The Rapid Analysis Method for SVC Fault Location without Tests and Simulation

Jingbo Wu 1, *, Shangfeng Xiong 2, Zhengwen Li3, Weijun Zhu 1, Siyuan Guo1 and Quan Hong1

1 State Grid Hunan Electric Power Co. Ltd. Power Research Institute, Changsha 410007, Hunan Province, China;
2 Hunan Xiangdian Test Research Institute Co., Ltd., Changsha 410004, Hunan Province, China;
3 State Grid Hunan Electric Power Co. Ltd., Changsha 410004, Hunan Province, China.

* jinbowu1112@qq.com

Abstract: The existing analysis methods for SVC fault location almost require the result of tests or lab fault simulation. That is too much time and too high cost. This paper proposed a novel rapid analysis method for SVC fault location without lab tests nor fault simulation. They can quickly identify SVC fault type, locate the fault source, improve the efficiency of fault analysis. Their validity and feasibility were verified by using the proposed methods to locate actual SVC fault.

1. Introduction

The static var compensator (SVC) [1-2] is a mature FACTS device. That has been widely used in all aspects of power generation, transmission and distribution of modern power systems[3-4]. Different from conventional capacitors and inductors, SVC could provide reactive power quickly and smoothly by the high frequency switching of power electronics. SVC is generally composed of a thyristor control reactor branch and some capacitor branches. The TCR absorbs reactive power and the capacitor branch emits reactive power. The TCR branch is the core part. And it has complex structure.

In recent years, serious failures in the TCR branch [5], such as the reactors destruction, have become common occurrences. The existing fault location methods require the test results or simulation results of failure in the lab environment [6]. That is too much time and too high cost.

In this paper, a rapid analysis method for TCR single-phase fault location is proposed. It finds the difference between the thyristor fault and reactor fault on the current waveform. This is the hardest. This method does not rely on tests or laboratory simulation results. A single-phase faults can be rapidly identified as thyristor fault or reactor fault by calculation the current waveform during fault. Based on the method for TCR single-phase fault location, this paper proposes a rapid analysis method of SVC fault location. It can effectively improve the efficiency of locating fault. Using the proposed method, the fault of a 180MVar SVC reactor accident in a 500kV substation was quickly located. The effectiveness of the proposed method was verified.

2. The structure and principle of SVC
2.1. The structure of SVC
A common SVC consists of a set of TCR branches and multiple sets of capacitor branches. All branches are connected in parallel on the same AC bus. Capacitor branch circuits are divided into monotone filter branches that filter out odd-numbered harmonics such as 3 and 5, and shunt capacitor branches that are only used for reactive power regulation. The monotonic filter branch must be put in/out with the TCR, and the shunt capacitor branch should be retired according to the reactive compensation requirement.

TCR branch is the core of SVC reactive power compensation. It is generally composed of phase-controlled reactor, valve group, valve control and control system[7]. The structure is shown in Figure 1. There are two phase-controlled reactors in each phase, which are arranged up and down and three-phase reactors are arranged horizontally. Two reactors in each phase are connected in series to the valve group. The valve group is generally composed of multiple pairs of positive and negative parallel thyristors.

![Figure 1. The structure diagram of SVC TCR.](image)

2.2. The working principle of TCR
The TCR branch controls the continuous change of the conduction angle of the thyristor to realize the continuous adjustment of the voltage applied to the phase-controlled reactor, thereby realizing the dynamic adjustment of the absorbed reactive power. Because the parallel bus voltage does not change under normal circumstances, the external characteristics of the TCR branch can be considered as a varactor. Because the trigger angle of the valve group is greater than 90°, the in-angle current waveform is not a complete sine wave and there is a harmonic component. The positive and negative half-waves of the valve group are theoretically symmetric conduction. The current harmonics in the angle are mainly odd-numbered harmonic components, and the even-numbered harmonic components are small.

The formula for calculating the fundamental current component \( I_1 \) and the harmonic component \( I_n \) of each phase in the TCR branch angle is as follows:

\[
I_1 = \frac{U}{\omega L \cdot \pi} (2\pi - 2\alpha + \sin 2\alpha) \quad (1)
\]

\[
I_n = \frac{U}{\omega L \cdot \pi} \left[ \frac{\sin \alpha \cos n\alpha - n \cos \alpha \sin n\alpha}{n(n^2 - 1)} \right] \quad (2)
\]

Among them, \( n = 3, 5, 7... \) is the odd harmonic times, \( U \) is the voltage of the bus connected to SVC, \( \omega \) is the frequency, the unit is rad/s, \( \alpha \) is the conduction angle of the valve group, and the unit is rad. The range is \( \pi/2 \sim \pi \), \( L \) is the rated equivalent inductor.
3. Single phase fault fast identification method for TCR

3.1. Theoretical basis

Before the TCR malfunctions, the current waveform is usually abnormal. The abnormality of the current waveform is directly related to the type of fault. TCR faults can be classified into three types: single-phase faults, three-phase faults, and external faults. Single-phase fault refers to an abnormality that occurs in one phase of the TCR branch and is caused by an internal fault source; a three-phase fault refers to an abnormality that occurs in three phases of the TCR branch and is caused by an internal fault source; an external fault is caused by faults caused by external causes of the TCR branch.

TCR single-phase faults are more common than other faults, and it is more difficult to locate fault sources. According to the fault equipment classification, single-phase faults can be divided into valve group conduction failures and reactor failures. Reactor faults include short-circuit between gates, short-circuit to ground, and broken strands in reactors. Its external characteristics are the changes in rated equivalent inductance. Valve group conduction faults include valve control system failures, valve group thyristor failures, phase-locked-loop faults, etc. The external characteristic is the abnormal change in the conduction angle of the valve group. According to equations (1) and (2), it can be seen that the current waveform caused by the above two types of faults is abnormal, that is, the fundamental wave component and the harmonic component change are different. Therefore, in theory, abnormal data of the comparison current waveform can be analyzed and calculated to quickly identify valve group conduction failure or reactor failure.

3.2. Identification method

Based on the above theory, a single-phase fault identification method for TCR is proposed. First, assume that the fault type is the valve group conduction fault or reactor fault. Calculate the actual trigger angle or the actual rated equivalent inductance value through the current fundamental wave components, and then compare them. Theoretically, the difference between the current third harmonic component and the actual third harmonic component of the two types of faults is used to identify the fault type.

3.3. Specific steps

The proposed TCR single-phase fault rapid identification method, the specific steps shown in Figure 2, where T is the time point that current waveform appears abnormal before TCR fault.
4. The fault location rapid identification method for TCR single phase fault

4.1. Positioning method
For the single-phase fault of TCR, a fast identification method is proposed. Based on this, a quick identification method for three-phase faults and external faults is added, and a complete fault location quick analysis method of SVC is proposed.

The most obvious difference between a three-phase fault and a single-phase fault is that an abnormality occurs at the same time in the three phases of the TCR branch or in one phase. The three-phase fault source is the main part of the SVC control system, including sampling link, trigger angle calculation link and three-phase phase locking link.

Unlike internal faults such as single-phase faults and three-phase faults, external faults are caused by faults outside the TCR branch. Voltage abnormalities and current anomalies appear at the same time and correspond to each other.

4.2. Specific steps
The proposed fault location quick analysis method of SVC, where T is the time point current waveform obviously abnormal before the TCR failure:

1) Obtain the record waveform during the fault, and determine the three-phase current $I_{ab}$, $I_{bc}$, $I_{ca}$ and bus voltages $U_{ab}$, $U_{bc}$, $U_{ca}$ of the TCR branch;

2) Compare and determine if there is a significant change in the voltage waveform before and after T. If the phase of voltage waveform has a significant change and it is consistent with the phase which has abnormal current, then perform step 3), otherwise go to step 4);

3) Investigate whether the change of voltage waveform is caused by an external fault. You can query whether serious faults such as near-field short-circuit occur in the power grid at this moment and
the near-zone grid protection action. If it is determined that the voltage waveform change is caused by an external fault, determine the fault type as external fault, otherwise skip to step 4;

4) Determine the type of fault is internal fault, compare and judge whether current waveforms at time T have abnormal three phases at the same time. If three-phase current is abnormal at the same time, then go to step 5; otherwise, skip to step 6;

5) The fault type is determined to be three-phase fault. The fault source is the main part of the SVC control system. The sampling link, the trigger angle calculation link, and the three-phase phase locking of the control system can be checked one by one to further locate the fault source.

6) Determine the fault type as single-phase fault, identify the single-phase fault type by using the single-phase fault identification method of TCR, if the fault type is identified as the fault of the valve group, skip to step 7; otherwise, skip to step 8;

7) Judgment that the fault type is the valve group conduction fault, the fault source is the abnormal phase thyristor valve group, valve control and abnormal phase’s phase locking. By checking it one by one, can further locate the source of the fault;

8) Judgment that the fault type is reactor fault, the fault source is the abnormal phase reactor body, and focus on the inter-turn short circuit.

5. Applications
In February 2016, a 500 kV substation SVC installation suffered from a phase reactor damage to the TCR branch. The SVC consists of TCR, 3rd order monotonic filter, 5th order monotonic filter, 7th order monotonic filter, and 2 sets of shunt capacitors. All the branches are connected in parallel on the main transformer low voltage side 35kV bus. The TCR and 3rd and 5th filters need to be input at the same time. The 7th filter and two sets of shunt capacitors are switched depending on the reactive voltage compensation requirement. The 7th filter is first input and then output. The TCR branch has a rated capacity of 180 MVar, and the SVC reactive output range is inductive from sensitive 120 MVar to capacitive 240 MVar. TCR branch each phase valve group consists of 24 pairs of forward and reverse parallel thyristors, conduction angle adjustment range of 118° ~165°, each equivalent value of the rated inductance of about 0.0275H (factory measured value).

According to the fault location quick analysis method of SVC, this fault is quickly analyzed and positioned:
1) Acquiring the record waveform of the three-phase currents $I_{ab}$, $I_{bc}$, $I_{ca}$ and the bus voltages $U_{ab}$, $U_{bc}$, $U_{ca}$ of the CR branch within the fault period, and determining the time point T when the current waveform of the TCR failure appears obviously abnormal;
2) $U_{ab}$, $U_{bc}$, $U_{ca}$ have no obvious change before and after T time, so the fault type is determined as internal fault;
3) Only the $I_{ab}$ waveform is abnormal before and after T time, $I_{bc}$, $I_{ca}$ waveform is normal, so the fault type is determined as single-phase fault;
4) $U=36kV$, $I_{0}≈1010A$, $I_{r0}≈1675A$, $I_{0}≈580A$ are obtained from the oscillographic data. According to the proposed TCR single-phase fault fast identification method, it is calculated that $\alpha_{0}=130°$, $\alpha_{1}≈119°$, $I_{30}≈176A$, $L'=0.0166H$, $I_{31}≈596A$, so $|I_{30}F3|>|I_{31}F3|$ is right, so it is determined that the fault type is a reactor fault.

After confirming that the source of the fault is the body of the a-phase reactor, inspecting it shows that the reactor does have short-circuit traces between the turns.

After replacing only phase-A reactors with Phase A, the SVC was put into operation in August 2016. No abnormalities occurred during the test run for one week, confirming that the proposed method was correctly positioned for fault location analysis.

6. Conclusion
The rapid analysis method for SVC fault location is proposed in this paper. It can quickly identify fault types and locates fault sources without relying on laboratory detection or simulation results. It could
effectively improves the efficiency of fault investigation and analysis. In the actual SVC failure, the proposed method was used. That confirms that the proposed method is effective and feasible.

Acknowledgments
This work was supported by Science & Technology Project of State Grid Electric Power Corporation in China (5216A018000Q), and Science & Technology Project of State Grid Hunan Electric Power Corporation in China (5216A515002V).

Reference
[1] Xiong Haoqing, Tang Yong, Zhang Xiaohua, et al. Allocation method of multiple SVCs considering operation scheme changing [J]. Proceedings of the CSEE, 2012, 32(13):44-51(in Chinese).
[2] Zhang Jiangkang, Su Xiaohua, Li Huaiqiang, et al. Impact of large-capacity SVC on transformer differential protection and the solutions[J]. Automation of Electric Power Systems, 2015, 39(7):164-168(in Chinese).
[3] Liu Zhenya, Zhang Qiping, Wang Yating, et al. Research on reactive compensation strategies for improving stability level of sending-end of 750kV grid in Northwest China[J]. Proceedings of the CSEE, 2015, 35(5):1015-1022(in Chinese).
[4] Lei Bangjun, Fei Shunmin, Zhai Junyong, et al. Coordinated control of automatic voltage regulator and SVC in multi-machine power system[J]. Transactions of China Electrotechnical Society, 2015, 20(18):131-139(in Chinese).
[5] Duan Hao, Xu Bingyin, Wu Shouyuan, et al. A new protection method of thyristor controlled reactors based on no-characteristic third harmonic current[J]. Automation of Electric Power Systems, 2012, 36(1):81-85(in Chinese).
[6] Duan Hao, Xu Bingyin, Wu Shouyuan, et al. Analysis of the third harmonic current at the fault state of thyristor controlled reactors[J]. Automation of Electric Power Systems, 2011, 35(23):64-69(in Chinese).
[7] Wu Jinbo, Sheng Yang, Li Hui. The Discussion on the Configuration of DC Control and Protection System[J]. Hunan Electric Power, 2013, 33(4): 38-40.