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Effect of cascade STATCOM on stabilising voltage in high voltage direct current

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Abstract: Yongfu high voltage direct current (HVDC) project in Yunnan is the main access to send the power out and also an important part of the channel of transmission of power in west to east in China southern power grid. However, the Funing Converter Station of the project connects to a weak AC system; thus, there is a need for a Static Synchronous Compensator (STATCOM) to compensate the reactive power. This study presents the principle of the STATCOM, all kinds of the topologies of STATCOM, with their advantages and disadvantages compared to each other and the representative projects. Then, the cascade STATCOM is emphatically analysed that is applied to the project. Also, the cascade STATCOM model and the project model are established in PSCAD/EMTDC. Afterwards, the effect of STATCOM on the converter station is studied, which works in steady state and in transient of varieties of short circuit faults. Finally, the simulation results verify the effectiveness of cascade STATCOM on stabilising the voltage.

1 Introduction

Yunnan Province has abundant water resources to generate power. As the sustainable strategy is further emphasised in China, Yunnan grid promotes the development of clean and new resources. During the 12th and the 13th Five-Year Plans, cascade hydropower stations in middle and lower Jinsha River and the Lancang River basins have been built and put into operation. However, according to power balance calculation, there is a large amount of power in northwest Yunnan needing to be sent out based on meeting local power demand. Before 2016, the power transmission channel could not meet the delivery conditions.

The Yunnan ± 500-kV Yongfu HVDC Transmission and Transformation project (hereinafter referred to as 'the project') is the first 500 kV DC transmission line within the province. The project will meet the power transmission needs from Yunnan to Guangxi, promoting the hydropower consumption and reliving the pressure of waste water. At the same time, the stability of the grid is further advanced. After the project being completed and put into operation, the Yunnan grid will disconnect to China southern power grid. As the AC grid around the Funing Converter Station (hereinafter referred as the 'Funing Station') is a weak AC system, a Static Synchronous Compensator (STATCOM) has been built to compensate the reactive power [1].

This paper first introduces the working principle of the STATCOM, compares the characteristics of various topologies of STATCOM and lists representative engineering application. Then, the STATCOM in the Funing Station of the project is studied, both by theory and by establishing the simulation models in PSCAD/EMTDC. Through the voltage waveforms of the Funing Station in steady state and different short-circuit faults, we can verify that STATCOM works effectively to compensate reactive power to stabilise the voltage of the weak AC system comparing with there being no STATCOM connected in a parallel manner to the system.

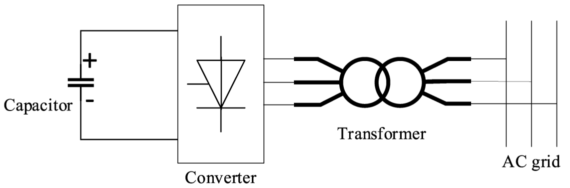

Fig. 1 *Working principle of STATCOM*

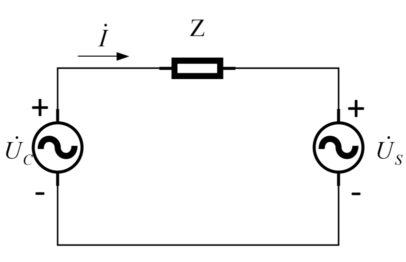

Fig. 2 *Equivalent circuit of STATCOM*

2 Working principle of STATCOM

In practical engineering applications, most of the STATCOMs adopted have full-bridge voltage source circuits. Fig. 1 shows the principle of the STATCOM. The DC side of the STATCOM is a capacitor, which supplies DC voltage support to the STATCOM. The converter usually consists of some converter bridges that convert DC voltage to AC voltage, and the AC voltage can be controlled by drive pulses of the switch devices. The transformer transforms the output voltage to system voltage, so that STATCOM can be connected in a parallel manner to the AC grid. The leakage reactance of the transformer can be used for limiting current to prevent the converter side faults or over current because of AC faults. The entire STATCOM can be regarded as a controllable voltage source, whose equivalent circuit is shown in Fig. 2.

As shown in Fig. 2, the output voltage of STATCOM is $\dot{U}_C$, the voltage of AC grid is $\dot{U}_S$ and the reference direction of current is illustrated by an arrow. The loss of inductor and the converter is equivalent to R, the inductor is L and Z represents R and L shown in Fig. 2. Fig. 3 illustrates the working condition vector diagram of STATCOM, where X represents the inductor.

Under an ideal condition, we ignore the loss of converter and the reactor is inductive. Under this condition, $R = 0$, and there is no active power exchange; thus, the phases of $\dot{U}_C$ and $\dot{U}_S$ remain the same. Here, the current $\dot{I}$ is

$$\dot{I} = \frac{\dot{U}_C - \dot{U}_S}{jX} \tag{1}$$

The single-phase output apparent power is

$$\bar{S} = \dot{U}_C \dot{I}^* = \dot{U}_C \left(\frac{\dot{U}_C - \dot{U}_S}{jX} \right)^* = \dot{U}_C \frac{\dot{U}_C^* - \dot{U}_S^*}{-jX} \quad (2)$$

where $\dot{I}^*$ is the complex conjugate of $\dot{I}$.

The single-phase output reactive power is

$$Q = \text{Im}(\bar{S}) = \dot{U}_C \frac{\dot{U}_C - \dot{U}_S}{X} \quad (3)$$

Following conclusions can be drawn from (3):

a. When $U_C > U_S$, the phase of current $\dot{I}$ is 90° ahead of $\dot{U}_C$. In this case, the converter issues reactive power and the STATCOM is equivalent to capacitance.

b. When $\dot{U}_C < \dot{U}_S$, the phase of current $\dot{I}$ is 90° behind of $\dot{U}_C$. In this case, the converter absorbs reactive power and the STATCOM is equivalent to inductance.

c. When $\dot{U}_C = \dot{U}_S$, there is no reactive power exchange.

The phase error of voltage and current of the grid is $90° - \delta$ rather than 90°, which supplies active power for the loss of circuit. The phase error of voltage of the converter and grid is also δ. Therefore, current with different amplitudes and phases can be produced by changing the amplitude of δ and $\dot{U}_C$, so that the STATCOM can issue or absorb reactive power from the grid.

3 Topology of STATCOM

3.1 Full-bridge configuration

The topology of a simple three-phase full-bridge STATCOM is shown in Fig. 4, which consists of three phases with two arms in each phase and a capacitor represented by *C*. Every arm has a transistor and a diode. The six arms make up the circuit of the converter, and the capacitor supplies voltage support.

3.1.1 Multiple configuration: As shown in Fig. 5, a typical multiple STATCOM with cascaded transformers mainly includes a group of capacitors, converter units, multiple coupling transformers and so on. The converter cells and the coupling transformers make up the main circuit. This kind of topology can greatly improve the total capacity of the apparatus. When adopting this topology, one must consider the phase shift among the different converters, the number of cascaded transformers and other issues; meanwhile, the harmonics, dynamic response and other effects also need to be taken into account.

3.1.2 Multi-level configuration: Since the emergence of the three-level neutral point clamped converter in the 1980s, multi-level technology has been developed rapidly. Compared to the traditional two-level converter, multi-level converter can achieve high-voltage output by using low-voltage devices, without the need of switching devices in direct series. Each switching device only needs to work at a lower switching frequency, but the equivalent switching frequency of the total output voltage is higher. Multi-level topology enables high-voltage and high-capacity apparatus to be easily implemented with a large number of levels of the converters, and has advantages of having modular and redundant designs. The STATCOM using a cascaded multi-level converter is also known as cascade STATCOM.

3.1.3 MMC configuration: Modular multi-level converter (MMC) configuration uses modular sub-modules as shown in Fig. 6. The converter connection mainly uses the double star connection. Its sub-module configuration is shown in Fig. 7, which comprises two IGBTs and two parallel diodes. The PCC bus is added to MMC configuration, making it easy to balance three-phase voltage. The superiority of this configuration is obvious; however, due to its complex control strategy, the actual projects found difficulty in applying this configuration.

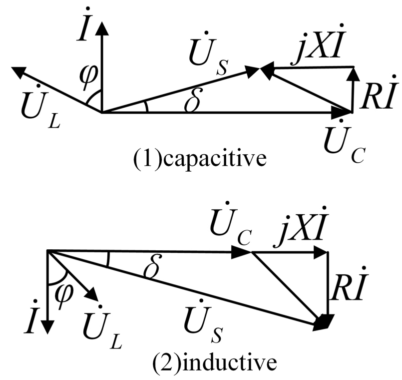

Fig. 3 *Vector diagram of STATCOM working condition*

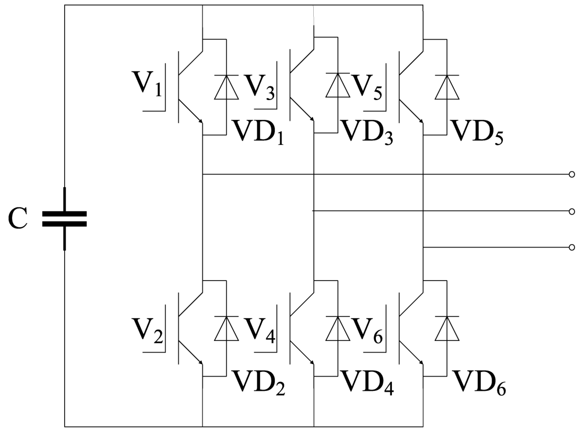

Fig. 4 *Full-bridge configuration of STATCOM*

The common configurations of STATCOM are as follows [2]: ***(a)*** multiple configuration; ***(b)*** multi-level configuration; ***(c)*** MMC configuration; ***(d)*** cascade configuration

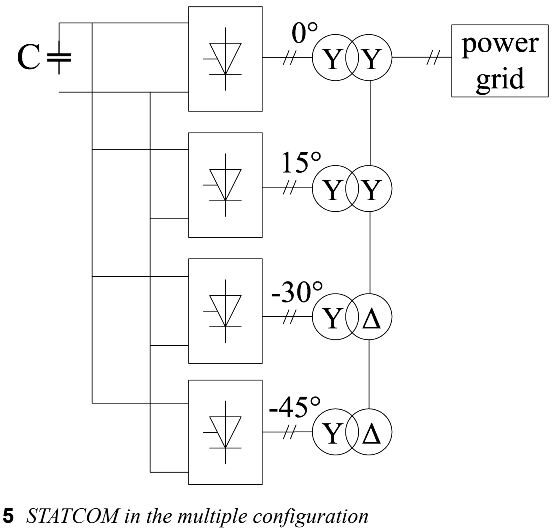

Fig. 5 *STATCOM in the multiple configuration*

3.2 Cascade configuration

The cascade STATCOM is a cascaded multi-level structure. The basic cell of single-phase bridge includes a DC capacitor group, switching devices and parallel diodes. Fig. 8 shows the main circuit of cascade STATCOM in *Y* connection. It can save transformers, make it easy for a modular design at the same time and has small size and small storage space. When the required number of voltage levels increases, the number of devices required for a cascade configuration is less than other configurations. Also, it is the easiest to achieve a large number of voltage levels, and the most

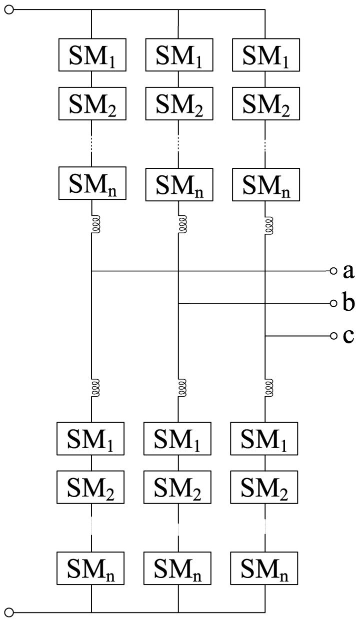

Fig. 6 *STATCOM in the MMC configuration*

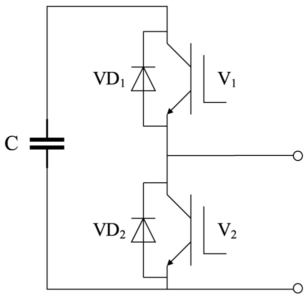

Fig. 7 *Sub-module configuration of MMC*

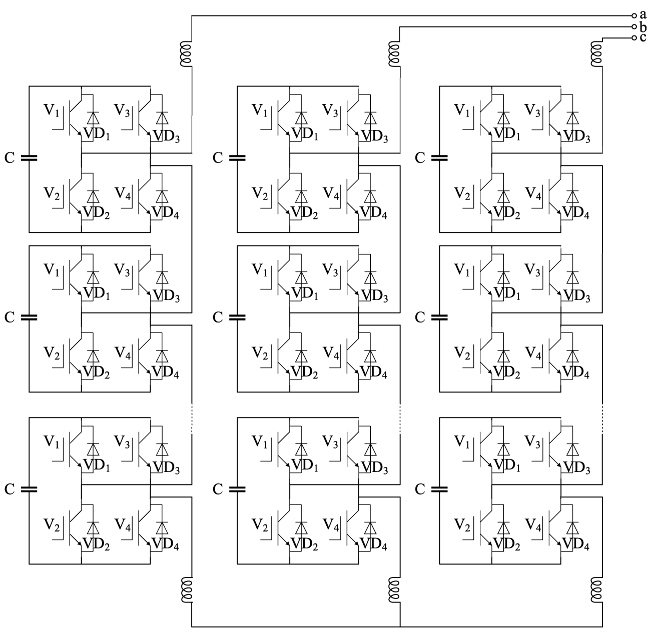

Fig. 8 *Cascade STATCOM in Y connection*

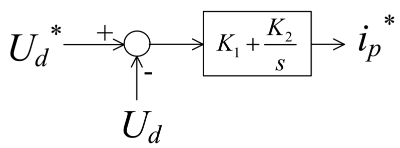

Fig. 9 *Control strategy diagram of DC side voltage*

suitable for high-voltage, high-capacity STATCOM. Moreover, the cascade converter can add redundant modules, greatly improving the reliability of the STATCOM. Currently, the cascade STATCOM is the most widely used and the most technologically advanced and mature among different configurations of the STATCOM.

4 Control strategy of STATCOM

4.1 Control strategy of reactive current

4.1.1 Direct current control: Direct current control means adopting the PWM tracking control technology to obtain PWM signals to drive IGBTs by real-time feedback control of instantaneous value of STATCOM current. The two common methods are ramp comparison control and hysteresis comparison methods. The control method adopts the dq coordinate decomposition method. The reactive current reference value is based on the instantaneous current reactive component. Multiplying the reactive current reference value by a sine wave behind the grid voltage of 90° and adding the result to the active component of current turn out to be the reactive current reference. According to the active power demand from the STATCOM, the phase of q-axis current reference i_q* is modified to obtain the total instantaneous current reference i*. Direct current control responses fast. Although the switching frequency of devices is relatively high, the switching frequency of a single device apparently reduces when a large number of cascaded sub-modules are used [3], which effectively improves the dynamic response characteristics of the STATCOM.

4.1.2 Indirect current control: In indirect current control, the STATCOM is equivalent to a controlled voltage source, connecting to the grid through a reactor. The reactive power is controlled by controlling the amplitude and phase of the output AC voltage of the STATCOM. Compared to the direct current control, the indirect current control has a lower switching frequency. However, it dynamically responses less slowly, and its control accuracy and response speed are not stable, thus making difficult to meet the requirements of a modem power system to compensate reactive power rapidly and stably.

4.2 Reactive power control

The input of the reactive power control is an inductive or capacitive reactive power reference Q*, and the control turns the reactive power reference into the corresponding reactive current reference. Then, the control system adjusts the converter switch to reach the specified current, and feedback signal of DC side voltage is used to ensure that the DC side voltage is maintained at a stable value. This control is more suitable for complex power systems, because reactive power in each line can be real-time distributed online through integrated automation in a large system. Therefore, branching with STATCOM can get accurate reactive power needed especially for a transmission power system.

4.3 DC voltage control

The variety of voltages of the STATCOM DC side capacitor depends on the active power exchanged with the grid, which depends on active current i_p [4]. The stabilising voltage control method stabilises the STATCOM input voltage, which is the grid voltage to the reference. Hence, the DC side voltage control applies proportional integral (PI) regulation; the achievement is shown in Fig. 9.

5 Engineering applications

5.1 Engineering applications of cascade STATCOM

French ALSTOM developed the first mobile cascade STATCOM in the world for the National Grid Company, which started operation in 1999. Compared with other STATCOMs, this apparatus has two special features. First, it consists of a ± 75-Mvar STATCOM and the other conventional reactive power apparatus is a static var

Conseil International Des Grands Reseaux Elecctriques proposed the AC/DC short-circuit ratio in 1992 and further proposed the concept of effective short-circuit ratio (ESCR) to evaluate the interaction between the rated capacity of an HVDC transmission system and the connected AC system. According to the relevant standards of IEC and national standards about DC transmission systems, when the ESCR is >3, it is considered that the connected AC system is a strong system. When ESCR is between 2 and 3, the connected AC system is a weak system. When the ESCR is <2, the connected AC system is a very weak system. When ESCR is <2, it indicates that the disturbance of AC/DC system may lead to voltage oscillation, needing dynamic converter reactive power control, static reactive power compensation etc. to avoid voltage instability and maintain the stability of reactive power. According to Wenshan grid operation data, Funing Station AC bus line has the short-circuit capacity S_{ac}, of which the large capacity is 9.82 GVA and the small capacity is 7.27 GVA; the rated DC power of converter P_{dN} of 3.0 GVA; the AC filter or reactive power compensation rated capacity Q_f of 1.76 GVA [1]:

$$\text{Large capacity: ESCR} = \frac{S_{ac} - Q_f}{P_{dN}} = 2.69$$

$$\text{Small capacity: ESCR} = \frac{S_{ac} - Q_f}{P_{dN}} = 1.84$$

As a result, the AC grid of the Funning Station side is a very weak AC system. In order to solve the lack of dynamic reactive power, ± 300-MVar STATCOMs were installed to compensate the reactive power and support the voltage.

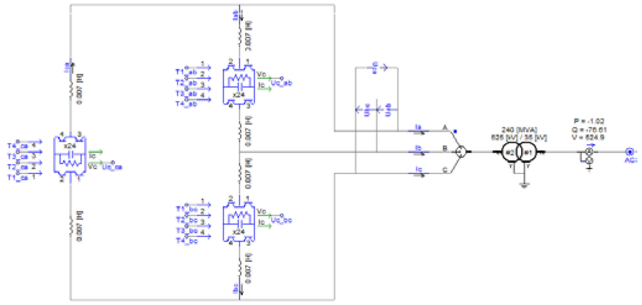

Fig. 10 *Simulation circuit of cascade STATCOM model*

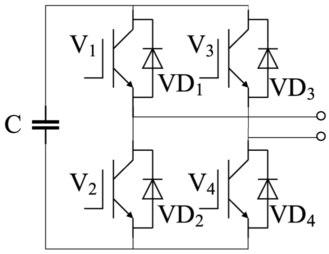

Fig. 11 *Cell configuration of cascade STATOM*

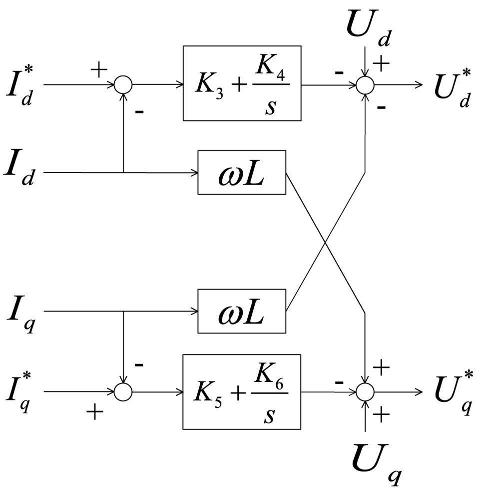

Fig. 12 *Diagram of current internal control*

system for boosting power transmission from north to south of the United Kingdom. Second, the apparatus is the first to have a cascade configuration, which consists of cascaded converter bridges. In 2003,a ±150-Mvar STATCOM was independently developed by ALSTOM using the same configuration and put into operation in the United States [5].

In October 2011,a ±200-Mvar STATCOM developed by Tsinghua University and Rongxin Power Electronic Limited by Share Ltd. was connected to the Dongguan Substation in Guangdong Province and put into operation. The apparatus consisted of two ± 100-Mvar cascade STATCOMs in parallel. In 2013,a ±200-Mvar cascade STATCOM of China Southern Power Grid was first applied to a 500 kV voltage level in Guangdong Shuixiang Station.

5.2 Yunnan Yongfu DC project

In 2016, the Yunnan Yongfu DC Project was put into operation, with rated transmission power of 3000 MW and rated DC voltage of ± 500 kV, and two new converter stations were established. The project first applied a high-capacity STATCOM to the HVDC transmission system and included reactive power control. The project uses the highest capacity cascade STATCOM of 100 Mvar of currently engineered designs, which directly connects a 35-kV bus line to meet the demand of reactive power compensation. The cascade STATCOM is in delta connection with full-bridge structure cells [6].

6 Simulation of cascade STATCOM

6.1 Establishing a cascade STATCOM model

A cascade STACOM model is established in PSCAD/EMTDC, which is in delta connection among the three phases, as shown in Fig. 10. In the model, there are 24 cells in series in each phase and every cell consists of capacitor and a full-bridge that contains 4 transistors and 4 parallel diodes, as shown in Fig. 11.

The controls of reactive power and voltage apply PI regulation, which is combining the error of the actual value with the reference of the reactive power and the DC side voltage to gain the current reference. Then, the current reference is input into the current internal control, as shown in Fig. 12.

This model has two operation modes, namely, constant-voltage mode and constant-reactive power mode. The constant voltage mode has references varying from 500 to 530 kV. The constant reactive power mode has references varying from −100 MVar to +100 MVar.

6.2 Analysis of the stabilising voltage function

In the model, the transformer is 35/525 kV, directly connected to a 525-kV bus line. The STATCOM is connected in parallel to the Funing Station in the line from Wuping to Funing, where the delivery of reactive power is focused on.

The bus line voltage of the Funing Station is 525 kV, thus setting up the reference of STATCOM voltage to be 525 kV. After connecting the STATCOM parallell to the Funing Station, the voltages are compared with those of the previous ones. Fig. 13 shows the waveforms of voltages including with and without STATCOM conditions, where the grey line represents the voltage of the Funing Station without STATCOM in the system and the black line represents the voltage of the Funing Station with STATCOM in the system. Comparing the two waveforms, we can apparently notice that the voltage with STATCOM is closer to the bus voltage – 525 kV.

Then, we set up the short-circuit faults in the Funing Station and analyse the voltage to verify the function of STATCOM in transient state. The start time of faults is set to be 0.5 s after the simulation start and the finish time is 0.5 s. Fig. 14 shows the

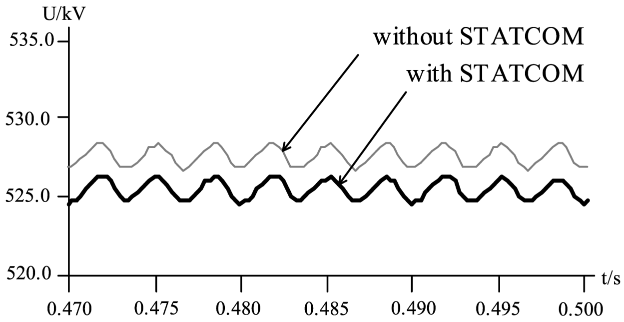

Fig. 13 *Voltage waveforms including with and without STATCOM conditions*

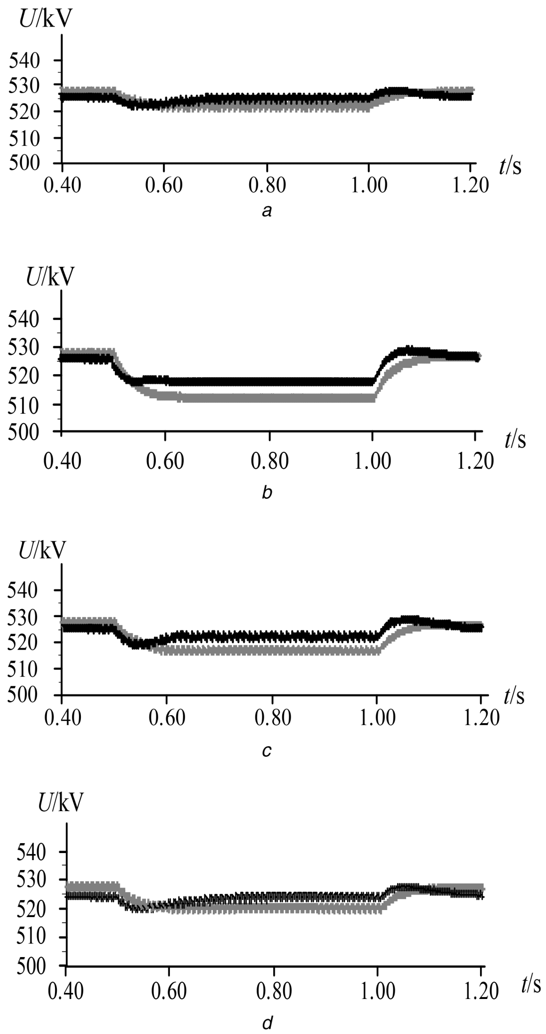

Fig. 14 *Voltage waveforms of faults*

(a) Phase A to ground fault, ***(b)*** Three phases to ground fault, ***(c)*** Phase A and B to ground fault, ***(d)*** Phase A to B fault

voltage waveforms in different faults, where the *x*-axis is simulation time (in seconds) and the *y*-axis is the voltage (in kilovolt). Likewise, the grey line represents the voltage of the Funing Station without STATCOM in the system and the black line represents the voltage of the Funing Station with STATCOM in the system.

From the waveforms in Fig. 14, we can find that the STATCOM decreases the voltage drop in faults and recovers from the fault faster after the fault end, which reduces the probability of commutation failure. Obviously, the STATCOM effectively stabilises the voltage of the Funing Station. As a result, the cascade STATCOM can improve the voltage stability for a weak AC grid like the Funing Station.

7 Conclusion

This paper states the basic principle, existing topologies, control strategies and engineering applications of the STATCOM. The cascade STATCOM applied in the AC grid around the Funing Station of Yunnan Yongfu HVDC project is emphatically introduced, which is concluded from calculations to be a very weak AC system. Then, a cascade STATCOM model is established in PSCAD/EMTDC for simulation. After setting up the voltage reference of the model to be the grid bus voltage and connecting the model in a parallel manner to the Funing Station, we can compare the voltage waveforms in conditions of steady state and different kinds of short-circuit faults whether there is a STATCOM in the system. Finally, from the simulation results, we can conclude that the cascade STATCOM works effectively to stabilise the voltage for the Funing Station, which is a weak AC system.

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