IOP Conf. Series: Earth and Environmental Science **170** (2018) 042083 doi:10.1088/1755-1315/170/4/042083

Rate-of-Current Based Protection for DC Distribution Network

Fanfan Ding[1, a], Dahai Zhang[1], Qiufang Zhang[1], Wanxing Sheng[2], Ming Wu[2] and Zhenhao Song[2]

[1]School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China
[2]China Electric Power Research Institute, Beijing, 100192, China

[a]afanfanding@bjtu.edu.cn

Abstract. When fault occurs in the DC distribution network, the fault current rises rapidly, and it is difficult to develop fast and reliable relay protection. In the paper, by analyzing the response characteristics of each circuit when bipolar fault occurs in the DC distribution line, a fast DC protection scheme based on communication is proposed, which use the contrary change rate of current before and after the fault point during the transient process of capacitor discharge as the protection criterion. Finally, the feasibility of the proposed method is verified by simulation with PSCAD/EMTDC, and it proves the scheme has certain superiority, avoiding problems such as the setting and matching difficulties in conventional current protection methods.

1. Introduction

With the rapid growth of load in the distribution area and wide access of the distributed generations, the traditional AC distribution network is facing a series of problems, such as the increasingly complicated primary system structure, insufficient power supply capacity and complex protection and control strategy [1-2]. By comparison, DC distribution network has more superior performance in aspect of increasing power transmission capacity, improving power supply quality and enhancing the controllability of system [3-4]. Therefore, DC distribution technology has a broader application prospect in the future development of distribution network.

When a fault occurs, the fault current rises rapidly, requiring that the detection, position and isolation of the fault should be finished before the steady state, as a result of which, the protection should have more excellent performance in the rapidity and reliability. At present, mature DC protection researches are mainly focusing on the DC transmission system of medium/high voltage level and special areas, such as power supply system for DC traction and ship [5-7]. For DC transmission system of medium/high voltage level, the types of main protection are travelling wave protection and differential under-voltage protection while the types of backup protection are current differential protection and low voltage protection [8]. Meanwhile, high current release and current mutation protection is widely used in the DC traction system of urban rail to serve as the main protection of fault at near or remote end [9]. In addition, a longitudinal protection principle based on direction changes of current at both ends of the fault line is proposed in the research of Multi-flexible DC transmission [10-11]. As for DC distribution network, the travelling wave head is difficult to capture and the difference of current changes among feeders is not obvious. So the above-mentioned

IOP Conf. Series: Earth and Environmental Science **170** (2018) 042083 doi:10.1088/1755-1315/170/4/042083

protection principle have a poor applicability in DC distribution network. Faster and more effective protection methods need to be developed [12-14].

The outline of this paper is given as follows. Section 1 presents an analysis of the fault response of each circuit during the transient process of capacitor discharge when a bipolar fault occurs at DC line. A new fast DC protection scheme based on communication is proposed in section 2, and is evaluated through simulation analysis in section 3. Finally, the conclusions of the work presented in this paper are drawn in Section 4.

2. Characteristics of DC Short-circuit Currents

A single-line-diagram for an example of Low Voltage DC (DC) distribution system is shown in Fig.1. It includes AC source, voltage source converter (VSC), multiple load branches and distributed generations. Meanwhile, a two-wire power supply mode is adopted and the positive direction of the current is from the bus to the line. Finally, the characteristics of fault current flowing through the location of the protection devices will be illustrated with a fault occurring at F2 point as an example in this section.

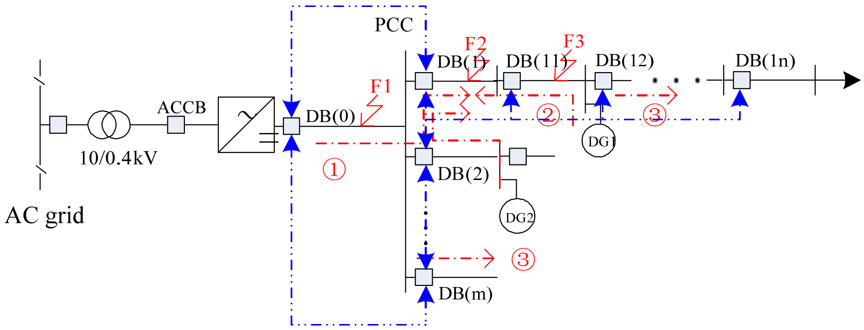

Fig 1. DC distribution network example.

(1)Fault circuit ①

When a bipolar short-circuit fault occurs, the fault current will rise rapidly, and the IGBT will turn off for self-protection when its current is more than twice the rated current. At the same time, the DC-side capacitor C will form the RLC second-order discharge circuit together with the fault line impedance. The fault circuit ① is shown in Fig.2 (a).

The relationship between voltage and current of fault circuit is as follows:

$$V_C = 2ri + 2l\frac{di}{dt}, i = -C\frac{dV_C}{dt} \tag{1}$$

Then,

$$\begin{cases} V_C = \dfrac{V_0\omega_0}{\omega} e^{-\delta t}\sin(\omega t + \beta) - \dfrac{I_0}{\omega C} e^{-\delta t}\sin\omega t \\ i = \dfrac{I_0\omega_0}{\omega} e^{-\delta t}\sin(\omega t - \beta) - \dfrac{V_0}{\omega l} e^{-\delta t}\sin\omega t \end{cases} \tag{2}$$

Where

$$\omega^2 = \frac{1}{lC} - (\frac{r}{2l})^2, \delta = \frac{r}{2l}, \omega_0 = \sqrt{\delta^2 + \omega^2}, \beta = \arctan(\frac{\omega}{\delta})$$

When the DC voltage drops to 0, the transient process of capacitor discharge ends. And during the process, the magnitude of the fault current increases rapidly and the rate ${}^{di}\!/_{dt}$ is greater than 0.

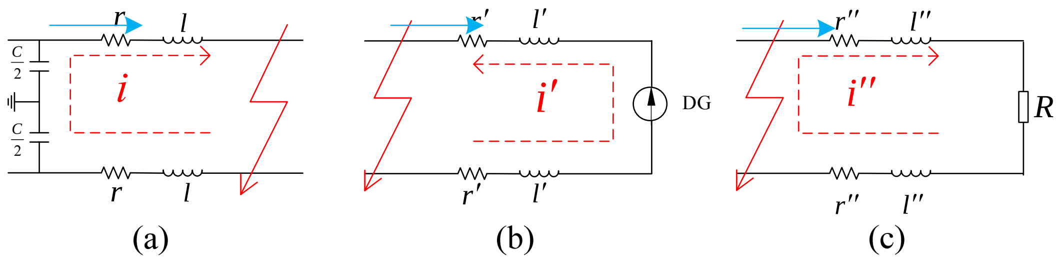

Fig 2. Fault circuits

(2)Fault circuit ②

The equivalent circuit of fault circuit ② is shown in Fig. 2 (b), in which the fault current is provided by DG after the fault point and on other feeders. DG is usually connected to the DC line through the DC / DC converter, with a filter capacitor in the grid side, which forms the RLC second-order discharge circuit with the line between DG and the fault point at the beginning of the fault. The discharge current is similar to in fault circuit ①, and the current rate is less than zero relative to the positive direction specified in this paper.

(3)The remaining circuit ③

The equivalent circuit of the remaining circuit ③after the fault is shown in Fig.2 (c). The remaining circuit forms the RL first-order free-discharge circuit through the fault point, and the response current is as follows:

$$i'' = I_0'' e^{-((2r''+R)/2l'')t} \tag{3}$$

It can be seen that the current rate ${}^{di''}\!/_{dt}$ of the remaining circuit is less than 0 at the initial time. And the current drops to 0 quickly in a very short period of time as a result of that the line reactance parameter of the DC distribution network is small.

According to the above analyses, the characteristics of fault current can be summarized as follows: during the initial transient process of the fault, the amplitude of the fault current between fault point and converter that detected by the protection device in the DC side increases rapidly with a positive change rate; while the fault current amplitude provided by DG after the fault point and on other feeders rises rapidly, the change rate is negative; in contrast to the above two, the amplitude of fault current in other remaining circuits decrease quickly with a negative change rate.

3. Fast Acting DC Protection Scheme

The new protection solution is communication-based fast acting electronic-based dc protection according to the conclusion of Section 1.Corresponding to fault characteristics of different loop given out in Section 1, the typical current waveform is shown in Fig.3.

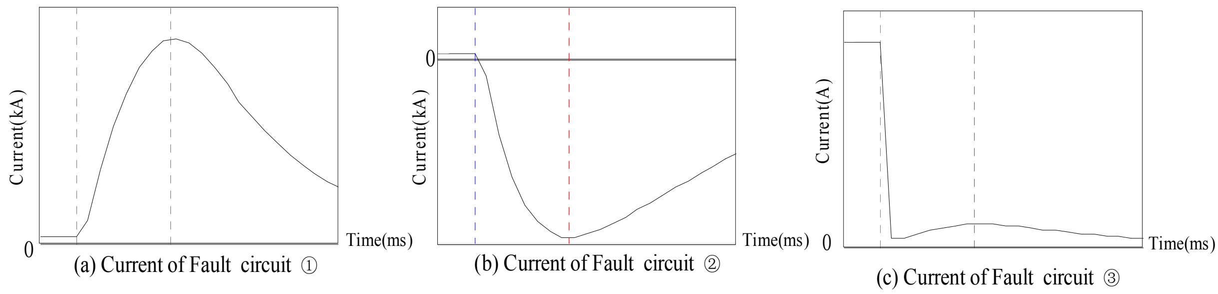

Fig 3. Typical current waveform of various fault circuits

When a bipolar short-circuit fault occurs on DC side, all protection devices will monitor the voltage and current changes immediately. The protection element takes the current amplitude exceeding a certain value as the starting criterion:

$$\left|i\right| \geq i_{set} \tag{4}$$

The IEDs divide the fault indication into 1 and 0 states according to the measured fault current information. When the measured current amplitude is higher than a certain value and the rate-of-current is greater than 0, the IED fault indication state is 1, otherwise 0. By comparing the fault indication status of IED (0) and IED (1-m, It can be identified the fault is located in the bus or a feeder. When the fault is on the feeder, it is judged that the fault is located in a segment of the line by comparing the fault indication status of the IEDs on the feeder. By combining the above information, the fault line can be finally located and a trip instruction will be issued. Algorithm of the developed dc protection scheme is shown in Fig.4.

When fault F1 as shown in Fig.1 is considered, the fault current flowing through IED (0) is provided by DC capacitor discharge in the shape shown in Fig.3 (a), then the fault indication state of IED (0) is 1. The current flowing through the IED (1-2) is provided by the DGs of the feeder like Fig.3 (b), and the current measured by the IED (3-m) is in the form shown in Fig.3 (c), the fault indication states of IED (1-m) are 0. Table 1 shows fault information and its protection action instructions of relays:

Table 1. Fault indication status with fault F1

Feeder	0	1	…	m
Relays	IED(0)	IED(1)	…	IED(m)
Fault indication status	1	0	0	0
Trip signal	+	-	-	-

In the case of fault F2 (see Fig.1), the fault current measured by IED (0) is provided by DC capacitor discharge. Thus the fault indication state of IED (0) is 1.While the fault indication states of IED (2-m) are 0. Then it can be judged that the fault occurred in feeder 1. For the feeder 1, IED (12) measured current provided by the downstream distributed power supply, waveform shown in Fig.3 (b), other IEDs measured current waveform as shown in Fig.3 (c), the fault indication state is 0, the fault is located in the first section of feeder 1. IED (12) measured current provided by the downstream DG, the other IEDs on feeder 1 measured current like Fig.3 (c), the fault indication states of above IEDs are 0, Then It can be identified the fault is located in the first section of feeder 1.

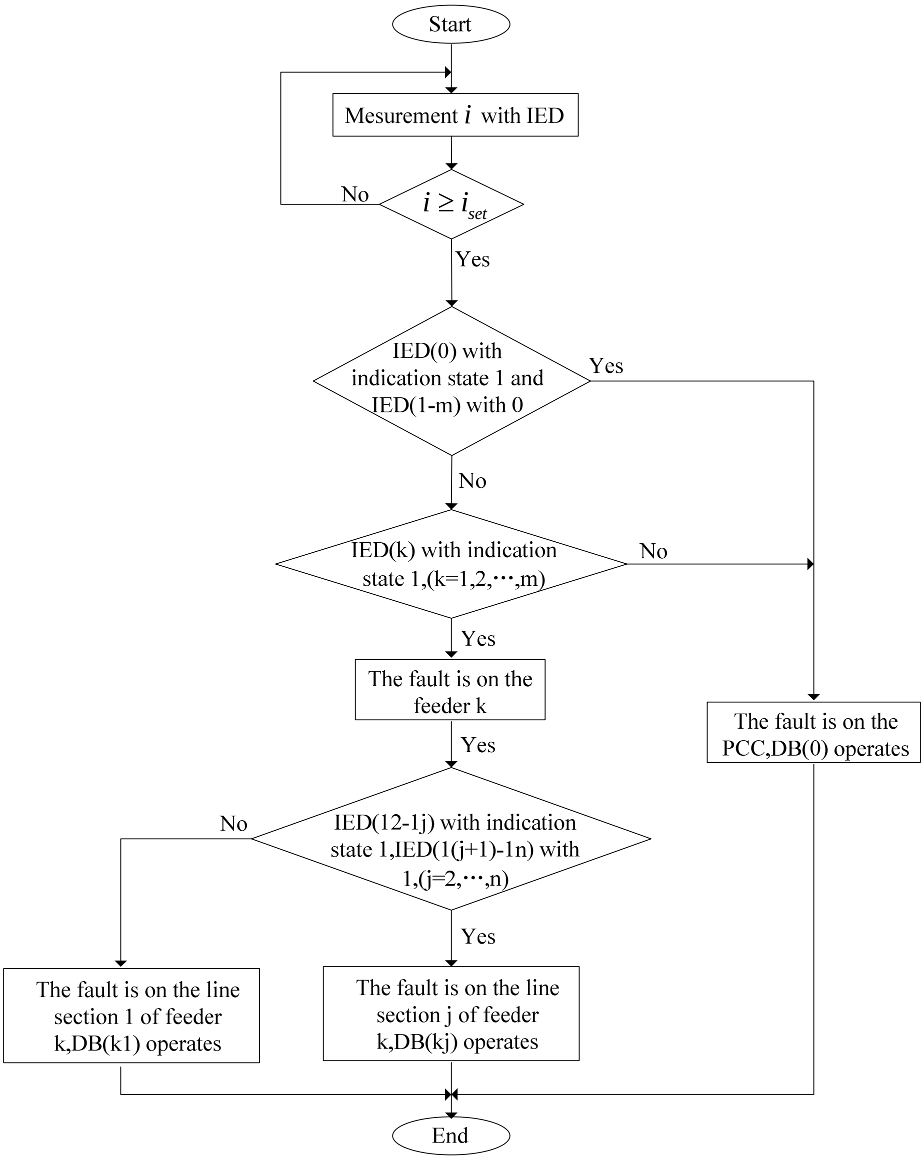

Fig 4. Algorithm of the developed dc protection scheme

Table 2. Fault indication status with fault F2

Feeder	0	1			
Relays	IED(0)	IED(1)	IED(11)	…	IED(1n)
Fault indication status	1	1	0	…	0
Trip signal	-	+	-	…	-
Feeder	2	…	m		
Relays	IED(2)	…	IED(m)		
Fault indication status	0	0	0		
Trip signal	-	-	-		

Similarly, with respect to the downstream fault F3 as shown in Fig.1, we can first determine the fault occurred in the feeder 1. Then, fault indication state of IED (12) is 1 while fault indication states of IED (13-1n) are 0. Then it can be identified that the fault occurs on the line 2 of the feeder 1.

IOP Conf. Series: Earth and Environmental Science **170** (2018) 042083 doi:10.1088/1755-1315/170/4/042083

4. Case Study

The DC test network as shown in Fig.1 is modelled using PSCAD/EMTDC, to verify the feasibility of the proposed principle. The AC line voltage is 380V, and DC voltage is 800V. The capacitor of DC side is 50mF. Resistance and inductance of unit DC line is 0.207 Ω / km and 0.219 mH / km.

The simulation sets three faults as shown in the Fig.1, and extracts the data within 1ms after the fault occurs to carry out the protection principle analysis. As shown in Fig.6, fault F1 creates a very high transient dc fault current, and its peak (about 30 times as normal operating current) is reached within 1ms. During this period, the rate-of-current measured by IED (1) is minus, and the current measured by IED (2) is attenuated to 0 at a very fast speed. According to the protection principle of this article, fault can be identified occurring at PCC and should be disconnected by DB (0).

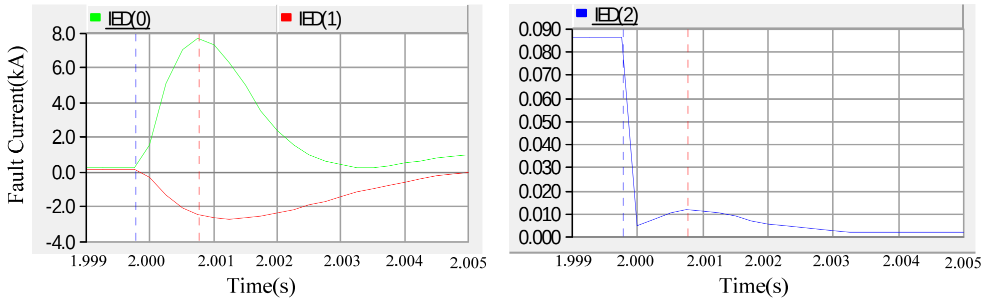

Fig 5. Transient fault characteristics with pole-to-pole dc fault at the PCC

When fault F2 is applied, fault current flowing through IED (0) and IED (1) is rapidly rising to a large value, and the rate-of-current of IED (2), IED (12) and IED (13) is less than 0 (see in Fig.7). The fault should be cleared by DB (1) according to the protection principle of this article. As shown in Fig.8, with respect to the fault 3, the fault current measured by IED (0), IED (1) and IED (12) rapidly rise to a large value, and the rate-of-current of IED (2) and IED (13) are less than 0. Therefore, DB (12) should operate to cut fault.

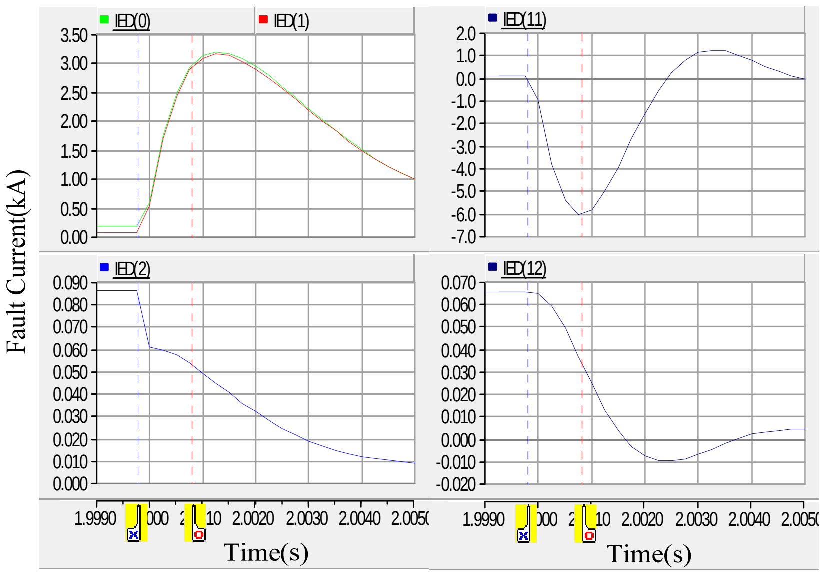

Fig 6. Transient fault characteristics with Pole-to-pole dc fault at F2

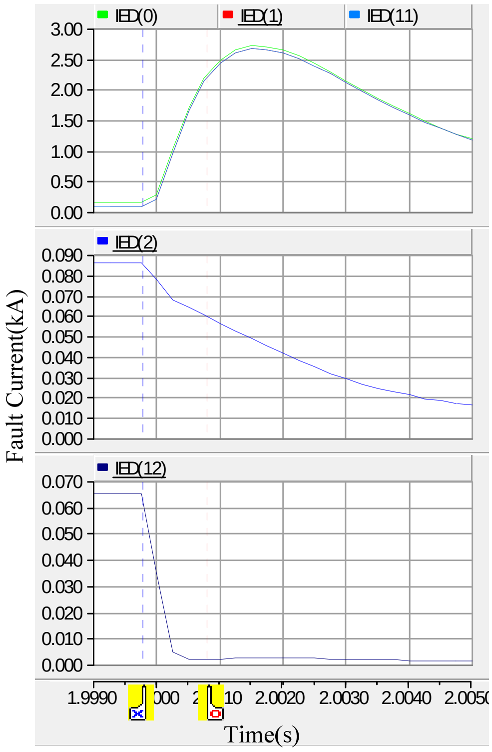

Fig 7. Transient fault characteristics with Pole-to-pole dc fault at F3

From the analysis above, it can be seen that, the protection scheme proposed in this paper can accurately determine the fault line.

5. Conclusion

This paper presents a new protection scheme which provides fast and selective tripping required for DC last mile distribution networks. This method can judge the fault line quickly and accurately by using the current change rate information in the transient process. Test model is constructed, and the results show the proposed protection method is effective and advantageous.

Acknowledgments

The work was supported by the National Key R&D Program of China (2016YFB0900400), the Fundamental Research Funds for the Central Universities (E15RC00040).

References

[1] JIANG Daozhuo, ZHENG Huan, "Research Status and Developing Prospect of DC Distribution Network," Automation of Electric Power System, vol. 36 (8), pp. 98-102, Apr. 2012.

[2] SONG Qiang, ZHAO Biao, LIU Wenhua, ZENG Rong, " An Overview of Research on Smart DC Distribution Power Network," Proceedings of the CSEE, vol. 33 (25), pp. 9-17, Apr. 2013.

[3] HU Jingjing, XU Xidong, QIU Peng, LU Yi, HUANG Xiaoming, "A Review of the Protection Methods in DC Distribution System", Power System Technology, vol.38 (04), pp.844-851. 2014.

[4] ZHENG Huan, "Research on some problems of DC distribution network," ZheJiang University, Apr. 2014.

[5] XUE Shimin, CHEN Chaochao, JIN Yi, SU Jian, WEI Tao, HE Jiali, WANG Ying, "A Research Review of Protection Technology for DC Distribution System," Proceedings of the

CSEE, vol. 34(19), pp. 3114-3119, Apr. 2014.
[6] CHEN Fufeng, WANG Yuting, " Adaptability analysis of single terminal traveling wave protection in mid-voltage DC distribution based on VSC," Power System Protection and Control, vol. 44 (22), pp. 51-54, Apr. 2016.
[7] MENG Fei, "The Research of Feeder Protection of DC Traction Supply System of Subway", East China Jiaotong University. 2012.
[8] LI Bin, HE Jiawei, "DC Fault Analysis and Current Limiting Technique for VSC-based DC Distribution System", Proceeding of the CSEE, VOL. 35 (12), PP.3026-3036. 2015.
[9] Salonen, Pasi, Kaipia, Tero, Nuutinen, Pasi, Peltoniemi, Pasi, Partanen, Jarmo. “An LVDC Distribution System Concept,” Nordic Workshop on Power and Industrial Electronics, June 9-11, 2008.
[10] SHI Bonian, ZHAO Yuming, SUN Gang, "Research and Implementation of Protection Scheme for MMC DC Distribution Network", Southern Power System Technology, vol.9 (09), pp. 11-16. 2015.
[11] SUN Yuanbing, DUAN Jiandong, ZHOU Yi, "Lineprotection scheme for multistage DC power distribution system based on current changing rate," journal of Xi’an University of Technology, vol. 31 (2), pp. 214-219, Apr. 2015.
[12] CHEN Chaochao, "Research of Protection Technology for DC Distribution System," Tianjin University, Apr. 2014.
[13] HE Jinghan, ZHOU Lin, LUO Guomin, LI Rui, " Transient protection based on single-end electrical signals for multi-terminal flexible DC distribution system," Electrical Power Automation Equipment, vol. 37 (8), pp. 158-164, Apr. 2017.
[14] A. A. S. Emhemed and G. M. Burt, "An Advanced Protection Scheme for Enabling an LVDC Last Mile Distribution Network," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2602-2609, Sept. 2014.