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Characteristics of very fast transient currents in ultra high-voltage power system with Hybrid reactive power compensation

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ABSTRACT

Hybrid reactive power compensation (HRPC) consists of a stepped controlled shunt reactor (SCSR) and a series compensation (SC), which will find applications in future ultra high-voltage (UHV) power grids to resolve the problems due to the frequent change of reactive power and bulk power transmission. However, very fast transient currents (VFTCs) are inevitably generated during switching, which would lead to insulation breakdown. In the present work, we first develop the equivalent model for HRPC, following which we deduce the expression of VFTCs in the time domain by using an inverse Laplace transform. The analysis indicates that the amplitude and frequency of VFTCs are both affected by the capacitance of the SCSR and of the SC, as well as the line length, stray capacitance, etc. The oscillating frequency, peak, and amplitude of the main frequency of the VFTCs in the substation can be modified by adjusting the silicon-controlled rectifiers in the SCSR when the disconnecting switch in gas-insulated switchgear is switched on. When the disconnecting switch in the SC is switched on, the VFTC oscillation frequency in SCSR decreases with increasing stray capacitance of SC, but the frequency and peak of the VFTC remains quite large. Increasing the line length between the SC and the SCSR suppresses the VFTC in UHV power systems. These results lay the foundation for developing HRPC methods to suppress VFTCs in UHV substations.

1. Introduction

Long-distance bulk-capacity low-loss transmission can be realized in an ultra high-voltage (UHV) AC power grid. In addition, UHV systems offer excellent performance, such as the optimal allocation of resources and the prevention of haze fog [1,2]. The large-scale construction of UHV power systems is becoming the new norm in China's electric power industry, which is an indication of China's current prosperity [3,4]. However, in the future, power transmission will significantly increase and reactive power will undergo frequent changes. The security and stability of the UHV synchronous power system will face new challenges, which are manifested in two main ways: (1) the rapid growth in demand for power transmission cannot be satisfied due to the impedance characteristics and the stability limitation of power systems [5], and (2) the increasing exchange of power between different regional grids amplifies the dynamic variations in reactive power in transmission lines and increases the amplitude and frequency of voltage variations, which makes it difficult to adjust the voltage with traditional reactive devices (only fixed shunt reactors) [6]. Hybrid reactive power compensation (HRPC), which consists of series compensation (SC) and a stepped controlled shunt reactor (SCSR) can balance the growth of active power transmission and the adjustment of reactive power [7–10]. This solution is ideal to overcome the disadvantages of traditional simple reactive compensation mode, which can increase the flexibility and reliability of reactive compensation of UHV systems. Thus, the HRPC technique will see use in China's future UHV transmission system.

Very fast transient currents (VFTCs) are generated when the disconnecting switch (DS) is operated and these currents can cause insulation breakdown in the associated power equipment [11]. In particular, a proper understanding of the characteristics of VFTCs is of great importance for protecting gas-insulated switchgear (GIS). Based on a 252 kV GIS experimental investigation, an arc model to simulate very fast transient overvoltage (VFTO) was proposed [12]. This work revealed the time dependence of the arc resistance. The peak magnitude of the VFTC and the dominant frequency content at various locations were also computed in a 245 kV GIS for different switching operations and substation configurations [13]. In other work, a derivative

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Gaussian current source and a short-time sinusoidal current source were used to evaluate the effectiveness of the shielding of gas-insulated bus ducts against transient electromagnetic fields generated in a GIS during switching [14].

However, given the high voltage and bulk power capacity of GIS UHV substations, the problems stemming from VFTCs are more challenging. The formation mechanism, key factors, and techniques to suppress VFTCs and VFTOs were extensively studied over the past decade [15,16]. Ref. [17] proposed a method to compute the voltage and current of key points along the transmission line, and Ref. [18] studied the three-dimensional electrostatic field of DSs by using the finite-element method and the distribution of electric field of the GIS. Other studies demonstrate that the amplitude-frequency characteristics of VFTOs are influenced by the substation or switching-station layout, as discussed in Refs. [19,20]. In addition, Ref. [21] analyzed the adverse effect of VFTOs on power equipment and the advantages and disadvantages of various suppression techniques [21]. By simplifying the DS arc resistance using a hyperbolic resistance model, Refs. [22,23] analyzed the frequency-domain solution of bus-bar voltage and how switch arc affects VFTOs and presented a series of experimental data, including the permeability of magnetic materials in the complex-frequency magnetic domain, to support power systems in practical applications. Installing an UHV substation with HRPC means that the substation will be exposed to a new type of VFTC. The amplitude and frequency characteristics of VFTCs are influenced by the SCSR and the SC, the line length, and the stray capacitance of the SC. However, these amplitude-frequency characteristics of the VFTC have yet to be studied in connection with UHV systems with HRPC. Thus, studying how HRPC affects the characteristics of VFTCs in GIS UHV substations is critically important.

This work is organized as follows: Section 2 presents the principle and equivalent model of HRPC. Section 3 uses an inverse Laplace transform to derive time-domain expression for VFTCs. Finally, Section 4 uses the model developed in Section 3 to study the characteristics of the VFTCs generated by the DS in GISs and the operation of DS in SC. The results reported herein provide a theoretical foundation for optimizing HRPC design and methods to suppress VFTCs in UHV substations.

2. Principle of hybrid reactive-power compensation

HRPC generally consists of SC combined with SCSR [24–26]. The former consists of a capacitor bank, a zinc-oxide arrester, a spark gap, a bypass breaker, and a damping device, as depicted in Fig. 1(a). During normal operation, only the capacitor bank is put into service. The arrester normally serves to protect the capacitor bank, whereas the spark gap is used to protect the arrester from overheating. The bypass disconnector and the two disconnecting switches are indispensable for system maintenance and scheduling. The bypass breaker is used to facilitate the deionization of the spark gap under fault conditions. The damping device restricts the discharge current and prevents equipment failure. The zinc-oxide arrester sustains the voltage across the capacitor with a safety margin of 2.3 times the nominal voltage across the capacitor bank. The zinc-oxide arrester bypasses the capacitor bank when the overvoltage across the capacitor bank exceeds the above sustained voltage. The spark-gap trigger voltage is 2.4 times the nominal voltage across the capacitor bank. Usually, the spark gap is triggered 1 ms after the zinc-oxide arrester is used. Subsequently, the bypass breaker is switched on after the over-current signal of the relay protection with about 30 ms delay due to its mechanical-action time. Thus bypass breaker usually closes about 40 ms after the overvoltage across the capacitor bank.

The SCSR consists of a high-impedance transformer, a set of series reactors, mechanical switches, and silicon-controlled rectifiers. The typical stepped capacity of a SCSR is: 25%, 50%, 75%, and 100%, as shown in Fig. 1(b). The inductive reactive power can be adjusted by the silicon-controlled rectifier. The secondary line winding of the SCSR is connected to a set of series reactors, the number of which is controlled by thyristors and mechanical switches. The thyristors provide fast regulation of the capacity of controlled shunt reactor, whereas the mechanical switches are used in bypass-mode during steady-state operation to allow the thyristors to cool.

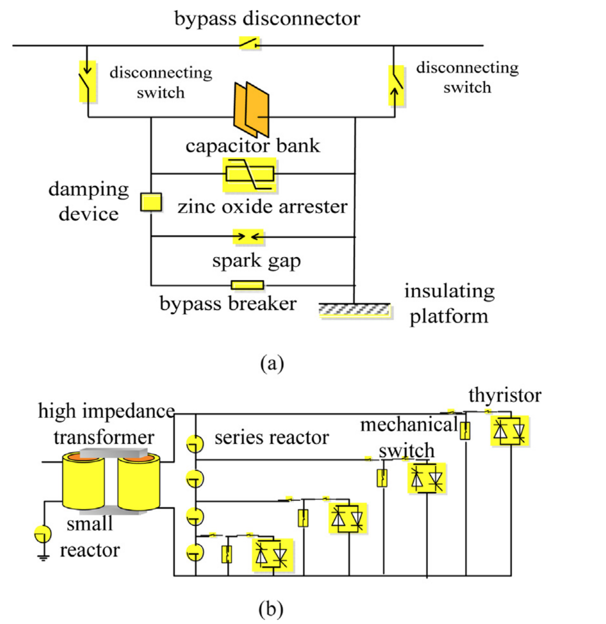

Fig. 1. Schematic diagram of hybrid reactive-power compensation: (a) series compensation, (b) stepped controlled shunt reactor.

The strategy to control the compensation degree of the SCSR is as follows: When the SCSR detects a change in the system voltage, the stepped capacity of SCSR should be rapidly adjusted. If the stepped capacity of SCSR should be decreased, one or more thyristors and the corresponding mechanical switches will be closed to increase the number of connected series reactors. After the mechanical switches are closed, the corresponding thyristors are blocked. If the stepped capacity of the SCSR should be increased, one or more of the mechanical switches will be opened to decrease the number of connected series reactors.

No model of HRPC including the effect of VFTCs yet exists. The CIGRE report provides a lumped-parameter model of a SC and a SCSR (see Fig. 2) [27].

Fig. 2(a) shows the SC model. Considering the real operating conditions, the two DSs at both ends of the capacitor bank are closed when a VFTC occurs. Thus, these two DSs are not modeled as capacitors. In Fig. 2(a), C_D, C_C, C_M, C_H, C_L, and C_S represent the capacitance of the bypass switch, capacitor bank, arrester, spark gap, damping device, and bypass breaker, respectively. Note that C_C is much larger than the other capacitances. Fig. 2(b) shows the model of a SCSR, where C_1 and C_2 represent the equivalent capacitance on the primary side and secondary

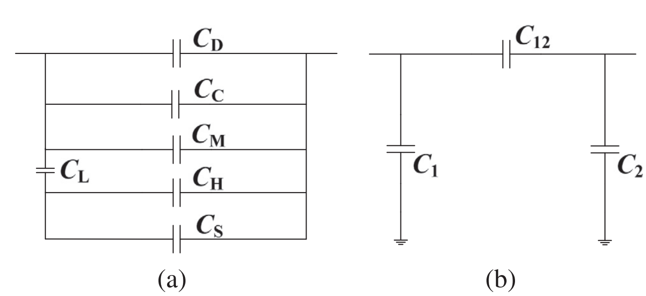

Fig. 2. Equivalent model of hybrid reactive power compensation: (a) series compensation, (b) stepped controlled shunt reactor.