Novel method for restraining 35 kV shunt reactor switching overvoltage – phase controlled breaker

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Abstract: Phenomena such as current chopping, arc reignition and equivalent current chopping might appear when cutting off shunt reactor. Overvoltage caused by switching will lead to interphase fault in related equipment and inter-turn insulation damage in the shunt reactor, which will threaten the safety of electrical equipment. In recent years, equipment breakdowns caused by 35 kV shunt reactor switching overvoltage in 220 kV substation occur frequently in China, endangering the safe and stable the power grid. In this study, the mechanism, perniciousness and suppression of shunt reactor switching overvoltage are systematically analysed. The strategy of phase controlled breaker is put forward, and the overvoltage measurement and power systems computer aided design (PSCAD) simulation analysis are carried out. The work and conclusion of this study provide the solutions and engineering experience for the switching overvoltage suppression of 35 kV shunt reactor.

1 Introduction

Vacuum circuit breaker has the advantage of simple structure, high reliability, long lifetime and suitable for frequent operations. Therefore, it is widely used in power system [1, 2]. When the 35 kV shunt reactor being cutting off by vacuum circuit breaker, phenomena such as current chopping, arc reigniting and equivalent current chopping might appear. The switching overvoltage may short out the reactor and bus, destroy inter-turn insulation, and even cause flashover in main transformer, affecting the safe operation of the power system [3, 4]. In recent years, there have been a number of equipment anomalies caused by switching overvoltage during the cutting-off operation of 35 kV shunt reactors [5]. Switches, substation transformers, grounding transformers and even main transformers were damaged in these accidents.

The available methods for controlling the cutting-off overvoltage of the shunt reactor include RC absorber [6], overvoltage protector [7], changing the position of the circuit breaker [8] and improving dielectric insulation recovery performance of the breakers [9, 10]. None of the above methods can theoretically eliminate the reignition phenomena of the circuit breaker during the cutting-off process. Thus, it is not possible to eliminate the overvoltage.

Phase controlled breaker [11] operates at the best phase position by the control system according to the load characteristics. This may possibly eliminate the inrush current, arc reignition and other phenomena that may lead to overflow or overvoltage completely. It becomes a frontier issue of the primary–secondary equipment integration and switch intelligentisation.

The overvoltage of the 35 kV shunt reactor was measured in several 220 kV substations, and the relevant PSCAD transient simulation analysis was also completed in this paper. Method and experience are provided for the engineering modification and operation maintenance of shunt reactors.

2 Mechanism of the overvoltage and the restraining methods

2.1 Mechanism of the overvoltage caused by cutting off the shunt reactor

There are mainly two kinds of overvoltage in the process of cutting off shunt reactor, reignition overvoltage and current chopping overvoltage [12, 13]. Due to the manufacturing process improvement of vacuum circuit breakers, the current chopping overvoltage is relatively lower and the upper limit is fixed in most cases. The main cause of the overvoltage is the reignition and the following equivalent current chopping of the non-first-cut phases. Fig. 1 shows the formation mechanism of the breaker reignition when inductive current is cut.

As shown in Fig. 1, I is the current flowing through the shunt reactor and circuit breaker. The system sends out the separation order at \(T_s\) and the operating mechanism of the breaker begins to take action. After the opening time \(t_o\), the contacts of the breaker starts to separate at \(T_s\) and the fracture dielectric insulation begins to recover, as shown by the fracture dielectric insulation recovery (FDIR) curve. After the arc time \(t_a\), the arc extinguishes since the current crosses zero at \(T_0\) (ideal state without chopping), and the fracture transient recovery voltage (FTRV) begins to appear between the fractures. If the arc time \(t_a\) is too short, the contacts of the circuit breaker cannot separate completely when the current crosses zero, and the distance between the moving and static contacts might be too small. If the FTRV is too high, it may lead to the breakdown and arc reignition. The reignited arc will be quickly extinguished when the current crosses zero point again. The recovery voltage will be regenerated between the contacts. If the recovery voltage exceeds the tolerance of the gap insulation, then the arc will be reignited again. Arc reignition process continues until the gap distance between the contacts is large enough to...
Due to the dispersion of the fracture dynamic insulation strength, arc reigniting is random. If the arc reignition appears, reignition cutting-off can be realised by phase controlled

Table 1. Major equipment parameters in the testing

| Equipment          | Main parameter                        |
|--------------------|---------------------------------------|
| shunt reactor      | oil-immersed, inductive reactance: 122.5 Ω |
| phase controlled breaker | vacuum breaker, 40.5/1250, 31.5 kA           |
| current transformer | voltage ratio: 1200/5                   |
| bus arrester       | rated voltage: 51 kV                   |
| main transformer arrester | rated voltage: 51 kV                  |
| shunt reactor attester | rated voltage: 51 kV                |
| connect cable      | length: 50 m                          |
| overhead lines     | total length: 55 km                    |

withstand FTRV [11]. Arc reignition mainly depends on FTRV and FDIR. Due to the dispersion of the fracture dynamic insulation strength, arc reigniting is random. If the arc reignition appears, overvoltage may uprush and affect devices in the system.

2.2 Restraining method of arc reignition and overvoltage

According to Fig. 1, when FTRV exceeding FDIR, arc reignites. Therefore, it is possible to restrain or even eliminate the arc reignition by extending the arcing time \( t_a \) (as shown in Fig. 2).

\[ T_{00} = \text{contacts separation time when FTRV curve and FDIR curve are tangent.} \]

\[ t_a < T_{00} + 0.5 \text{ ms}. \]

The reference voltage (1.0 pu) of 35 kV system is 33.07 kV. According to the specification, the peak values of transient overvoltage are all represented by the per-unit values in this paper.

3 35 kV Shunt reactor switching testing

3.1 Testing system pattern

The parameters of the major equipment in the testing are shown in Table 1.

The phase selection controlled strategy: B phase is cut off first, and \( t_a \) is set to 6.7 ms. The opening time discretisation of the breaker is within \( \pm 0.5 \) ms. Thus, the maximum \( t_a = 6.7 + 0.5 = 7.2 \) ms in theory.

Transient voltage signals of the bus and the reactor were obtained by the RC dividers. The waveforms were recorded by DL750P digital oscilloscope. Transient current was obtained from secondary side of current transformer by high-precision ammeter. The operation situation of the arresters connected to the bus, main transformer and shunt reactor were recorded after each operation. The related electrical monitoring points are shown in Figs. 3 and 4.

3.2 Testing results and analysis

The reference voltage (1.0 pu) of 35 kV system is 33.07 kV according to the specification. The peak values of transient overvoltage are all represented by the per-unit values in this paper.

3.2.1 Without phase controlled function: Twice cutting operations of the shunt reactor were carried out without phase controlled function. The switching overvoltage of the bus side and the reactor side were shown in Table 2.

It can be concluded from Table 2 that obvious overvoltage appears on the shunt reactor side during first cutting. The maximum value of inter-phase overvoltage is reaching 6.0 pu, exceeding the bearable value. During the 1st switching, the B and C phase of shunt reactor arrester operated, while the main transformer arrester and bus arrester did not. There was no arc reignition and obvious overvoltage during the 2nd cutting. Fig. 5 shows the voltage and current waveforms of the 1st switching without phase controlled function.

It can be seen from Fig. 5c that the current of A phase crosses zero point first after the circuit breaker operated. The duration of the arc reignition time was 1.8 ms. There was high-frequency current in B and C phase induced by arc reigniting, causing equivalent current chopping. The arc reigniting phenomenon is shown in Figs. 5b and c. The overvoltage of the bus was not high since there were three lines put into operation when switching. The overvoltage of the reactor was so high that led to the operations of the arresters.

3.2.2 With phase controlled function: After putting the phase controlled function into operation, ten switching operations of the shunt reactor were carried out. The switching overvoltage of the bus side and reactor side was shown in Table 3.

It can be seen that after the phase controlled function being put into operation, overvoltage of the bus side and the reactor side were both limited. No arc reignition occurs according to the current signal. The shunt reactor arrester, the main transformer arrester and the bus arrester did not operate as well. Fig. 6 shows the waveform of the voltage and current. The control objective of the phase controlled strategy is that the B phase current crosses zero first, and the actual monitor of the current waveforms are in accord with the strategy. As \( t_a \) is fixed and long enough, the voltage of the bus and the reactor during the tens times experiments were all close to each other, and there was no obvious overvoltage.

4 PSCAD simulation analysis

4.1 Simulation model

The electromagnetic transient simulation software PSCAD is used to simulate the switching overvoltage of 35 kV shunt reactor. The typical system configuration of the 35 kV shunt reactor is shown in Fig. 7.

The model of single-phase circuit breaker is constructed by three elements: \( I_c \) – chopping current, \( U_d \) – fracture dielectric recovery strength and \( \Delta I \) – high frequency current extinguishing ability. The rated voltage of reactor is 35 kV (37.5 kV), rated capacity is 10,000 kvar, Y-type connection, and neutral point is not
The inductance of each phase is 0.38 H and the resistance of the winding is 1 Ω. The distributed capacitance of the shunt reactor is set to 1500 pF. For the high frequency transient simulation, the high and low frequency characteristics should be both taken into consideration. The frequency-dependent model is best suited. For the 35 kV single-core 300 mm² crosslinked polyethylene cable, the simulation parameters are shown in Table 4.

The arresters are configured in accordance with the actual conditions, and the parameters of the arresters are set according to the data provided by the manufacturer. The susceptance of overhead lines is in the range of 2.3–3.1 \times 10^{-6} \Omega^{-1} km^{-1}(7.3–9.8 nF/km) [14]. When the line length is obtained, the bus-to-ground

| Overvoltage                  | 1     | 2     |
|-----------------------------|-------|-------|
| bus side, (phase to ground) | 1.17  | 0.96  |
| reactor side, (phase to ground) | 3.07  | 1.85  |
| bus side, (phase to phase)  | 1.83  | 1.61  |
| reactor side, (phase to phase) | 5.96  | 1.92  |
| reignition                   | yes   | No    |
| phenomenon                  |       | equivalent current chopping | –     |
Table 3  Bus and reactor overvoltage when cutting shunt reactor with phase controlled function, (pu)

| Overvoltage | Bus side, (phase to ground) | Reactor side, (phase to ground) |
|-------------|----------------------------|---------------------------------|
| 1           | 0.95                       | 1.85                            |
| 2           | 0.94                       | 1.77                            |
| 3           | 0.96                       | 1.84                            |
| 4           | 0.96                       | 1.84                            |
| 5           | 0.96                       | 1.83                            |
| 6           | 0.96                       | 1.80                            |
| 7           | 0.96                       | 1.90                            |
| 8           | 0.95                       | 1.78                            |
| 9           | 0.95                       | 1.89                            |
| 10          | 0.96                       | 1.82                            |

Fig. 6  Transient waveforms when cutting shunt reactor with phase controlled function
(a) Transient voltage of the shunt reactor, (b) Transient voltage of the bus, (c) Transient current

Fig. 7  PSCAD model system of switching 35 kV shunt reactor

Table 4  Simulation parameter of crosslinked polyethylene cable

| Parameter name                                      | Value       |
|-----------------------------------------------------|-------------|
| cable core radius                                   | 10.3 mm     |
| cable core resistivity                              | $1.68 \times 10^{-8} \Omega m$ |
| insulating layer radius                             | 10.5 mm     |
| relative dielectric constant of insulation layer    | 4.1         |
| depth                                               | 0.5 m       |
| earth resistivity                                   | 100 $\Omega m$ |
| arrangement                                         | horizontally|
| Phase-to-phase distance                             | 0.5 m       |

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capacitance can be estimated. The capacitance is set to 0.01 μF for the bus with no lines. There are 3 lines on the bus in the testing. According to the parameters in Table 1, the equal capacitance is about 0.52 μF.

4.2 Analysis of simulation results

Fig. 8 shows the voltage and current waveforms with or without phase controlled function. Table 5 is the simulation overvoltage result of the bus side and the reactor side.

It can be seen that the characteristics of waveforms and overvoltage between the simulation and measurement are basically same. The arc reignition phenomenon disappeared with phase controlled function. The strategy has obvious restraining effect on the shunt reactor switching overvoltage.

5 Conclusion

Phase controlled technology is the only method that can theoretically eliminate reignition phenomenon currently. It is the first-time application of the phase controlled breaker on the 35 kV shunt reactor in China. The main conclusions of the analysis are as follows:

i. The intersection of the FDIR and FTRV is the primary cause for the arc reignition. The reignition can be reduced or even completely eliminated by enlarging the arcing time $t_a$.

ii. Reignition and current chopping appeared when cutting off the shunt reactor without the phase controlled function. The maximum interphase overvoltage of the bus side was 3.07 pu,
and that of the reactor side was 5.96 pu, exceeding the tolerance value and leading to the operation of the arresters. The arc reignition and overvoltage did not occurred during ten times experiments with phase control function. The phase controlled breaker showed excellent performance in the testing. The control strategy coincided with the actual monitoring waveforms.

iii. The simulated waveforms were basically consistent with the measured waveforms. The maximum interphase overvoltage of the bus and the reactor were 2.72 and 5.26 pu, respectively, without phase controlled function. The arc reignition and overvoltage was disappeared with phase controlled function.

6 References

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