristor T1, T2 phase shift, rectification voltage is 0-Vd/4 (Vd is the total rectification voltage).

Stage 2: Maintaining winding a1b1 in operation, thyristor T1, T2 trigger, winding b1x1 put into system, thyristor T3, T4 phase shift, rectification voltage is Vd/4-Vd/2.

Stage 3: Maintaining winding a1b1 in operation, thyristor T5, T6 trigger, winding a2x2 put into the system, thyristor T1, T2 phase shift, rectification voltage is Vd/2-3Vd/4.

The fourth stage: thyristor T1, T2, T5, T6 trigger, thyristor T3, T4 phase shift, and rectification voltage is 3Vd/4-Vd.

The main circuit of SS4 electric locomotive can achieve the effect of equal four-stage voltage regulation by changing the working state of the half-control bridge.

The traction control characteristic function of SS4 electric locomotive [9] is shown in Formula (1). The speed and level of locomotive determine the armature current of traction motor.

$$I_d = \begin{cases} 150N \\ 600N - 54v \\ 1096 \end{cases} \tag{1}$$

In the formula, N denotes the locomotive level, usually 0-10, v denotes the locomotive speed, and in km/h and Id denotes the armature current of the traction motor, in A. Its value varies with the locomotive speed and level, and the minimum value in the above formula is taken.

The traction characteristic control function determines the armature current of the motor through the locomotive speed and level. The rectifier circuit voltage Vd can be determined according to the rectifier circuit voltage formula (2).

$$V_{\mathrm{d}} = E + \sum RI_d \tag{2}$$

In the model, *E* is the back electromotive force of the traction motor, $\sum R$ is the total resistance of the rectifier circuit, including the smoothing reactor and the total resistance in the motor circuit.

4. Research on Control of DSSC for Grid-connected Electric Locomotive System

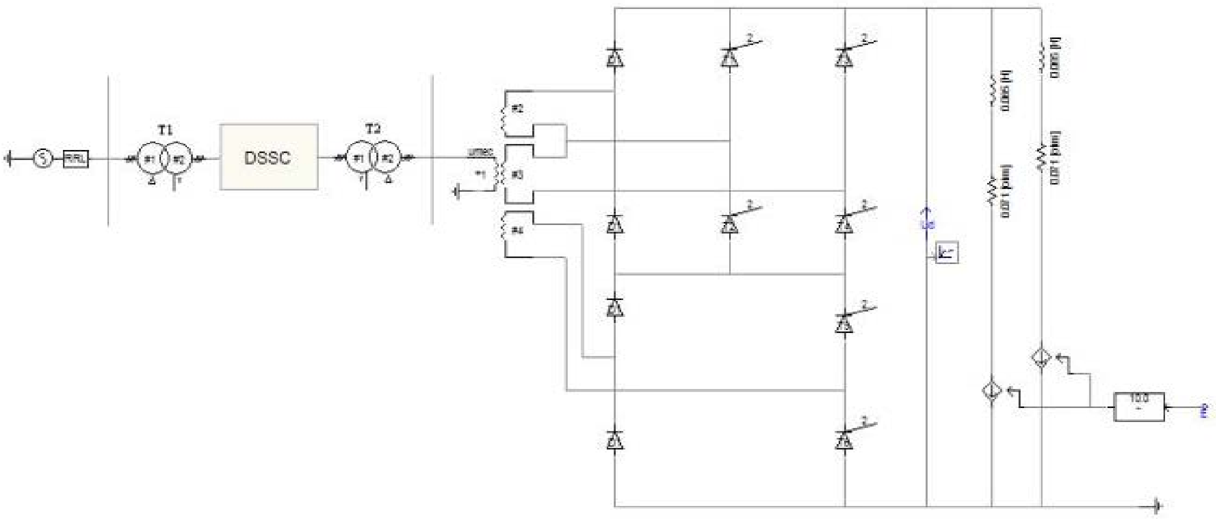
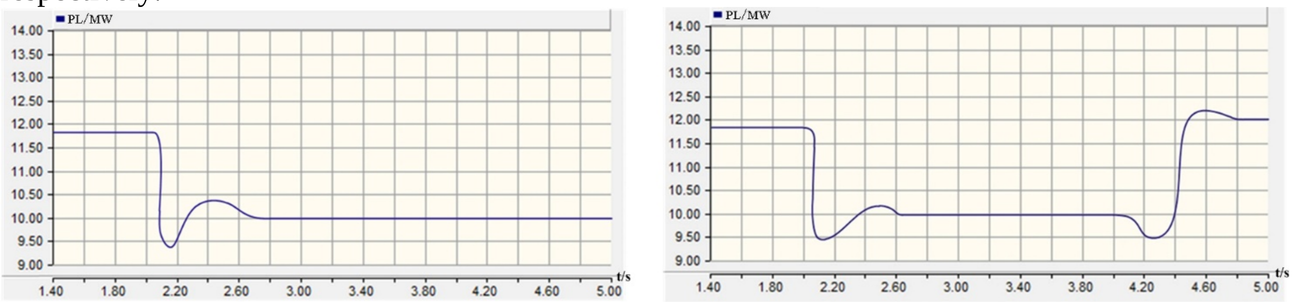


Fig. 4 System simulation model with DSSC

In order to analyze the control of DSSC to the system containing electric locomotive, a detailed simulation model of DSSC system is built under the environment of PSCAD/EMTDC, as shown in Fig. 4. The system has 110 kV grid voltage, LGJ-185 transmission line specification, 0.17+j0.4Ω/km impedance and 100 km total line length. The model of transformer T_1 is SF-15000/110, using Δ-Y connection method. Its capacity is 15 MVA, conversion ratio is 10.5 kV/110 kV, no-load loss ΔP_1 is 22 kW and short-circuit voltage percentage $V_{s1}\%$ is 10%. The model of transformer T_2 is SF-15000/10, using Y-Δ connection method. Its capacity is 15 MVA, conversion ratio is 110 kV/25 kV, no-load loss ΔP_2 is 22 kW and short-circuit voltage percentage $V_{s2}\%$ is 10%. In DSSC,the ratio of transformer T_3 is 110 kV/0.1 kV, the DC capacitance is 2×103 μF and the capacitance voltage is set to 0.1V.

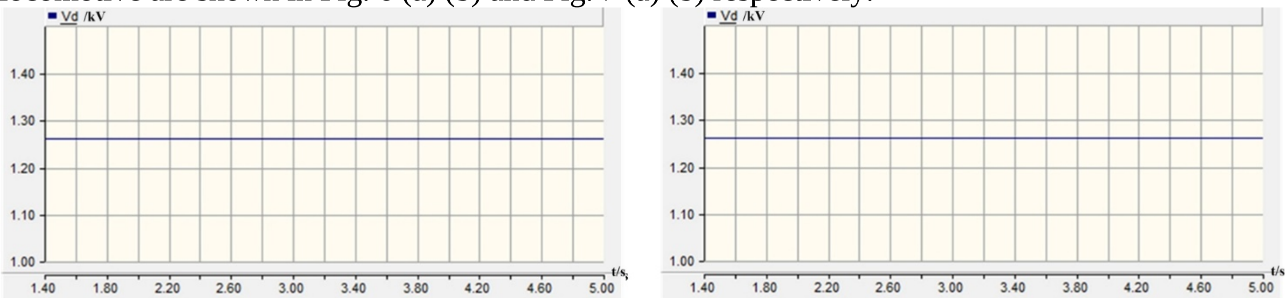
In the process of simulation, the operation state of the system is set as follows: the system is connected to the electric locomotive after 2 seconds of stable operation, the level and speed of the electric locomotive are set as follows: *N*=6, v=50km/h. After 4 seconds of operation, the system is connected to the DSSC device, and the target value of its active power P_{Lref} is set to 12MW. Finally, when the system runs steadily, the parameters of each time period are observed. The active power P of the line after 2 seconds and 4 seconds of the system is shown in Fig. 5(a) and Fig. 5(b) respectively:



（a） Active Power of Line at 2s （b)Active Power of Line at 4s

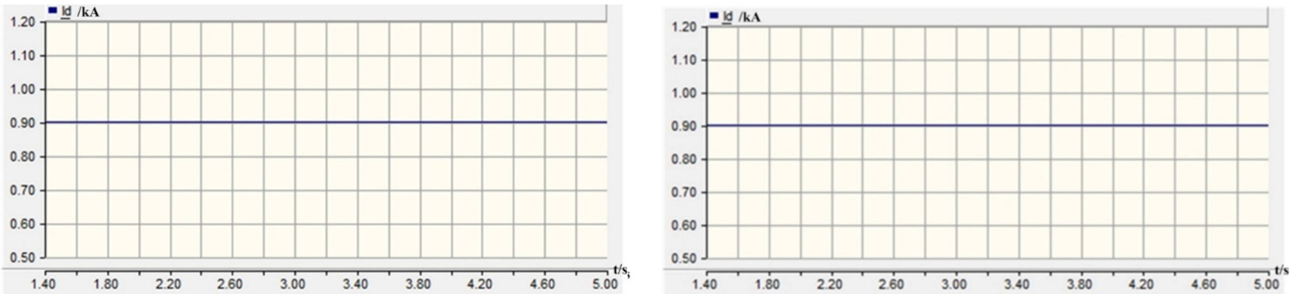
Fig. 5 Active Power of Line P_L

After running for 2 seconds and 4 seconds, the output DC voltage V_d and DC current I_d of electric locomotive are shown in Fig. 6 (a) (b) and Fig. 7 (a) (b) respectively.



（a） DC side voltage of electric locomotive at 2s （b) DC side voltage of electric locomotiveat 4s

Fig. 6 DC side voltage of electric locomotive V_d



（a） DC side current of electric locomotive at 2s （b)DC side current of electric locomotive at 4s

Fig. 7 DC side current of electric locomotive I_d

As shown in Fig. 5, the system reaches a stable state between 1.4 seconds and 2 seconds and the active power of the line is 11.8MW at this time. At 2 seconds, the system is connected to the electric locomotive and reaches a stable state after 0.7 seconds. At this time, the active power of the line is reduced from 11.8MW to 10MW. At 4 seconds, DSSC device is connected to the system and the target value of active power PLref is set to 12MW. After 0.8 seconds, the line active power reaches the target value and the system maintains stable state.

From Fig. 6 and Fig. 7, it can be seen that the DC side voltage Vd and current Id output by electric locomotives have basically not changed, and their values are 1.26 kV and 0.9 kA respectively.

From the above simulation results, it can be seen that when the electric locomotive is connected to the power system, the active power transmitted by the transmission line will be reduced. After the system is stable, the active power of the transmission line can also be maintained constant. When the DSSC device is connected to the system, although it will cause less vibration of the system, it can make the active power transmitted by the line stable at the target value while the electric locomotive is running steadily, thus achieving the purpose of regulating the power flow of the line.

5. Conclusion

With the electric locomotive grid-connected technology gradually becoming an important research direction of power system, it is particularly important to solve the impact on power system line power flow after the electric locomotive is connected to the grid. The paper studies the application of distributed static series compensator (DSSC) to power system power flow control after the electric locomotive is integrated into the grid. Firstly, the principle and function of DSSC are analyzed. Then, taking SS4 electric locomotive as an example, the working principle of electric locomotive is studied and the model is built. Finally, on this foundation, the ability of DSSC to control and regulate the power flow of power grid is demonstrated while the system is running steadily after the electric locomotive is connected to the grid.

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