

Comparison and analysis of the fault arc characteristics of flexible DC transmission lines

Botong Li¹ ✉, Hanqing Cui¹, Yichao Liu¹, Bin Li¹

¹The Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, People's Republic of China

✉ E-mail: libotong@tju.edu.cn

eISSN 2051-3305

Received on 23rd August 2018

Accepted on 19th September 2018

E-First on 18th January 2019

doi: 10.1049/joe.2018.8524

www.ietdl.org

Abstract: VSC-HVDC grid is one of the important development directions of the smart grid in the future. The arc characteristics of transient fault on the transmission line are the theoretical basis for determining reclosing time and reclosing strategy of DC circuit breaker. In this study, the process of the transient single-pole ground fault on the true bipolar VSC-HVDC transmission line is analysed and the arc model of the fault is determined according to the fault characteristics. Then a two-terminal voltage source converter-high voltage direct current (VSC-HVDC) system including this arc model is built in power systems computer aided design (PSCAD). The primary and secondary arc characteristics of the transient single-pole ground fault on the transmission lines are simulated and compared with the arc in AC system. It is shown that the arc extinction time of the flexible DC transmission system is lesser than that of the AC system at the same voltage level.

1 Introduction

The flexible DC transmission technology is a new type of DC transmission technology based on voltage source converters and full-controlled power electronic devices. It has obvious advantages in many fields such as grid integration of large-scale distributed energy, island power supply, loss reduction of long-distance transmission and it has received widespread attention of scholars at home and abroad [1].

The multi-terminal DC transmission is the main form of the flexible DC transmission at present, and it eventually develops into the flexible DC grid as the number and capacity of converters continue to escalate. Compared with the multi-terminal DC transmission, the flexible DC grid has many advantages: from the economic considerations, it can save the line corridor and reduce investment costs [2]; from the reliability of power supply considerations, it has higher system redundancy and power supply reliability [3]; from the grid integration of distributed energy considerations, it can solve the transmission problem of multi-power supply and multi-power consumption, which is suitable for the dispersion of distributed energy. Also, it can reduce the impact of distributed energy on grid stability [4].

The existing flexible DC transmission projects generally use DC cables as transmission lines, which can reduce the probability of transmission line fault. With the rapid development of DC circuit breakers and taking into account the advantages of overhead lines in reducing investment costs, the flexible DC grid based on overhead lines will become the main direction for the flexible DC transmission. However, because of the poor external environment of overhead lines, the probability of line fault is higher, which is more likely to cause the large-scale blackout [5]. Considering that the faults of the DC transmission line are mostly transient faults, the reclosing operation of the breakers can restore the power supply, which can improve the reliability of the power supply.

In order to improve the success rate of reclosing, it must be confirmed before reclosing that the fault is a transient fault and the insulation of the fault line has recovered. The reclosing time of the circuit breakers consists of arc time, deionisation time, and recovery time of the circuit breakers, and the last two can be determined according to the voltage level [6]. Hence, the study on the arc time becomes the key for getting the reclosing time.

Analysis of the arc characteristics of the transient faults is important for identifying the line fault types. The study on fault arc characteristics is mainly about AC fault arc at present. Li *et al.* [7] point out that the arc voltage of AC system is approximately a

periodic square wave signal and the odd harmonic content during the secondary arc is significantly higher than that of the permanent ground fault, which can be used to distinguish the fault types. Sun *et al.* [8] point out that the arc current contains high-frequency interference and it distributes in a wide range of frequency bands. Hence, the method of wavelet entropy can be used to distinguish the transient arc fault. Djurić and Terzija [9] point out that the arc fault is a non-linear process, and there are higher harmonics in arc voltage and arc current. The fault types can be distinguished by detecting the voltage and current of the fault lines.

Building an accurate arc model is the precondition to study fault arc characteristics and arc time. In this paper, the arc model suitable for transient fault of HVDC transmission lines is determined and then a DC transmission model including this arc model is built in PSCAD. The changes of the electrical data during the DC arc fault are analysed in detail and compared with the extinction process of AC arc. The overall analysis can be the foundation for the follow-up study on reclosing.

2 Arc model for analysis of transient faults in flexible DC grid

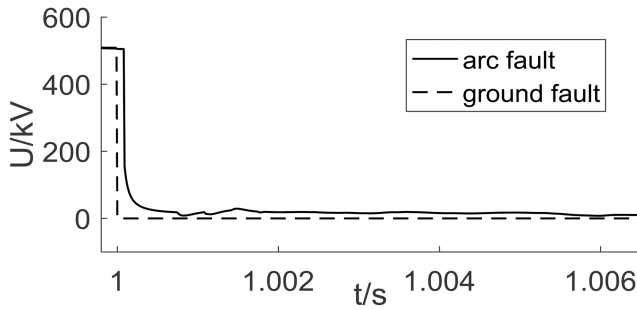
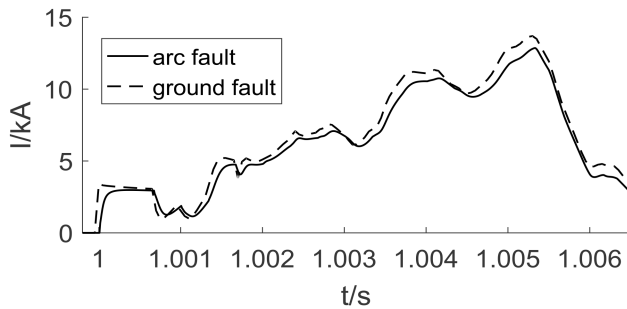
Most of the existing DC arc models are based on the AC arc models. Hu and Wang [10] propose an improved Habedank model on the basis of the conductance of the minor variation of the DC arc. This model has larger error as it cannot reflect the exact change of DC arc conductance. Andrea *et al.* [11] propose the meta-model on the basis of the Mayr model and the Ayrton model, and the corona discharge process is considered. Li *et al.* [12] propose the Zeller model on the basis of the principle of thermal equilibrium and the physical properties of air. It is assumed that there is an arc column and the voltage drop is mainly on the arc column. On the basis of the Mayr arc model, Johns *et al.* [13] propose a model that can reflect the dynamic change of arc conductance.

Considering the characteristics of the above existing model and the flexible DC fault arc, the arc model introduced in Johns *et al.* [13] is adopted in this paper. In this model, the fault arc is divided into primary and secondary arcs according to the development of the fault. According to the different characteristics of primary and secondary arcs, the modelling methods of primary and secondary arcs are given in this model.

The arc from the moment of fault to the operation of the breakers is the primary arc. During this period, the fault current is

Table 1 Main parameters of the DC arc model

Initial arc length, m	Peak current of primary current, kA	Peak current of secondary current, A
10	14	50

**Fig. 1** Curve of voltage at fault point**Fig. 2** Curve of current at fault point

supplied by the power system on both sides of the lines, which is heavy. However, there is no significant elongation of the arc length. The dynamic characteristics of the primary arc can be described as

$$\frac{dg_p}{dt} = \frac{1}{T_p}(G_p - g_p) \quad (1)$$

where g_p is the primary arc conductance changing over time, T_p is the time constant of the primary arc, and G_p is the primary arc conductance at steady state.

The secondary arc is the arc after the operation of breakers. During the secondary arc, the fault current is supplied by the residual energy of the line and the coupling of the sound phase. Compared with the primary arc, the secondary arc current is generally small, but its arc length can change significantly. So the arc length can no longer be regarded as a constant. The dynamic characteristics of the secondary arc can be described as

$$\frac{dg_s}{dt} = \frac{1}{T_s}(G_s - g_s) \quad (2)$$

where g_s is the secondary arc conductance changing over time, T_s is the time constant of the secondary arc, and G_s is the secondary arc conductance at steady state.

During the secondary arc, not only the change of arc length needs to be considered but also the arc extinction and re-ignition need to be considered. Therefore, the arc extinction and re-ignition criteria need to be given for determining whether the secondary arc is permanently extinguished.

The re-ignition voltage is related to the arc length and the peak current. According to the empirical formula, the re-ignition voltage gradients can be calculated as:

$$V_r(t_r) = \frac{5 + 1620T_e}{(2.15 + I_s)} \times (t_r - T_e) \times h(i) \times 10^3 \quad (3)$$

where T_e is the time from the initiation of secondary arc to extinction (including arc temporary and permanent extinction), t_r is the time from the initiation of secondary arc, I_s is the peak current of the secondary arc, and $h(i)$ is the step function of the arc current:

$$h(i) = \begin{cases} 1, & i = 0 \\ 0, & i \neq 0 \end{cases} \quad (4)$$

Formula (4) shows that when the arc burns (the value of the arc current is not 0), the value of re-ignition voltage gradient V_r is 0. When the arc is extinguished (the value of the arc current is 0), the re-ignition voltage gradient V_r is proportional to t_r .

3 Simulation and analysis for transient process of the transient single-pole fault on DC transmission lines

A flexible DC transmission model including the arc model is built for simulation and analysis in PSCAD. This model is a true bipolar two-terminal DC transmission system. The left modular multilevel converter (MMC) adopts the control of constant active power and the setting value is 1500 MW. The right one adopts the control of constant voltage and the setting value is 500 kV. The model of the DC transmission lines is frequency-dependent model and length is 250 km. A single-pole arc fault occurred at the distance of 150 km from the left MMC. The main parameters of the arc model are shown in Table 1.

The transient single-pole fault occurred at 1 s on the transmission lines and the fault arc was generated. At this point, the relay protection device on the line had not yet issued a trip signal and there was no action of the DC circuit breakers. The fault arc at this stage is the primary arc. During the primary arc, the curve of the voltage at the fault point is shown by the solid line in Fig. 1. The transient arc fault in the simulation system was changed to the permanent ground fault and the simulation was performed again. Then the voltage curve of the fault point is shown by the dotted line in Fig. 1. In this figure, the fault occurred at 1 s; the relay protection device issued a trip signal at 1.003 s; the circuit breaker was fully tripped and the value of the current at the line became 0 at 1.0054 s, i.e. the period of the primary arc is 1–1.0054 s.

Fig. 1 shows that the voltage at the fault point drops rapidly when a transient arc fault occurs on DC transmission lines. The voltage drops about 90% in 1 ms, and then fluctuates within a small range. In contrast, when a permanent ground fault occurs, the value of voltage at the fault point drops to 0 instantaneously and stays at 0 all the time.

The voltage at the fault point is related to the current through the fault point and the grounding resistance. When a permanent ground fault occurs, the grounding resistance becomes 0 from the insulation resistance of air directly. Hence, the value of the voltage becomes 0. When an arc fault occurs, the grounding resistance becomes the arc resistance from the insulation resistance of air, and the arc current increases instantaneously. Affected by these two, the arc voltage fluctuates in a small range.

The curve of the current at the fault point during primary arc is shown in Fig. 2.

The solid line in Fig. 2 shows the current of the transient arc fault and the dotted line shows the current of permanent ground fault. It can be seen from this figure that the trend of the fault currents of the two faults is the same basically, but the value of the current is different. Compared with the permanent ground fault, the arc fault has a certain grounding resistance. However, the grounding resistance is small and it cannot have a greater impact on the trend of the fault current.

It can be seen from Fig. 2 that the fault current is continuously increasing in oscillation during the primary arc (1–1.0054 s). This is mainly caused by the charging and discharging of the capacitors on the fault lines. The fault current is the combined effect of the short-circuit current provided by the converters and the charge and discharge of the inductance and capacitor. When the fault occurs, the short-circuit current provided by the converters increases immediately. The voltage on the transmission lines will oscillate,

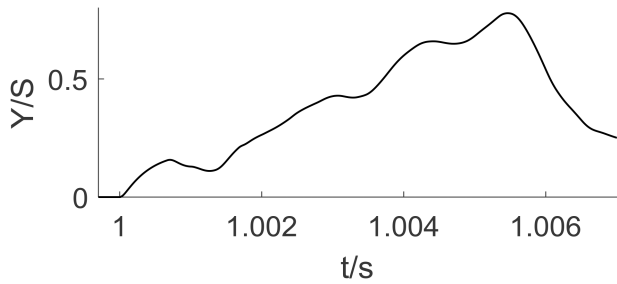


Fig. 3 Curve of voltage at fault point

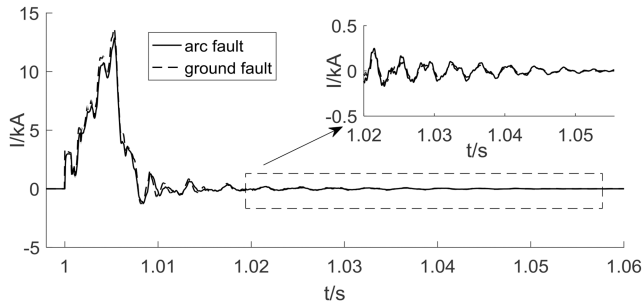


Fig. 4 Curve of current at fault point

resulting in constant charge and discharge of the capacitor on the fault lines. The fault current will increase during discharge of the capacitor, while it will decrease during charging, causing the fault current to increase in oscillation.

Fig. 3 shows the curve of arc conductance during the primary arc and the value of the conductance is calculated by formula (1). It can be seen from this graph that the value of the arc conductance has been increasing during the primary arc.

About 3 ms after the fault, the relay protection device on the fault lines issued the trip signal and then, the DC circuit breakers begin to trip.

Owing to the heavy fault current and the complex internal breaking process of the DC circuit breaker, the DC circuit breaker needs some time to break the fault line completely. About 4.5 ms after the fault, the operation of the DC circuit breaker on the lines was accomplished and the fault line was disconnected completely. The fault arc begins to transform from primary arc to secondary arc, Fig. 4 shows the curve of the fault current.

When the fault line is disconnected completely, the power supply no longer supplies the short-circuit current to the fault point. So the fault current will decrease rapidly. However, due to the influence of the energy storage and the coupling of the sound phase, the value of the arc current will not become 0 but fluctuates in a small range. As shown in Fig. 4, the trend of the fault current of the arc fault and the ground fault is the same basically during the secondary arc. During the secondary arc, the arc resistance changes little, and its value is small compared with the line impedance. So it does not have a large influence. The arc of the transient fault is extinguished completely at 1.051 s and the fault current drops to 0. On the contrary, the fault current of the permanent ground fault does not drop to 0.

The curve of arc conductance during the secondary arc is shown in Fig. 5. As can be seen from the figure, during the secondary arc, the arc conductance will continue to decline to a small value. There will be the phenomena that the arc conductance can drop to 0 and increase immediately. This is because the arc extinguishes at this moment, but the arc voltage is greater than the re-ignition voltage in the next moment. So the phenomenon of re-ignition will occur soon after the extinction of the fault arc. Re-ignition of the arc or not is determined by the arc voltage and the re-ignition voltage. Fig. 6 shows the curves of the arc voltage and re-ignition voltage.

As shown in Fig. 6, the insulation is recovered at the fault gradually 51 ms later, and the re-ignition voltage begins to increase. Then the arc voltage is always less than the re-ignition voltage, the arc is extinguished and no longer re-ignited. So, the arc is extinguished completely.

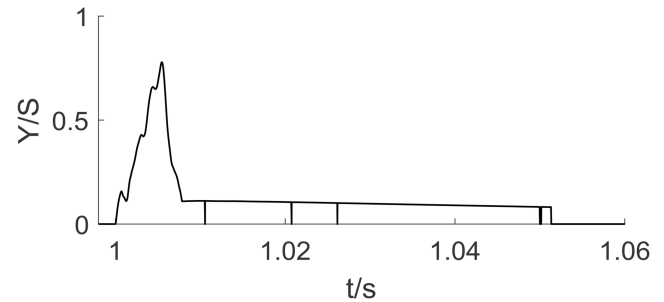


Fig. 5 Curve of arc conductance

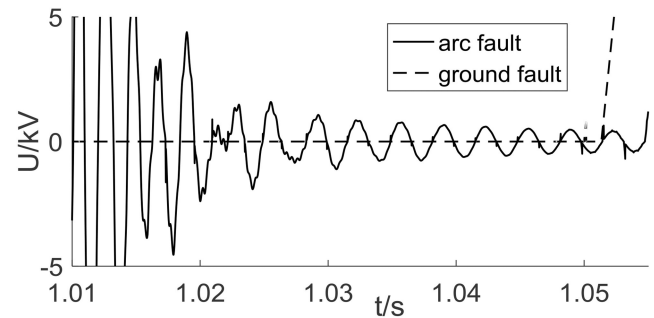


Fig. 6 Curves of arc voltage and re-ignition voltage

Table 2 Main parameters of the AC arc model

Initial arc length, m	Peak current of primary current, kA	Peak current of secondary current, A
10	14	50

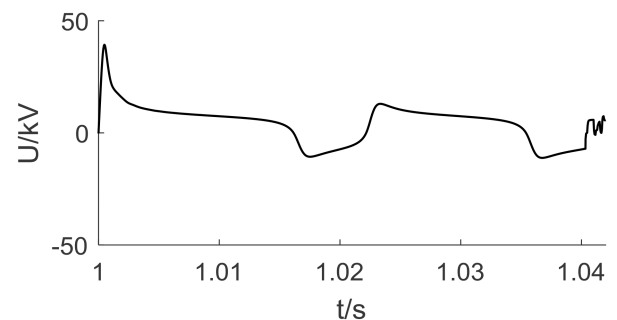


Fig. 7 Curve of voltage at fault point

4 Comparison and analysis of extinguishing process of AC system and VSC-HVDC at the same voltage level

The AC transmission model including the arc model is built for comparison and analysis in PSCAD. The voltage of the AC transmission system is also 500 kV. The model of the transmission lines is frequency-dependent model and length is 250 km. A single-pole arc fault occurred at the distance of 150 km from the left transformer. The main parameters of the arc model are shown in Table 2.

The single-pole fault occurred at 1 s on the transmission lines and the fault arc was generated. At this point, the relay protection device on the line had not yet issued a trip signal and there was no action of the DC circuit breakers. The fault arc at this stage is the primary arc. During the primary arc, the curve of the voltage at the fault point is shown in Fig. 7.

As shown in Fig. 7, the waveform of the AC arc voltage is approximately the square wave during the primary arc. Compared with the DC arc voltage, its waveform has clear changes, so the transient arc fault can be distinguished easily according to the arc voltage in the AC system.

Compared with the flexible DC transmission system, the AC system is more stable and short-term fault will not lead to system

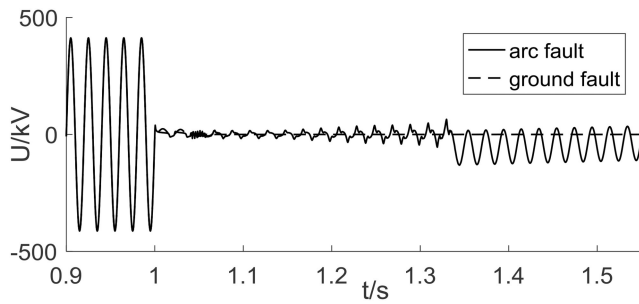


Fig. 8 Curve of voltage at fault point

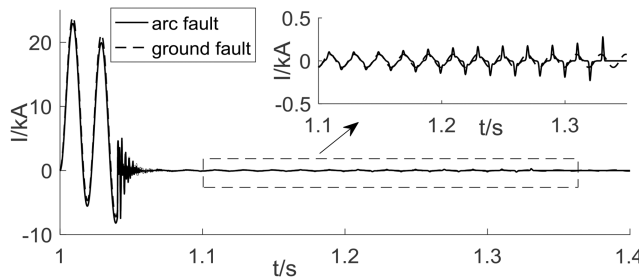


Fig. 9 Curve of current at fault point

crash immediately, so the protection device on the lines has higher redundancy in the time of detecting fault. The time of detecting the fault is set at 1.04 s. Then the relay protection device on the line issued the trip signal and the fault line was disconnected completely. Then the fault arc begins to transform from primary arc to the secondary arc. The dotted line in Fig. 8 is the curve of the voltage at the fault point. In this figure, the fault occurs at 1 s; the relay protection device issues a trip signal at 1.04 s; the time of arc extinction is 1.332 s, i.e. the period of the primary arc is 1–1.04 s and the period of the secondary arc is 1.04–1.332 s.

Compared with the curve of DC arc voltage in Fig. 1, the harmonic component in the AC arc voltage is larger and the waveform distortion is more obvious. The coupling of the AC lines is stronger, so the time of the secondary arc is much longer.

Fig. 9 is the curve of current at fault point, where the solid line is transient arc fault and the dashed line is permanent ground fault. Distortion of the AC arc current during the secondary arc is seriously affected by higher harmonics. Fig. 10 shows the curve of arc conductance at fault point. There will be the phenomena that the arc conductance can drop to 0 and increases immediately. This is because the arc extinguishes at this moment, but the arc voltage is greater than the re-ignition voltage in the next moment. So the phenomenon of re-ignition will occur soon after the extinction of the fault arc. Compared with the DC system in Fig. 6, the coupling of the AC system is stronger and there are multiple extinction and re-ignition during the secondary arc.

Re-ignition of the arc or not is determined by the arc voltage and the re-ignition voltage. Fig. 11 shows the curves of the arc voltage and the re-ignition voltage.

As shown in Fig. 11, after several extinction and re-ignition, the re-ignition voltage begins to increase continuously 1.332 s later. Then the arc voltage is always less than the re-ignition voltage, the arc is extinguished and no longer re-ignited. The arc is extinguished completely.

Comparing the arc characteristics of the flexible DC transmission system with the AC system, it can be seen that the arc current and voltage distortion in DC arc are not obvious. It is difficult to distinguish between transient arc fault and permanent ground fault only by analysing fault arc current and arc voltage. Compared with the AC system, the coupling in DC system is weaker and the frequency of extinction and re-ignition in DC system is less and the extinction of the DC fault arc is easier under the same conditions.

5 Conclusion

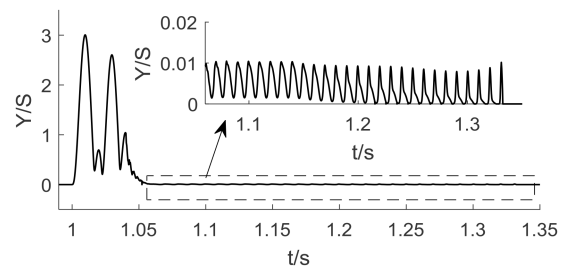


Fig. 10 Curve of arc conductance

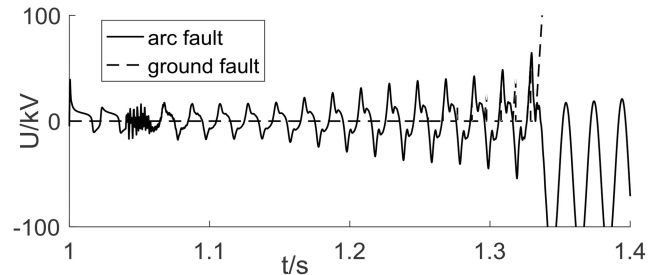


Fig. 11 Curves of arc voltage and re-ignition voltage

The arc model for transient arc fault of HVDC transmission lines is determined in this paper. Then a DC transmission model including this arc model is built in PSCAD. Then it is compared with the arc extinguishing process of AC arc. Some conclusions are as follows:

The arc voltage drops rapidly, but it will not decrease to 0. The arc current will continue to rise in oscillation affected by the energy storage during the primary arc.

There will be the phenomena that the arc conductance can drop to 0 and increase immediately because of the re-ignition of the arc. The arc current and voltage distortion in DC arc are not obvious. It is difficult to distinguish between transient arc fault and permanent ground fault only by analysing arc current and arc voltage. However, the residual voltage of the transient fault lines will gradually increase after the extinction, which can be used to study adaptive reclosing.

The extinction time of the flexible DC transmission system is less than the AC system under the condition of the same voltage level and arc parameters. This is because the coupling between the DC system lines is weaker than the AC system during the secondary arc.

6 Acknowledgments

This work was supported in part by the National Nature Science Foundation of China (NSFC) under grant no. 51677125, and in part by The National Key Research and Development Program (grant no. 2016YFB0900901), and in part by the 2016 Science and Technology Project of China Southern Power Grid under grant no. CSGTRC-K163001.

7 References

- [1] Li, B., He, J.W., Feng, Y.D., *et al.*: 'Key techniques for protection of multi-terminal flexible DC grid', *Autom. Electr. Power Syst.*, 2016, **40**, (21), pp. 2–12
- [2] Li, R., Xu, L., Holliday, D., *et al.*: 'Continuous operation of radial multiterminal HVDC systems under DC fault', *IEEE Trans. Power Deliv.*, 2016, **31**, (1), pp. 351–361
- [3] Lu, W., Ooi, B.T.: 'Multiterminal LVDC system for optimal acquisition of power in wind-farm using induction generators', *IEEE Trans. Power Electr.*, 2002, **17**, (4), pp. 558–563
- [4] Ackermann, T., Andersson, G., Söder, L.: 'Distributed generation: a definition', *Electr. Power Syst. Res.*, 2001, **57**, (3), pp. 195–204
- [5] Liu, J., Tai, N.L., Fan, C.J., *et al.*: 'Comments on fault handling and protection technology for VSC-HVDC transmission line', *Autom. Electr. Power Syst.*, 2015, **39**, (20), pp. 158–167
- [6] Suonan, J.L., Liang, Z.F., Song, G.B.: 'Study of single-phase reclosure with adaptive secondary Arc extinction', *Power Syst. Protect. Control*, 2012, **40**, (5), pp. 37–41
- [7] Li, B., Li, Y.L., Zeng, Z.A., *et al.*: 'Study on single-pole adaptive reclosure based on analysis of voltage harmonic signal', *Power Syst. Technol.*, 2012, **26**, (10), pp. 53–57

- [8] Sun, Z.P., Zheng, Z.C., Yan, R.N., *et al.*: 'Detection method of arc fault in series with wavelet entropy', *Proc. CSEE*, 2010, **30**, (s1), pp. 232–236
- [9] Djurić, M.B., Terzija, V.V.: 'A new approach to the arcing faults detection for fast auto-reclosure in transmission systems', *IEEE Trans. Power Deliv.*, 1995, **10**, (4), pp. 1793–1798
- [10] Hu, M.H., Wang, L.: 'Arc fault modeling and simulation in DC system based on Habedank model'. Prognostics and System Health Management Conf., Chengdu, China, October 2016, pp. 1–4
- [11] Andrea, J., Schweitzer, P., Tisserand, E.: 'A new DC and AC arc fault electrical model'. Electrical Contacts, Charleston, USA, October 2010, pp. 1–6
- [12] Li, J., Thomas, D.W.P., Sumner, M., *et al.*: 'Series Arc fault studies and modeling for a DC distribution system'. Power and Energy Engineering Conf., Kowloon, China, December 2013, pp. 1–6
- [13] Johns, A.T., Aggarwal, R.K., Song, Y.H.: 'Improved techniques for modelling fault arcs an faulted EHV transmission systems', *IEE Proc. Gener. Trans. Distrib.*, 1994, **141**, (2), pp. 148–154