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Study on the Operating Performance of HVDC Transmission Line Protection and its Improved Algorithm

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ABSTRACT

Abstract in italiano

Rispetto alla tecnologia AC, la trasmissione in “corrente continua ad alta tensione” (HVDC) presenta una netta superiorità nel trasporto di potenza elevata, su elevate distanze e nella flessibilità della regolazione. Per questo, la trasmissione in HVDC è largamente utilizzata nei collegamenti inter-regionali della rete elettrica, nel trasporto e distribuzione di potenza ad alta capacità e grandi lunghezze.

Con la rapida crescita del sistema HVDC, la probabilità di un guasto in esso aumenta conseguentemente, che danneggia le operazioni dell’intera rete.

Dal momento che i progetti HVDC hanno lunghe linee che scorrono in ambienti complessi, le linee di trasmissione (TL) in HVDC hanno alta probabilità di guasto.

Al momento, la protezione di linee HVDC necessità di analisi teoriche e metodi sistematici. Per questo motivo, la soluzione è spesso offerta dal costruttore, e modificata in corso d’opera. Quindi, uno studio delle protezioni delle TL è altamente significativo e richiesto.

I principali argomenti affrontati in questa tesi sono:

1. La modellizzazione della trasmissione HVDC in PSCAD/EMTDC

Le caratteristiche e i parametri di ogni elemento, come i convertitori, e il loro controllo in HVDC sono inizialmente introdotti e poi modellizzati in PSCAD/EMTDC. Quindi, l’intero sistema HVDC è modellizzato e, grazie alla simulazione, verificato in regime stazionario e transitorio.

2. Studio delle caratteristiche operative delle protezioni delle line in HVDC

In merito alla propagazione delle onde e le modifiche delle caratteristiche di tensione e corrente, l’influenza dei componenti ausiliari, la distanza dal guasto e l’impedenza di guasto sulle caratteristiche della protezione di linea sono analizzate.

Lo studio mostra: l'attenuazione del fronte d'onda a causa dei componenti presenti, il sistema di controllo ha effetto sulla caratteristica transitoria di tensione e corrente; la distanza e l'impedenza del guasto influenza l'ampiezza della quantità elettrica.

3. Studio della soglia e delle prestazioni delle protezioni delle linee HVDC

In merito alla selezione delle soglie di protezione richieste, queste sono ottenute tramite le simulazioni. Sono ipotizzati diversi tipi di guasto sulle TL: le prestazioni del sistema di protezione sono analizzate. Lo studio rivela: l'onda di protezione opera molto velocemente (in 10 ms), ma è molto sensibile alla frequenza di campionamento e lavora correttamente sotto determinati valori di impedenza di guasto; la derivata della protezione opera più lentamente dell'onda di protezione (e opera solo in presenza di stringenti limiti di impedenza di guasto). La protezione longitudinale differenziale agisce con alti valori di impedenza di guasto, ma risulta molto lenta.

4. Onda di protezione migliorata

Con l'obiettivo di migliorare la sensitività dell'onda di protezione, quest'ultima è stata sostituita dall'onda differenziale per assicurare la selezione richiesta. Lo studio rivela che l'algoritmo migliorato ha una maggiore sensibilità.

Abstract in inglese

Compared with AC transmission technology, high voltage direct current (HVDC) transmission technology has superiority in high transmission power, long transmission distance and flexible power adjusting, therefore HVDC transmission technology is widely applied in inter-regional power grid interconnection, high capacity and long distance transmission and distributed power access. With the rapid growth of HVDC system, the fault probability in HVDC system increases gradually, which does damage to the operation of the whole power grid. Since HVDC project has long transmission line which runs under complicated environment, transmission line (TL) has highest probability for fault in HVDC system. For now, HVDC transmission line protection is lack of systematic theoretic analysis and setting method. For this reason, the threshold is usually offered by the manufacturer, and adjusted according to the running state. Therefore, the deep study on the TL protection is highly meaningful and required.

The main works in this paper conclude:

1. The modeling of HVDC transmission system on PSCAD/EMTDC

The characteristics and parameters of each element like converter and its control system in HVDC system are introduced firstly, and then are modeled on PSCAD/EMTDC. In this way, the whole HVDC system is modeled, and by the simulation, the model is verified in steady-state operation and transient-state operation.

2. Study on the operating characteristic of HVDC TL protection

Concerning the propagating characteristic of travelling wave and the changing characteristic of voltage and current after line fault, the influence of boundary equipment, fault distance and fault impedance on operating characteristic of TL protection is studied. The study shows: the step wave front is attenuated by border device; control system has effect on the transient characteristic of voltage and current; fault impedance and distance only affects the amplitude of electric quantity.

3. Study on the threshold and operating performance of HVDC TL protection

According to the selection request of protection, the thresholds are computed from the simulation results. By simulation of different TL fault types, the operating performances of line protections are analyzed. The study shows: travelling wave protection can operate very fast within 10ms, but it has very high request on sampling frequency and it can only operate correctly under limited fault impedance; derivative and level protection operates slower than travelling wave protection, and it can also only operate under limited fault impedance; longitudinal differential protection can operate under high fault impedance, but it operates very slowly.

4. Improved travelling wave protection

In order to improve the sensitivity of travelling wave protection, the travelling wave is substituted by the differential mode wave to assure the selection request. The study shows: the improved algorithm has higher sensitivity.

1 INTRODUCTION

1.1 The study background and significance

Compared to the AC transmission technique, HVDC transmission technique has better performance in large-capacity and long-distance power transferring, interconnection between large grid and economic operation. Therefore, HVDC transmission technique is developed very rapidly and applied largely in inter-region connection and large-capacity and long-distance transmission[1-4]. Because of the long distance of DC line and the complicated environment it bears, DC transmission line is the element that has the highest probability for fault in HVDC system. So DC line protection is very important for the stable operation of the whole HVDC system[5]. For HVDC transmission system, overhead line is usually used, since it is convenient to maintain and economical. While for cable, it has larger capacitance compared to overhead line.

Unlike to AC transmission line protection, because the DC line voltage and current are under effect of control system, which is very difficult to present, so there is no systematic theory about DC line protection. Most of the DC transmission line protection device are from ABB and SIEMENS Company, and out of secrecy, the design principle and the setting principle of threshold are unknown to users, which is difficult for operation personnel to do daily maintenance, upgrading and localization[6,7].

Therefore, in order to improve the stable operation of HVDC system, the deep research on function of HVDC transmission line protection criterion, setting principle of threshold, the affecting factors on protection and the performance of DC line protection are very significant.

1.2 The study status

Currently, HVDC transmission line protection schema is mostly provided by ABB or SIEMENS Company. HVDC transmission line protection schema of ABB and SIEMENS Company is configured with travelling wave protection as main protection, derivative and level protection and DC line longitudinal differential protection as background protection. The research status of HVDC transmission line protection will be introduced in this part.

1.2.1 Travelling wave protection

During the time of fault on DC transmission line, travelling wave will be produced at fault point to propagate along DC transmission line, and reflects between boundary equipment, which are smoothing reactor and DC filter. This travelling wave is high-frequency signal, which concludes extensive transient information. Therefore, travelling wave protection makes use of the transient information of this travelling wave in the beginning of fault to detect fault. Nowadays, both ABB and SIEMENS company configure travelling wave protection, but they have some difference: travelling wave protection of ABB company uses pole wave to detect fault and common mode wave to discriminate the fault pole; SIEMENS company uses the derivative of voltage as protection starting criterion, and by integrating the derivative of voltage in 10ms to detect fault, while the discrimination of pole wave is achieved by the derivative of current. Although both travelling wave protection can trip speedy, but the fault impedance they can detect is limited. Moreover, travelling wave protection has some problem: high requirement on sampling frequency, no reasonable setting method and strict theoretical support[8].

As to the problem of travelling wave protection, large of research are done to the improved travelling wave protection. Currently, the research can be classified into two aspects: one is using signal processing techniques such as wavelet transform and mathematical morphology filtering technique to filter and process transient signal; the other one is getting reference from border protection of AC transmission line to create transient border protection for DC transmission line.

In order to improve sensitivity and fault impedance travelling wave protection can detect, paper [9-12] takes advantage of modulus maximum of wavelet transform to detect singularity of signal, i.e. travelling wave directional protection based on wavelet transform, which relies on the communication channel. In order to improve the stability, and decrease rely on communication channel, paper [12] makes use of the location and time of mutation to create travelling wave distance protection based on wavelet transform. Paper [13, 14] applies morphological filtering technique and morphological gradient on filtering of transient travelling wave and capture of wave front to improve anti-interference ability. To improve the stability and speed of travelling wave, modulus maximum of wavelet transform is used in paper [15] to detect fault on DC transmission line rapidly. Paper [16] make uses of the ratio of common mode and differential mode to create novel travelling wave protection based on polarity comparison, which can be almost not affected by fault impedance. In order to improve the speed and anti-interference ability of travelling wave protection, paper [17] create criterion based on the difference characteristic of the ratio between high frequency and low frequency of transient voltage wave under different transient condition as fault inside and outside if DC transmission line protection zone and lighting.

Reference to the transient border protection principle of AC transmission line protection, by making use of the border composed of DC filter and smoothing reactor in HVDC system, transient border protection of HVDC transmission line is generated. In order to improve the fault impedance travelling wave protection can detect, paper [18] makes use of high frequency component and low frequency component of transients to detect fault. Paper [19, 20] uses the attenuation effect of boundary equipment on high frequency component, to create novel protection principle to improve fault impedance protection can detect, which uses high frequency component sum to discriminate fault inside or outside DC transmission line protection zone. Paper [21] uses the different influence of boundary equipment on specific band impedance characteristic and specific band current, to create HVDC transmission line speed protection based on the single-ended current.

Based on the superiority of wavelet transform and border principle, the combination of wavelet transform and border principle is applied to create novel protection principle, such as in paper [22]. In order to improve the fault impedance protection can detect, paper [23] proposes the transient harmonic current protection based on the analysis of boundary condition. Based on the boundary characteristic of HVDC transmission line, paper [24] uses the modulus maximum of transient voltage wave front to create starting criterion, and uses the energy ratio of high frequency and low frequency to create action criterion.

As mentioned before, wavelet transform offers a novel technique for travelling wave protection, so novel protection principle based on wavelet transform get large research in recent years. But as wavelet transform has high requirement on sampling frequency and sampling data window, and generation of band signal on high scale relies on the low frequency band signal of previous layer, which decreases the speed and implement of travelling wave protection[25]. Morphological filtering technique has been applied in travelling wave protection principle, but since morphological has no dividing frequency characteristic, so dividing frequency process on signal cannot be implemented. In overall, both these two novel principle have too high requirement on sampling frequency, which makes them difficult to be applied on practical HVDC transmission system.

1.2.2 Derivative and level protection

Derivative and level protection relies on the derivative of voltage and voltage level to implement protection. Currently, ABB and SIEMENS Company have slight difference on the protection principle: derivative and level protection of SIEMNS company uses the voltage derivative and voltage level to achieve protection; except to criterion voltage derivative and voltage level, ABB company measures current to discriminate fault. As the rising delay of voltage derivative is 20ms (for travelling wave 6ms), so when travelling wave protection out of operation, derivative and level protection can operate as backup protection, but for the fault with high fault impedance, it also cannot operate accurately[26].

1.2.3 DC line longitudinal differential protection

DC line longitudinal differential protection uses the sum of DC current in rectifier and inverter side as criterion. Theoretically, similar to AC transmission line, since longitudinal differential protection makes use of the sum of current, from principle point of view, the selectivity can be achieved. But since HVDC transmission line has larger capacitor, which has larger current flowing through under transient operation. So, if only using the simple sum of DC current, not considering the current on capacitor, the longitudinal differential protection would dis-operate under transient condition. Therefore, in order to avoid such dis-operation, criterion is designed only to be active after transients. Moreover, longitudinal differential protection is designed for fault with high fault impedance as the backup protection for HVDC transmission line.

Because of the long delay of longitudinal differential protection, HVDC transmission system is easy to be blocked. For the design, SIEMENS Company uses “synchronous transmission fault delay” function: because of the large fluctuation in the beginning of fault, longitudinal differential protection has to been active after 600ms delay, and considering the delay of differential criterion, protection can trip at least after 110ms. In this period, fault pole is blocked due to the operation of pole control low voltage protection and the maximum firing angle protection, so longitudinal differential protection is not effective for fault with high impedance [27, 28].

In order to improve the performance of current longitudinal differential protection, many researchers have done much work on the improvement. Paper [29] tries to improve the sensitivity of longitudinal differential protection by capacitor current compensation. Due to the different polarity of DC current mutation for fault inside and outside DC transmission line, paper [30] uses directional component to create current pilot protection. Paper [31] proposes a novel protection principle based on the analysis of transient energy: fault detection and fault pole discrimination are implemented according to the transient characteristic of low frequency energy difference in the transient process. As to the long delay of longitudinal differential protection, paper [32] proposes suggestion as: eliminate the 600ms delay for current fluctuation; optimize the time coordination of DC line low voltage protection, pole control low voltage protection and the maximum firing angle protection. Paper [33] proposes capacitor compensation method based on distributed model, so longitudinal differential protection can be applied in the whole transient process, and protection can trip speedy. Paper [34] proposes DC line current pilot protection based on the mutation characteristic of DC current, which has no requirement on strict synchronous data and high communication speed.

Although large research have been done on the capacitor current and current mutation to create novel longitudinal differential protection, differential current is largely affected by control system, and protection relies on communication channel and strict synchronous data. Therefore, novel longitudinal differential protection is difficult to be applied on practical HVDC project.

1.3 The main contents of the paper

Because of the technique limit, novel HVDC transmission line protection has not been applied in practical HVDC project, so this paper will still do study on the current HVDC transmission line protection in practical HVDC project. In order to offer theoretic support for practical operation of HVDC transmission system, this paper mainly does research on the function of criterion, the setting principle of threshold, the affecting factors on protection and the performance of DC line protection, which include:

1) The modeling of HVDC transmission system on PSCAD/EMTDC

The characteristics and parameters of each elements like converter and its control system in HVDC system are introduced firstly, then HVDC transmission system are modeled on PSCAD/EMTDC, and by the simulation, the model is verified both in steady state and transient state.

2) The Operating characteristic of DC line protection

The principle, algorithm and setting principle of threshold are introduced and analyzed firstly. Then by simulation, the impact mechanism of affecting factors like sampling frequency, boundary elements, fault distance and fault impedance on DC line is researched.

3) The performance of DC line protection

According to the setting principle of thresholds, the threshold is gained by simulation and calculation. Then by simulation and calculation, the operating characteristic like sensitivity and speed of each DC line protection are analyzed and concluded. Meanwhile, by setting various DC line fault and fault outside the protection zone, the whole DC line protection performance is analyzed and concluded.

4) Improved travelling wave protection

In order to improve the sensitivity of travelling wave protection, the travelling wave is substituted by the differential mode wave to form the criterion for assuring the selection request.

2 MODELING OF HVDC SYSTEM BASED ON THE PSCAD/EMTDC SOFTWARE

2.1 About PSCAD/EMTDC

PSCAD stands for "Power System Computer Aided Design". It is software for modeling power systems with variable complexity and size, and simulating voltage and current transients in a graphical interface. PSCAD is the user interface. This program is based on the work in Electromagnetic Transient Programming by Hermann Dommel and Scott Meyer. Changes to the system, such as applying fault or changing certain input parameters to the control system can be done while the simulations are being run. Currents and voltages can be plotted as they are being calculated.

PSCAD was chosen for this work primarily because it has a very advanced cable model which takes into account the frequency dependency of cable parameters and offers DC correction. This makes it very suitable for modeling fault transients in an HVDC system. It also has an interpolate function for handling switching actions in the system (switching action are for example connecting/disconnecting breakers or turning IGBTs on and off).

2.2 Model of HVDC transmission system

2.2.1 Construction of HVDC transmission system

HVDC transmission system can be classified into two kinds according to the number of terminals: single-pole HVDC transmission system and double-pole HVDC transmission system. In this paper, the research is based on the double-pole HVDC system, which can be divided into three parts: AC power sources, converter stations and DC transmission line as shown in Figure 2-1. When the power flows from converter1 to converter 2, converter1 is the rectifier and converter2 is the inverter; on the contrary, converter1 is the inverter and converter2 is the rectifier. The converter station usually concludes converter, AC filter, transformer, reactor and DC filter.

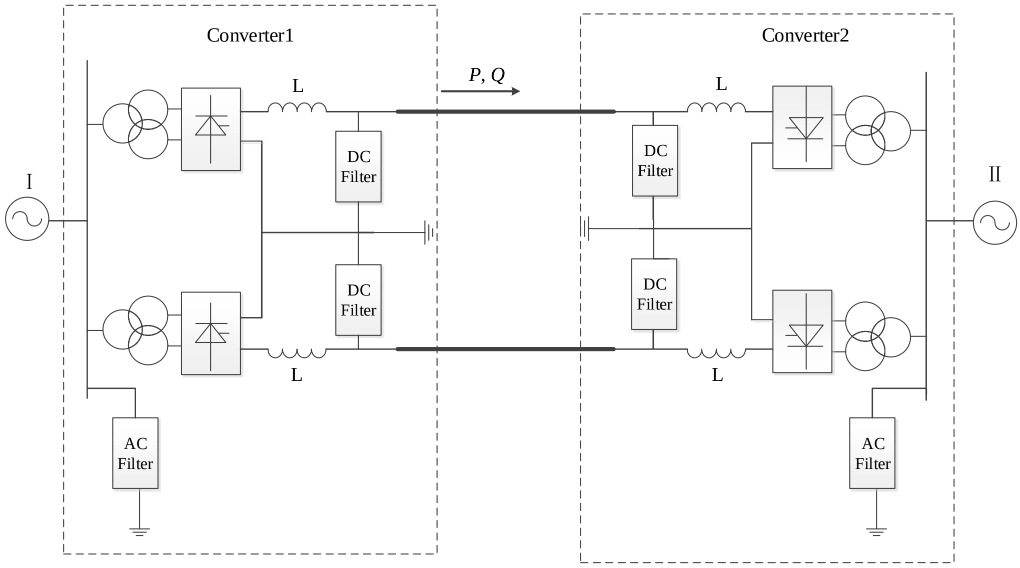


Figure 2-1 the construction of HVDC transmission system

2.2.2 Model of HVDC transmission system on PSCAD/EMTDC

In this paper, the model is based on a practical HVDC transmission project. The transmission power is 3000MW, the rated DC voltage and current are ±500kV and 3000A corresponding, the DC transmission line length is 1000km.

2.2.2.1 12-pulses converter

One 12 pulses converter is composed by the series connection of two 6 pulses converters. The two 6 pulses converters are parallel connected, and in the AC side, they are connected by triangle connection and star connection to AC source corresponding, as shown in Figure 2-2, which is the construction of 12 pulses converter.

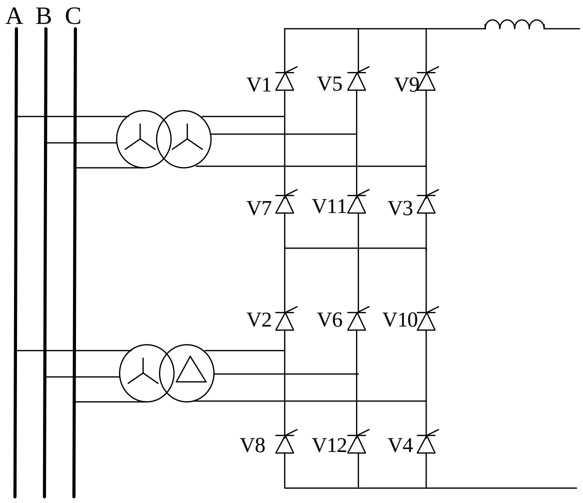


Figure 2-2 the construction of 12 pulses converter

Figure 2-3 shows the IGBT part, which is integrated with 6-phase Graetz Converter Bridge (can be inverter and rectifier), an internal phase locked oscillator, firing and valve blocking controls and firing angle extinction angle measurements.

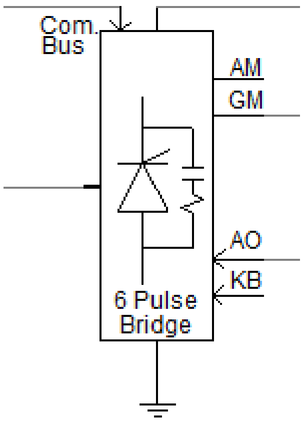


Figure 2-3 the module of 6 pulses converter

The input and output ports are:

AO: input alpha order for the converter;

KB: input block/deblock control signal;

AM: measured alpha (firing angle) output;

GM: measured gamma (extinction angle) output.

2.2.2.2 Control system

The control system of converter in HVDC transmission system uses hierarchy structure, which has six layers according to the level of function: system control layer, converter station control layer, bipolar control layer, polar control layer, converter control layer and converter valve control layer, as shown in Figure 2-4. System control layer is the highest control level, whose function are receiving the control command from dispatching center, senting running information to communication center and giving control command to converter station control layer. Converter station control is the control level responsible for the data sampling, data communication and coordination of two converters. Bipolar control layer aims to coordinate the operation of positive and negative poles. The pole control layer is to calculate the rated current value according to the command from bipolar control layer, and set current command to converter control. Converter control is responsible for receiving command from pole converter, and sent firing pulse command to converter valve by the calculation and process of regulators. Converter valve control is the lowest level, which is designed to receive firing pulse command from converter control layer and convert it to firing pulse signal for thyristor.

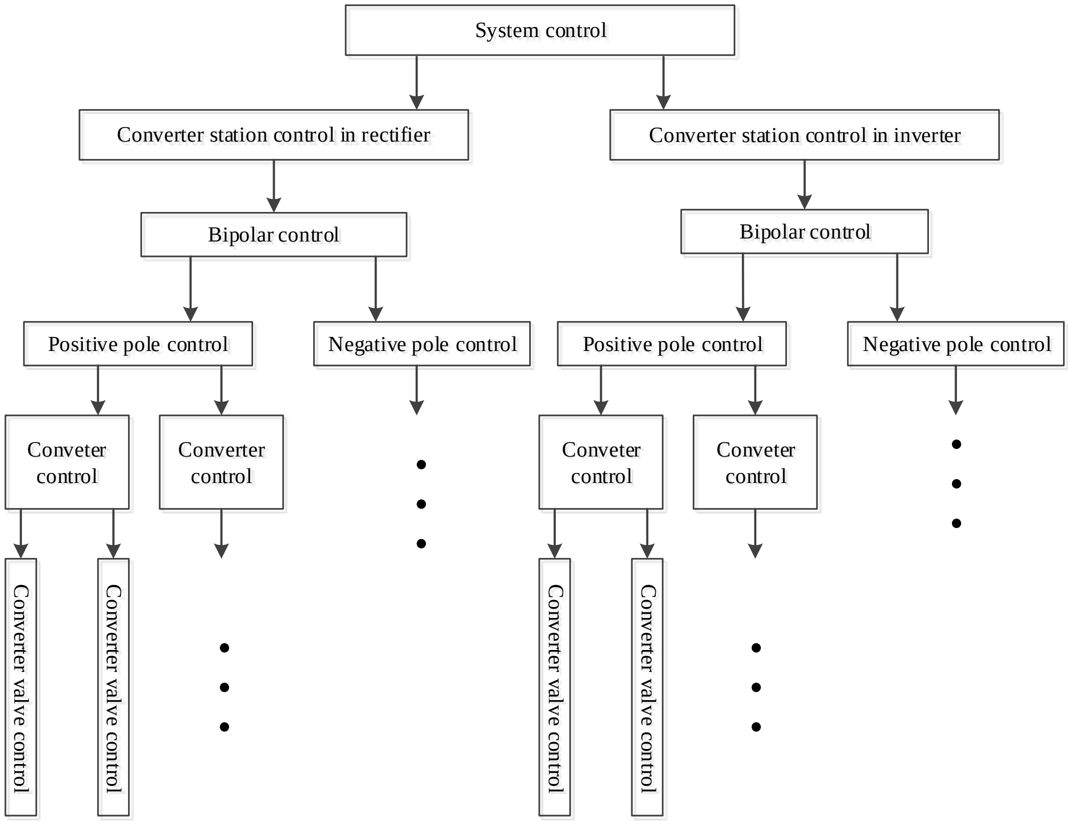


Figure 2-4 the layered construction of converter control system

Figure 2-5 shows the control characteristic of HVDC system, line A-B-C-D-E is the control characteristic of rectifier, and the line F-G-H-I-J is the control characteristic of inverter. Under steady-state operation, the inverter is assigned with the task of controlling the DC voltage, which may be done by maintaining a constant extinction angle γ which causes the DC voltage to drop with increasing DC current as shown in the minimum constant extinction angle γ characteristic F-N-G in Figure 2-5. If the inverter is operating in a minimum constant extinction angle γ characteristic, the rectifier must control the DC current, which can be done so long as the delay firing angle α is not at its minimum limit (usually 5°). The steady state constant current characteristic of the rectifier is shown in Figure 2-5 as the vertical section B-N-C. Where the rectifier and inverter characteristic intersect, as point N, is the normal operating point of the HVDC system. When the direct voltage decreases and causes the direct current under a certain value, the inverter will transfer to constant current control characteristic G-H. In case of the constant current control of rectifier and inverter operating simultaneously and causing the instability, the setting value of rectifier modifier is set 0.1 p.u. lower than that of rectifier, which is the current margin. During disturbances where the AC voltage at the rectifier or inverter is depressed, it will not be helpful to weaken AC system if the HVDC transmission system attempts to maintain full load current. A sag in AC voltage at either end will result in a lowed DC voltage too. The DC control characteristics shown in figure 2-5 indicates the DC current order is reduced if the DC voltage is lowed. This can be observed in the rectifier characteristic C-D-E and in the inverter characteristic H-I-J. The controller which reduces the maximum current order is known as a voltage dependent current order limit or VDCOL. The VDCOL control, if invoked by an AC system disturbance will keep the DC current to the lowered limit during recovery which aids the corresponding recovery of the DC system. Only when DC voltage has recovered sufficiently will the DC current return to the original rated level.

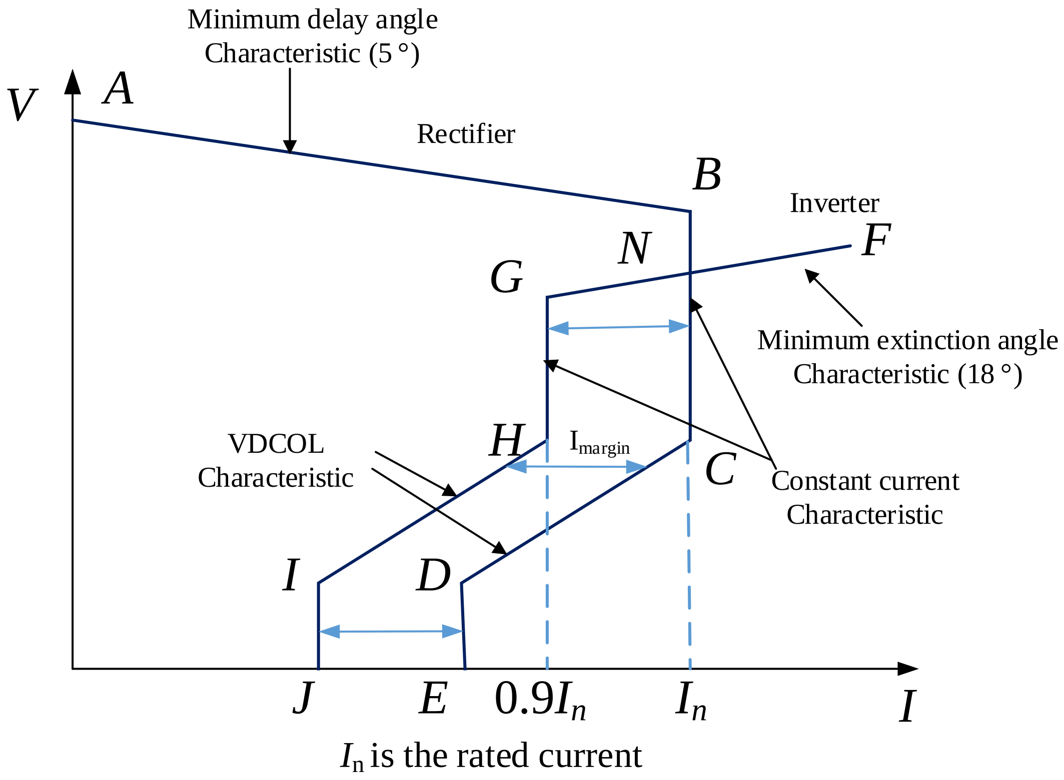
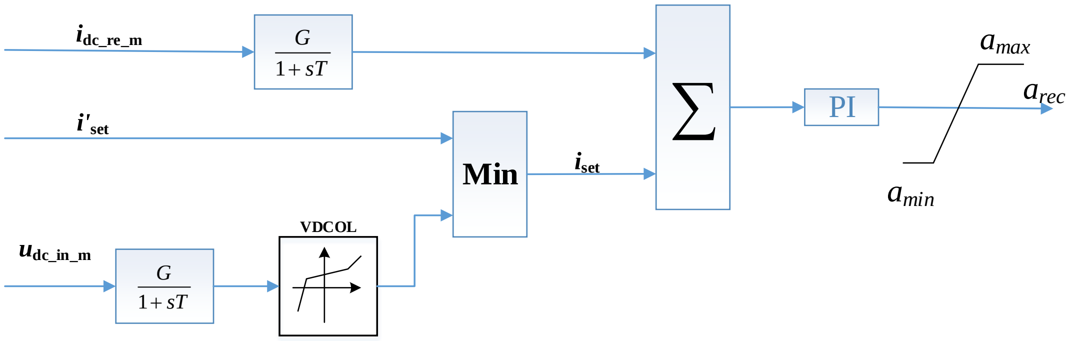
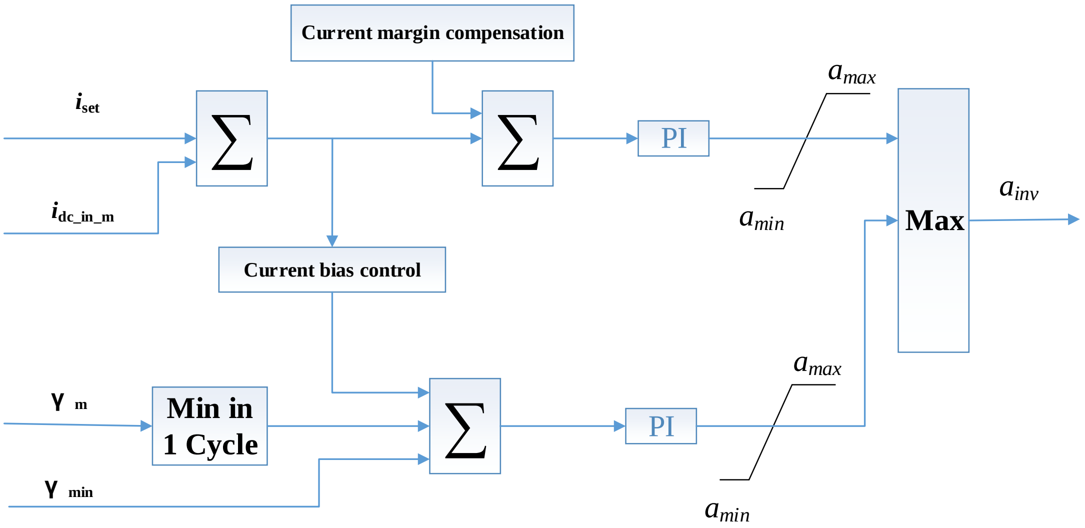


Figure 2-5 the control characteristic of HVDC system

Figure 2-6 shows the schematic diagram of how HVDC transmission system controls are usually implemented. Figure 2-6(a) and (b) show the converter control in rectifier and inverter corresponding. In rectifier, the control mode is constant current control, which is implemented as: firstly the rated current value i_{set} is gained from the comparison of the rated value i'_{set}, which is from the command of pole control layer, and the output of VDCOL with the measured DC voltage in the inverter side $u_{dc\_in\_m}$ as input; then the difference between measured DC current in rectifier side $i_{dc\_re\_m}$ and i_{set} goes into PI control to get the firing angle signal α_{rec} for valve in rectifier. In inverter, the control mode is constant current control or minimum extinction angle control: the AOI(the firing current order for inverter) α_{inv} is generated by the comparison of the output of constant current control and minimum extinction control; the constant current control is implemented by decreasing the difference between measured current in inverter side $i_{dc\_in\_m}$ and the rated current i_{set} through PI control; the minimum extinction angle control is implemented by decreasing the difference between the measured extinction angle γ_m and the minimum extinction angle γ_{min} through PI control.



(a) The converter control in the rectifier



(b) The converter control in the inverter

Figure 2-6 the schematic diagram of HVDC transmission converter control system

2.2.2.3 Converter transformer

Converter transformer is one of the most important instruments for AC-DC transformation. In this paper, the model uses two sets of three phase double-winding converter transformer with one star connection and one delta connection in valve side to the converter. So for the two 6-pulses converters, it can has two AC voltages which have 30° angle difference, which makes the two 6-pulses converters become a 12-pulses converter. Table 2-1 shows the parameters of the transformer.

Table 2-1 the parameters of the transformer

	Transformer in rectifier side		Transformer in inverter side	
Type	Y_N/Δ	Y_N/Y	Y_N/Δ	Y_N/Y
Rated power (MVA)	892.5	892.5	851.1	851.1
Line to line voltage (kV)	$\frac{525}{\sqrt{3}*210.4}$	$\frac{525}{\sqrt{3}*210.4*\sqrt{3}}$	$\frac{525}{\sqrt{3}*200.6}$	$\frac{525}{\sqrt{3}*200.6*\sqrt{3}}$
Short-circuit impedance (%)	16	16	16	16

2.2.2.4 AC and DC filter

For AC system, the converter is similar to a harmonic current source; for DC system, the converter is similar to a harmonic voltage source. The harmonics are not good for the stability of power system. The number of harmonic is related to the number of pulses: the number of harmonic into AC system is $p \times k \pm 1$ (k is any natural number); the number of harmonic into DC system is $p \times k$. In this way, for this model, the number of harmonics into AC system is 11 and 13, and the number of harmonics into DC system is 12, 24 and 36. In case that the harmonics have influence on the stable operation of AC and DC system, the AC filters and DC filters are necessary to be installed on the AC and DC bus. Moreover, because the operation of HVDC system needs large number of reactive power to be consumed, reactive power compensators are also needed.

2.2.2.4.1 AC filter

In this paper, three sets of reactive AC filters in rectifier side are parallel connected to the AC bus as shown in figure 2-7(a): 11/13 double-tuned filter, 24/36 double-tuned filter, HP3 filter to filter 3th harmonic and capacitor to offer reactive power. Table2-2 shows the parameters of AC filters at rectifier side. Filters at rectifier side can offer 1371MVar reactive power in total, which is 45.7% of rated power.

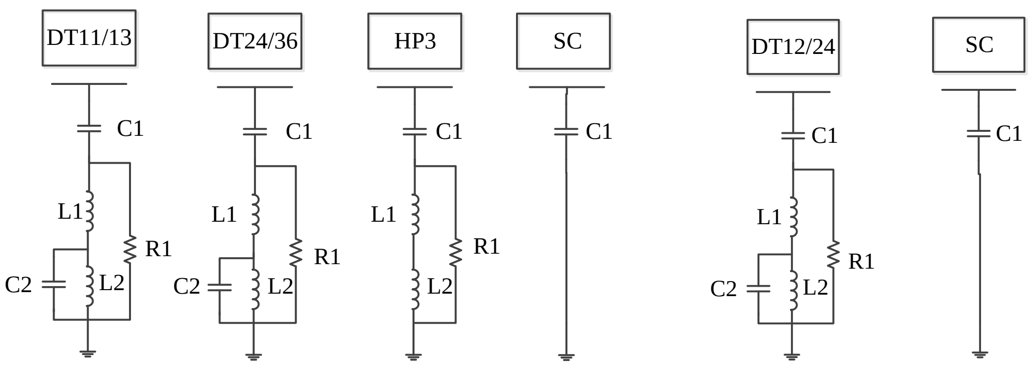
The AC system at inverter side is designed with two kinds of AC filters: five sets of 12/24 double-tuned filters and four sets of reactive power capacitors as shown in figure 2-7(b). Table 2-3 shows the parameters, in which the total reactive power offered by AC filters is 1890MVar, which is 63% of rated power.

Table 2-2 the parameters of AC filters at rectifier side

Filter type	DT11/13	DT24/36	HP3	SC
number	3	3	2	1
Reacitive power（MVar）	145.4	145.4	166.2	166.2
R1(Ω)	2000	500	1800	——
L1（mH）	43.82	7.25	685.4	——
C1(μF)	1.167	1.167	1.848	1.848
L2（mH）	1.226	1.209	14.782	——
C2(μF)	57.8	9.701	14.782	——

Table 2-3 the parameters of AC filters at inverter side

Filter type	DT12/24	SC
number	5	4
Reacive power（MVar）	210	210
R1(Ω)	290	——
L1（mH）	13.62	——
C1(μF)	2.659	2.674
L2（mH）	7.407	——
C2(μF)	4.886	——



(a) AC filter at rectifier side (b) AC filter at inverter side

Figure 2-7 the schematic figure of AC filter

2.2.2.4.2 DC filter

During the operation of HVDC transmission system, 12th, 24th and 36th harmonics are produced in DC system, which has bad influence on the stable operation of DC system, even damage the DC equipment, so DC filter is significant. Compared with AC filter, DC filter only can filter harmonics, but cannot offer reactive power as compensator. In this paper, DC filter is designed with one 6/12 double-tuned filter and one 24/36 double-tuned filter as shown in Figure 2-8. The parameters of DC filter are shown in Table 2-4.

Table 2-4 the parameters of DC filter

Filter type	DT6/12	DT24/36
number	1	1
L1（mH）	127.931	5.099
C1(μF)	0.7	3.2
L2（mH）	58.744	0.208
C2(μF)	3.764	40.627

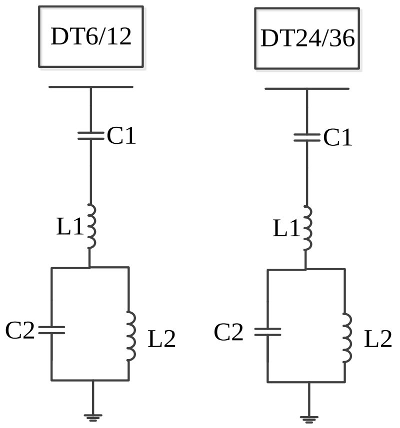


Figure 2-8 the schematic figure of DC filter

2.2.2.5 The model of HVDC transmission system on PSCAD/EMTDC

The model is based on a practical HVDC transmission project, which has bipolar transmission line modeled by frequency dependent model, smoothing reactor as 290mH, and one Y/Y and one Y/Δ transformer. Because the main concern is the HVDC system, the AC system is simplified as AC power with RRL(R stands for positive sequence series resistance and parallel resistance, L stands for parallel inductance). Figure 2-9 shows the model of HVDC transmission system on PSCAD/EMTDC.

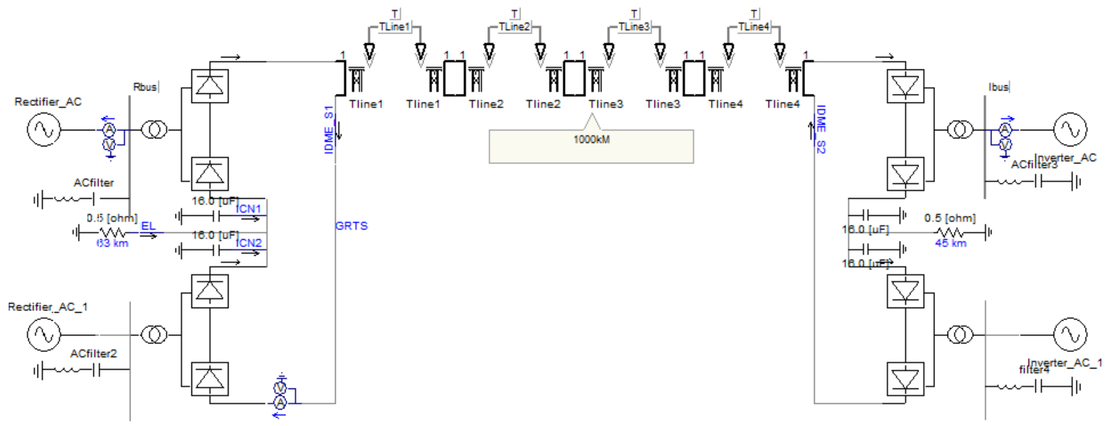


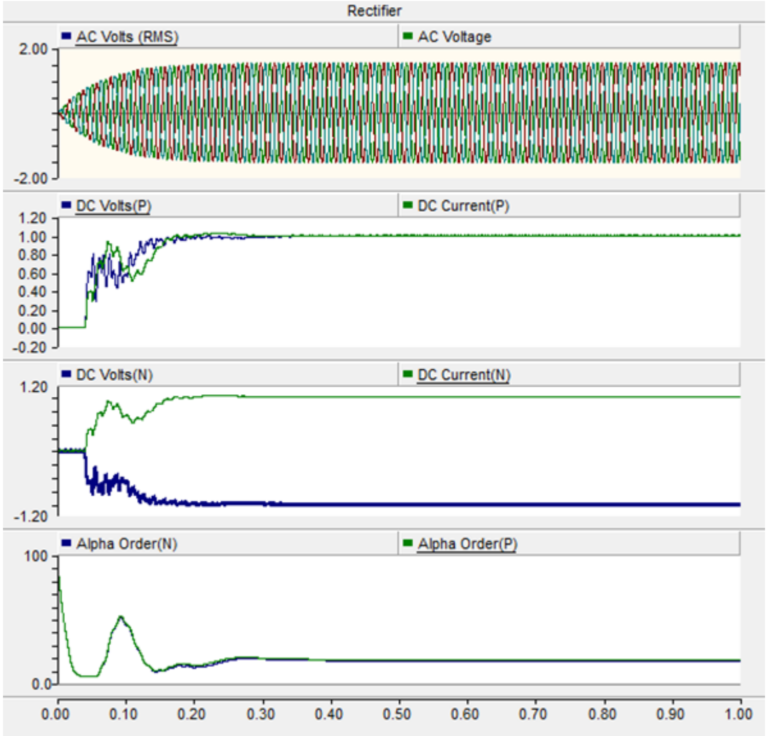
Figure 2-9 the model of HVDC transmission system on PSCAD/EMTDC

2.3 The analysis of fault characteristic and model verification of HVDC system model

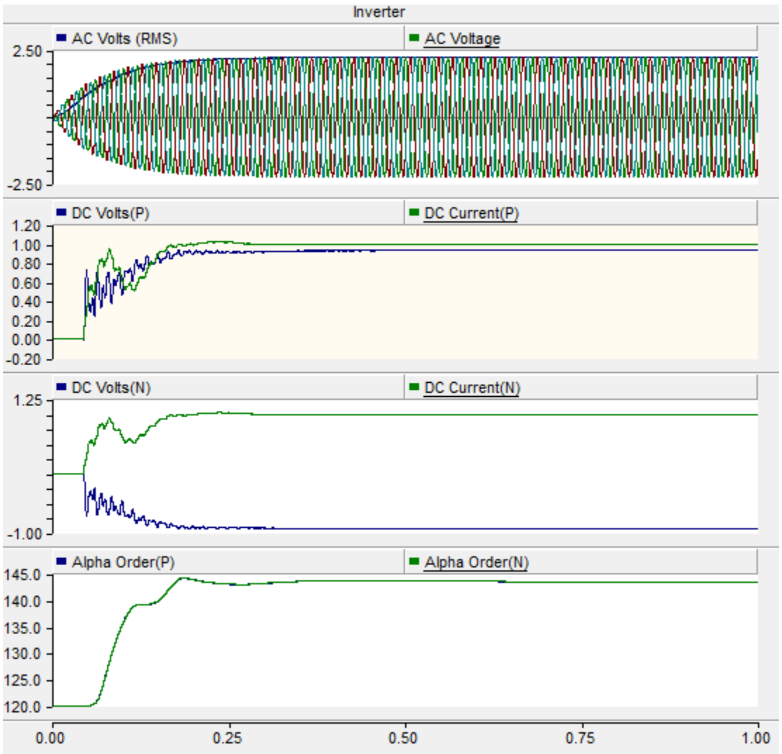
The model is verified from steady-state operation and transient-state operation. Based on the transient-state operation, the fault characteristic is analyzed.

2.3.1 Steady-state operation

Figure 2-10(a) and (b) shows the simulation result of HVDC under steady-state operation for rectifier and inverter. The curves from up to down are AC voltage, direct voltage and current of positive pole, direct voltage and current of negative pole, and firing angle of converter. From the simulation result, under steady-state operation, the three-phase AC voltages are stable with 120º phase angle difference. The direct voltage of rectifier equals to the setting value as 1.0p.u. The direct voltage of inverter is slightly lower than the setting value as to the line loss; both the direct current of positive and negative pole equal to the setting value as 1.0p.u. The firing angle at rectifier side is stable as 18º, and the firing angle at inverter side is stable as143º.



(a) Rectifier



(b) Inverter

Figure 2-10 the response curve of HVDC under steady running state

2.3.2 Transient-state operation

In order to verify the model under transient-state operation, all transient operations are simulated: three phase grounded fault and single line grounded fault at AC system side, single line grounded phase on DC transmission line.

2.3.2.1 Three phase grounded fault on AC side of rectifier

Figure 2-11 shows the figure of power circuit under three phase fault on AC side of rectifier. The three phase fault occurs at 0.4s, and the duration of fault is 0.1s. The simulation step is 10us. Figure 2-11 shows the simulation result, and (a) and (b) show the response curve of rectifier and inverter corresponding. The curves from up to down are AC voltage in rectifier side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power.

From the simulation result, under three phase grounded fault in AC side of rectifier, the AC three phases voltage decrease to zero immediately, so direct voltage decreases rapidly, then the control system operates to make the direct voltage back to the normal running range, so the direct voltage has slight oscillation. Simultaneously, the direct current and power decrease corresponding, so the constant current control operates promptly, by decreasing the extinction angle α to increase direct voltage. When the fault is removed, the system regains the steady running state under oscillation.

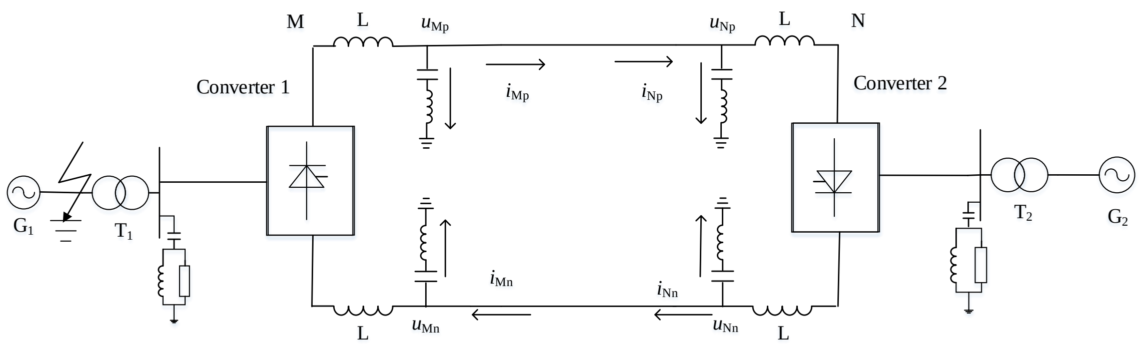
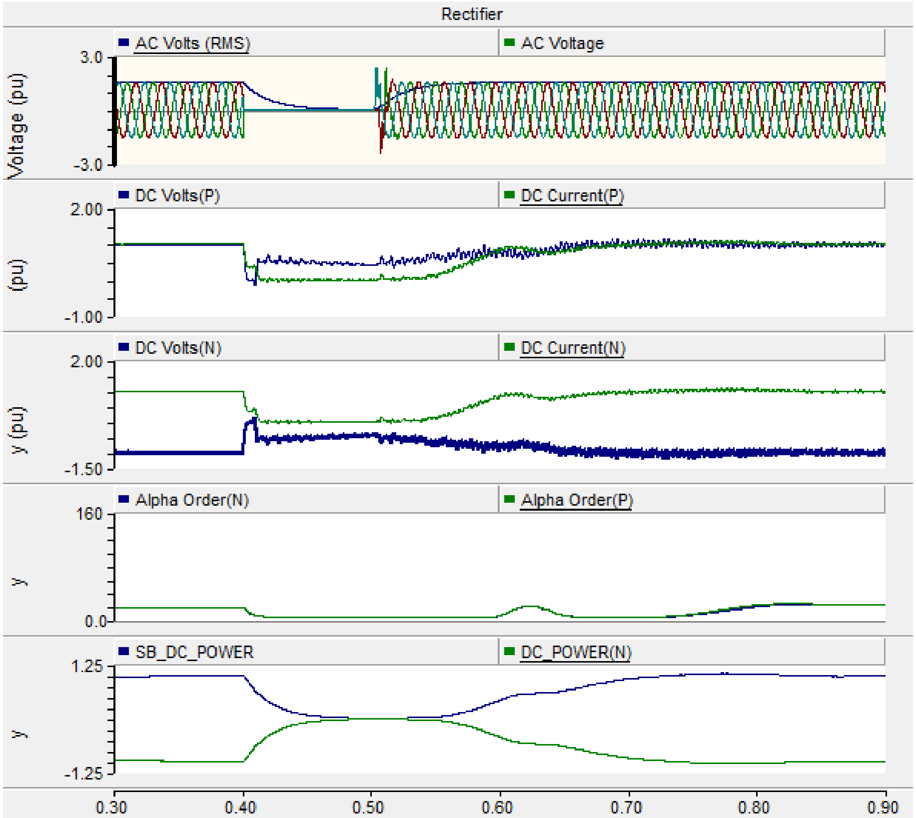
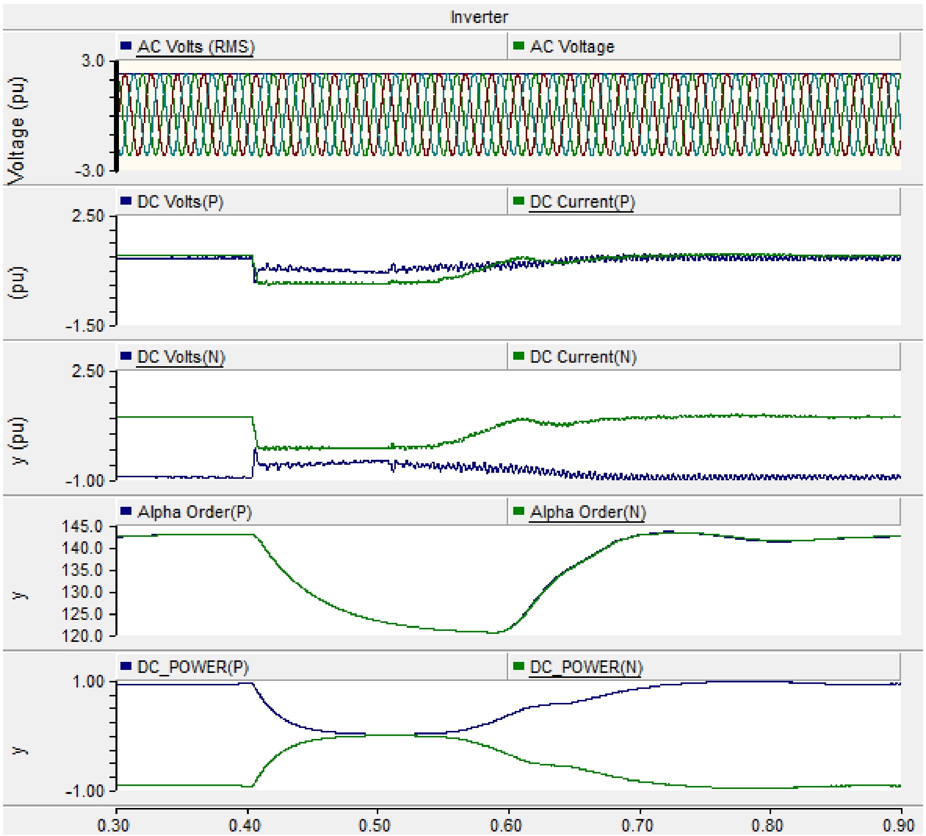


Figure 2-11 the figure of power circuit under three phase fault on AC side of rectifier



(a) Rectifier



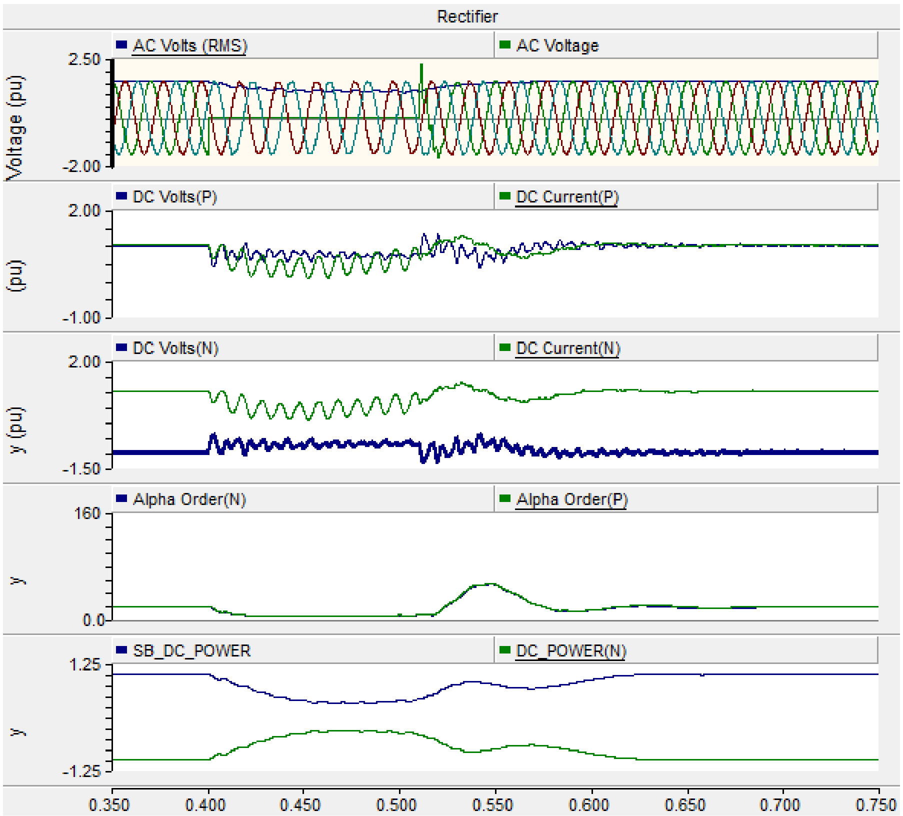
(b) Inverter

Figure 2-12 the response curve under three phase fault on AC system of rectifier

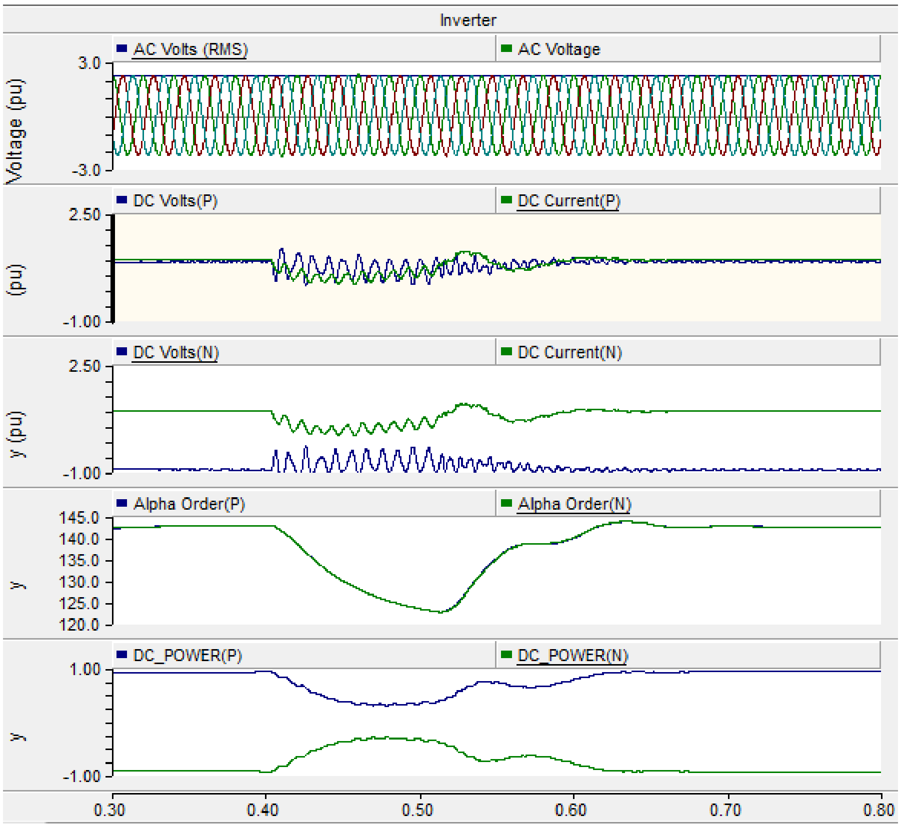
2.3.2.2 Three phase grounded fault on the AC side of rectifier

Figure 2-13 shows the response curve under single line grounded fault on AC system in rectifier side. The fault occurs at 0.4s, and the duration is 0.1s. The curves from up to down are AC voltage in rectifier side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power.

From the simulation result, under single phase to ground fault in AC side, the direct voltage decreases rapidly, then the control system operates to make the direct voltage back to the normal running range, so the direct voltage has oscillation. Simultaneously, the direct current and power decrease corresponding, so the constant current control operates promptly, by decreasing the extinction angle α to increase direct voltage. When the fault is removed, the system regains the steady running state under short time oscillation.



(a) Rectifier



(b) Inverter

Figure 2-13 the response curve under single phase to ground fault on AC system of rectifier

2.3.2.3 Three phase grounded fault on the AC side of inverter

Figure 2-14 shows the figure of electric circuit with fault in the AC side of inverter. Figure 2-15 shows the response curve under three phase grounded fault on AC system in inverter side, and (a) and (b) show the response curve of rectifier and inverter corresponding. The fault occurs at 0.4s, the duration is 0.1s. The curves from up to down are AC voltage in inverter side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power.

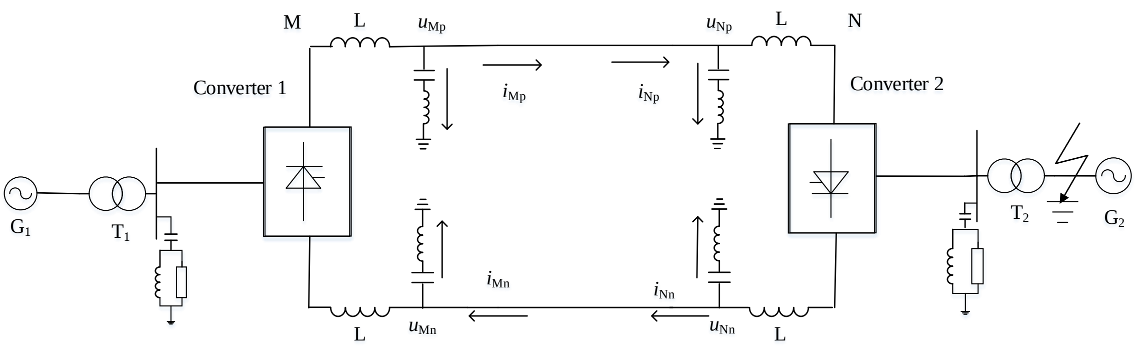
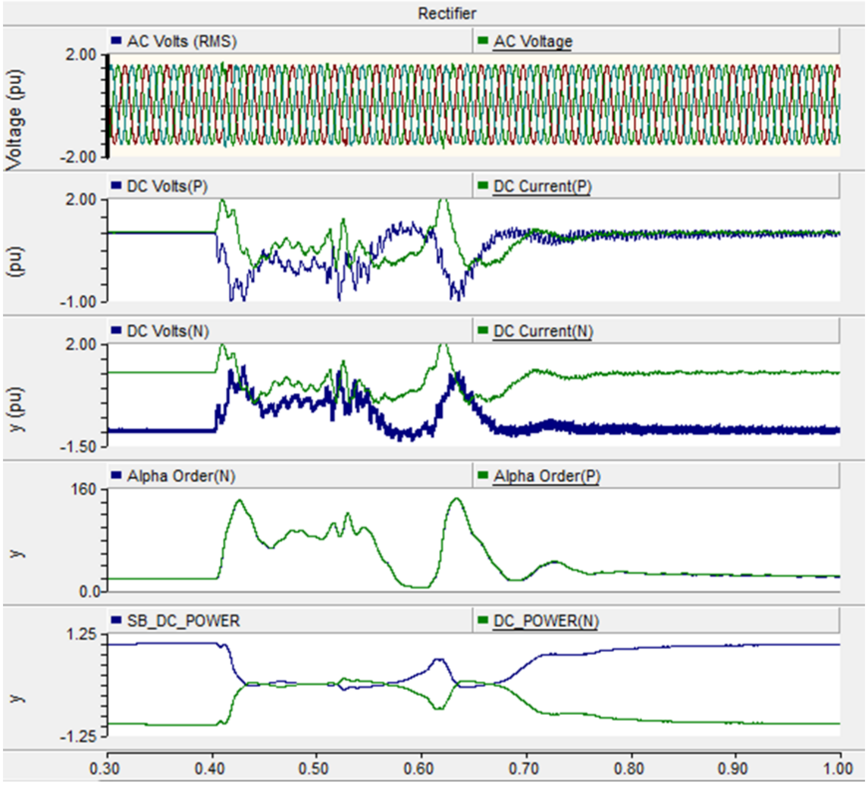
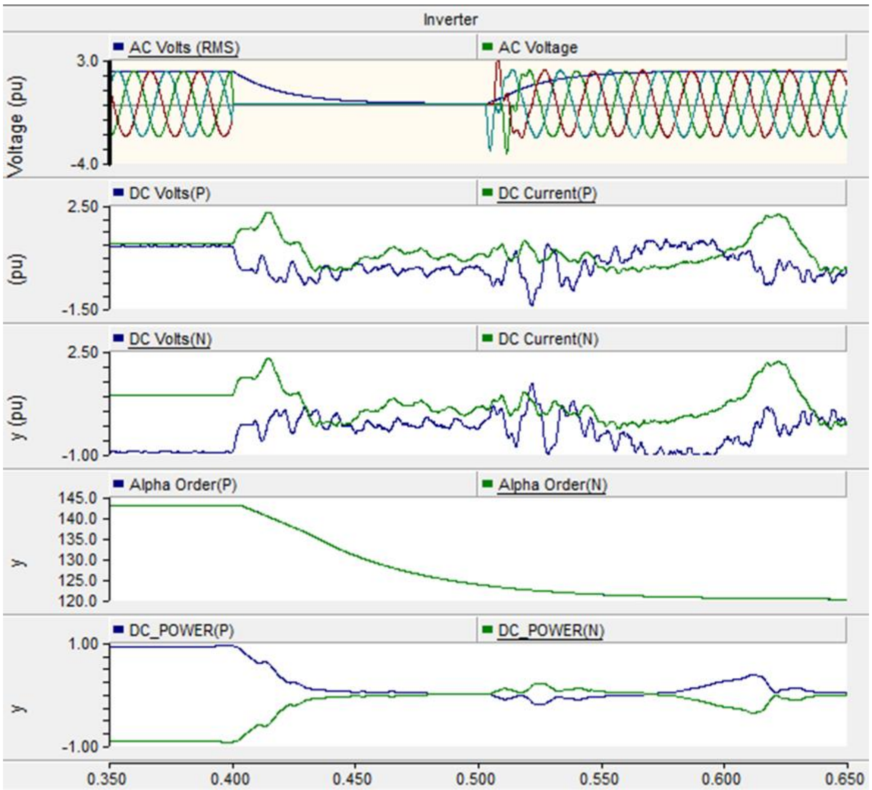


Figure 2-14 the figure of power circuit under three phase fault on AC side of inverter



(a) Rectifier



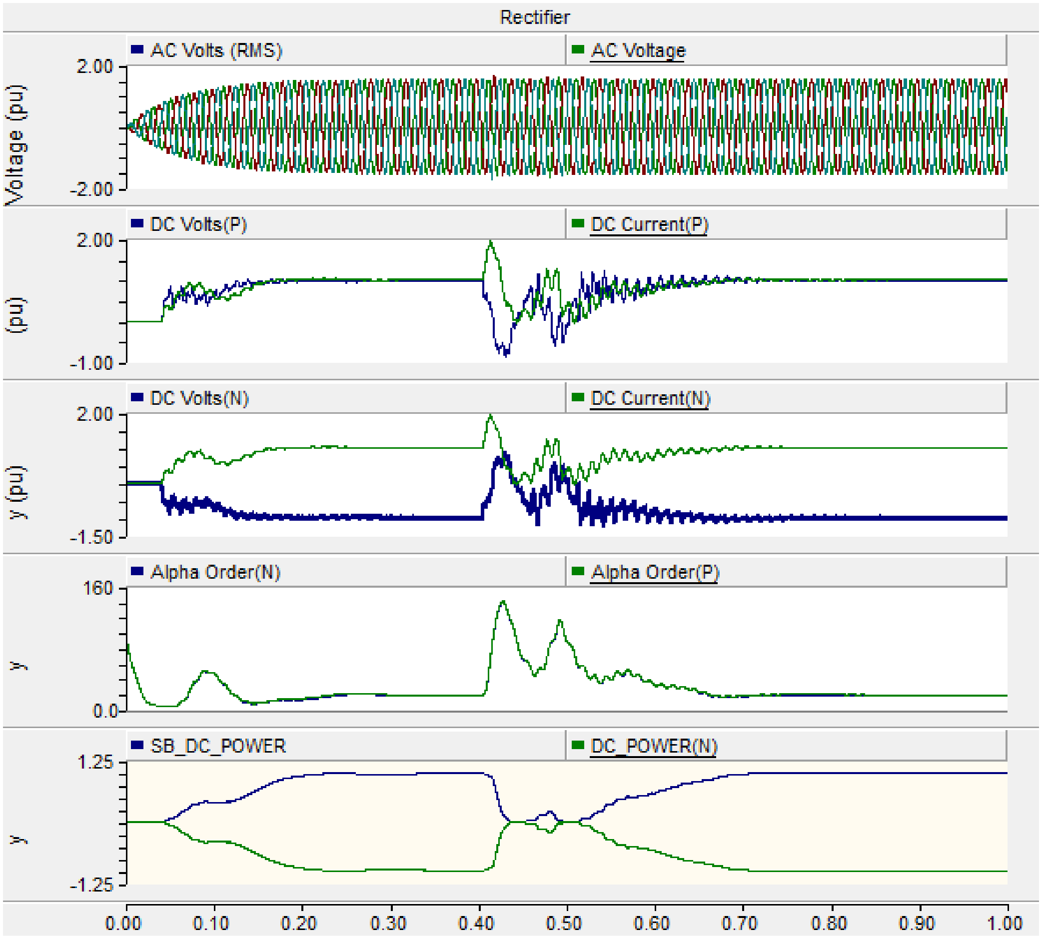
(b) Inverter

Figure 2-15 the response curve under three phase fault on AC system of inverter

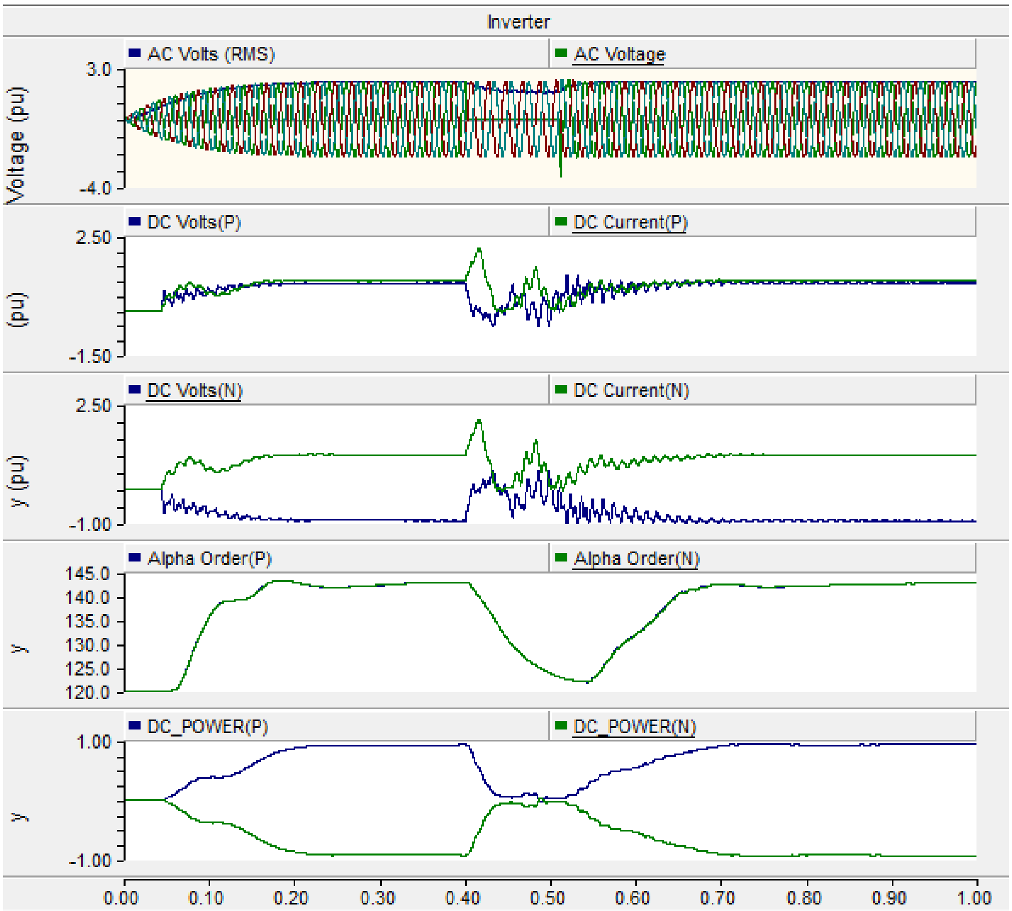
From the simulation result, under three phase grounded fault on AC side of inverter, the direct voltage both in rectifier and inverter side decrease to zero rapidly, but the direct current both in rectifier and inverter increases. The rectifier is under constant current control mode and the inverter is under constant extinction angle control mode, to stabilize the DC system. When the fault is removed, the control system tries to decrease oscillation and makes the system back to the steady state.

2.3.2.4 Single line grounded fault on the AC side of inverter

Figure 2-16 shows the response curve under the fault on AC system in inverter side. The fault occurs at 0.4s, the duration is 0.1s. The curves from up to down are AC voltage in inverter side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power.



(a) Rectifier



(a) Inverter

Figure 2-16 the response curve under single line grounded fault on AC system of inverter

From the simulation result, under single line fault on AC side of inverter, the direct voltage decreases to zero rapidly, but the direct current increases. The rectifier is under constant current control mode and the inverter is under constant extinction angle control mode, to stabilize the DC system. When the fault is removed, the control system tries to decrease oscillation and makes the system back to the steady state.

2.3.2.5 Fault on DC line

Figure 2-17 shows the figure of electric circuit with fault on DC TL line.Figure 2-18 shows the response curve under fault on DC line of positive pole. The fault occurs at 0.4s, and the duration is 0.1s. The curves from up to down are AC voltage in both side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power.

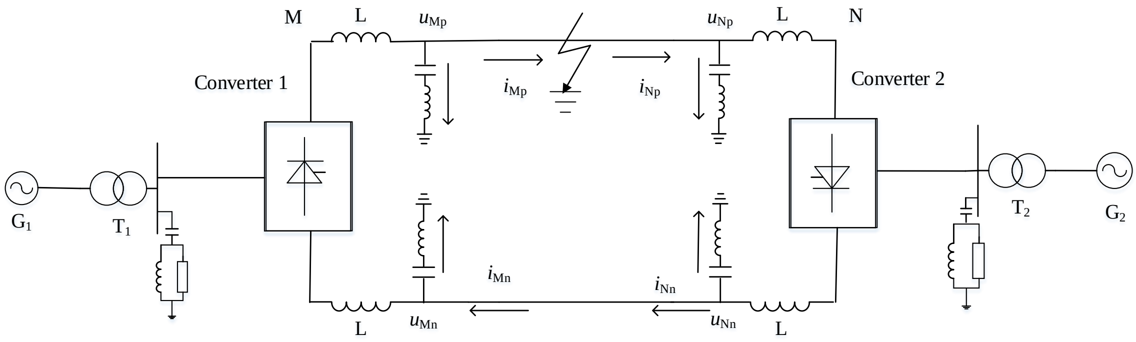
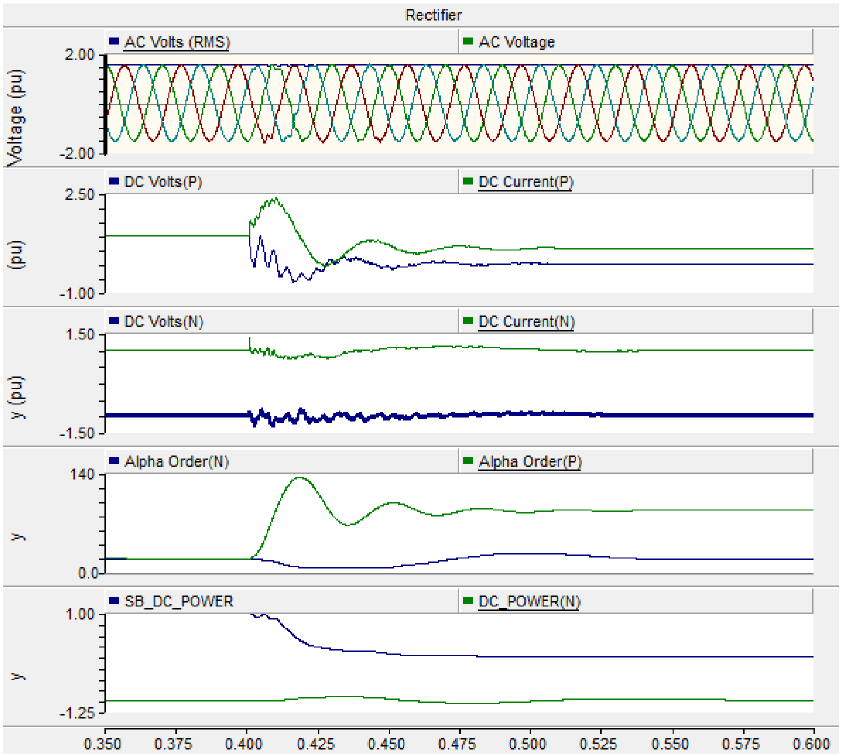
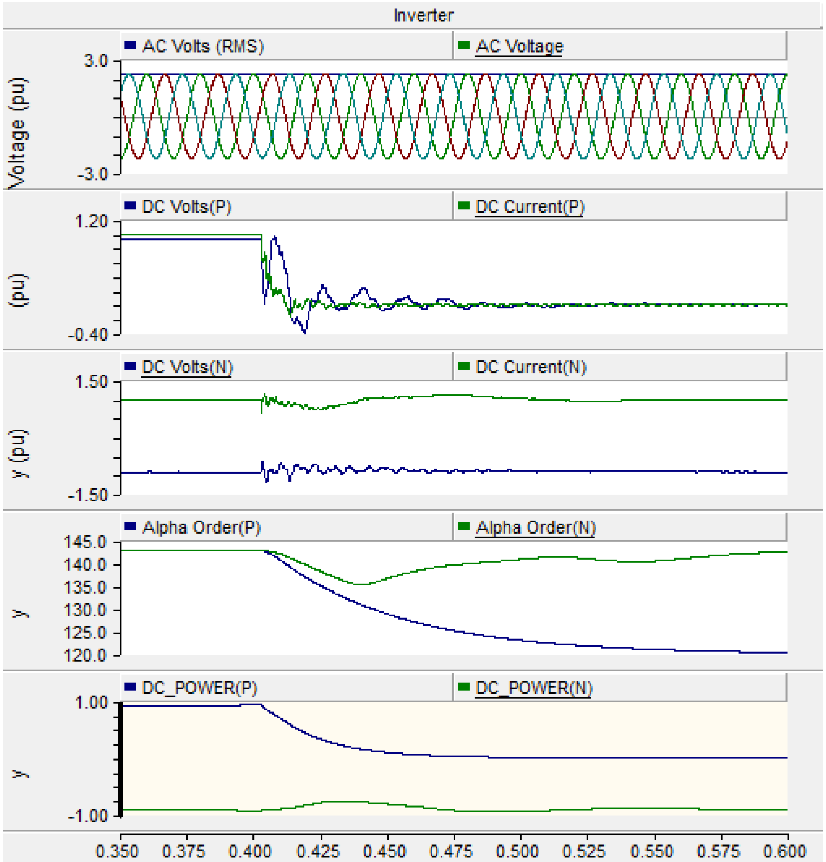


Figure 2-17 the figure of power circuit under three phase fault on AC side of inverter



(a) Rectifier



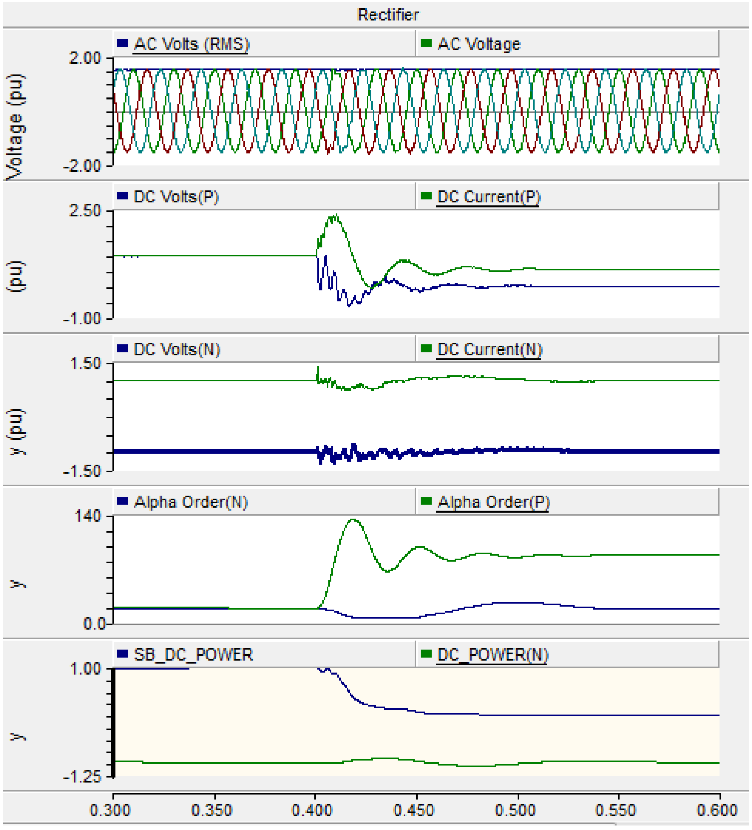
(b) Inverter

Figure 2-18 the response curve of single line to ground fault on DC TL line

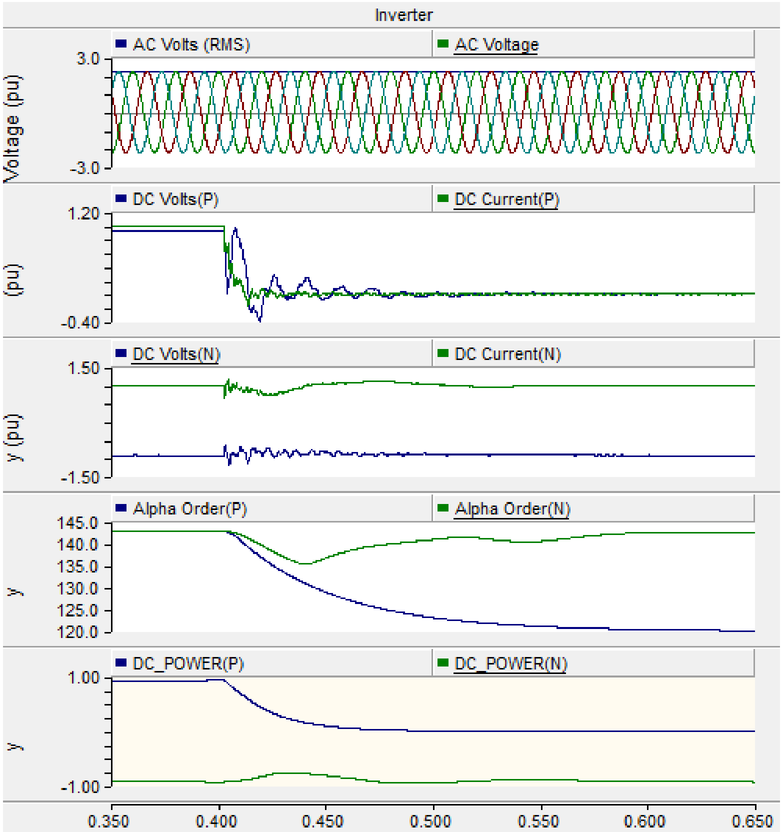
From the simulation result, under fault on DC line of positive pole, in rectifier side the direct voltage decreases and the direct current of fault pole increases rapidly, because the DC impedance decreases. While for healthy pole the voltage and current only has slight oscillation and then come back to the steady state. Then, the control system operates, both converters transfer to constant current control mode to stabilize the DC current. However due to the long duration of fault, the DC current and voltage of fault pole cannot recover to the steady-state any more, and there is no DC power transferred in the fault pole.

2.3.2.6 The fault characteristic analysis

Figure 2-19 shows the response curve under fault on DC line. The fault occurs at 0.4s, and the duration is 1s, which means the fault is permanent. The curves from up to down are AC voltage in both side, the voltage and current of positive pole, the voltage and current of negative pole, firing angle α and the transferred power. The fault characteristic of the permanent fault in the time of fault is similar to the fault characteristic of the temporary fault: in the failure moment, the direct voltage decreases and the direct current increases rapidly for the fault line. Then comes the fault transient period, the control system operates, and the current and voltage in both side oscillate. Finally, the system comes to the fault steady date, both converter is under constant current control. Because of the fall of the voltage, VDCOL acts, therefore the direct current is stable at the minimum output value 0.55 p.u., while the direct current in inverter side is stable at 0.45p.u. due to the current margin. The current in both side is stable at 0. While, the current and voltage of the intact pole come back to steady state under slight oscillation.



(a) Rectifier



(b) Inverter

Figure 2-19 the response curve under fault on DC line

2.4 Conclusion

In this chapter, the numerical simulation model of HVDC transmission system is built on PSCAD/EMTDC, and the converter and its control system are introduced specially. Then by the simulation of the steady and transient running state, the HVDC model on PSCAD/EMTDC can simulate the real electrical quantity under fault, which is the base for fault simulation protection research. Moreover, the fault characteristic is analyzed, which is essential for the protection principles.

3 THE PROTECTION OF HVDC LINE AND ITS OPERATING CHARACTERISITC

3.1 Configuration of HVDC transmission line protection

HVDC transmission line protection is configured with travelling wave protection as main protection, derivative and level protection and longitudinal differential protection as backup protection. In the time of fault on DC transmission line, transient travelling wave is produced at the fault point to propagate along transmission line. Travelling wave protection make use of this travelling wave, which propagate in extremely fast speed like light speed, to offer a speedy main protection for DC transmission line. Moreover, from the analysis of transient characteristic under fault on DC transmission line, DC voltage at rectifier side decreases very rapidly, and DC current at rectifier side increases very rapidly. Derivative and level protection is based on this transient characteristic. Since travelling wave and derivative and level protection have poor performance under fault with high impedance, longitudinal differential protection is needed as backup protection. During normal operation, the current at rectifier and inverter side are almost equal. But under fault on DC transmission line, the difference of the current at rectifier and inverter side would be greater than a threshold. Therefore longitudinal differential protection uses this current difference as criterion to discriminate the fault.

3.2 Travelling wave propagation characteristic

As travelling wave protection is based on the transient travelling wave, it is required to analyze the propagation characteristic of traveling wave. This part is intended to analyze the fault transient characteristic of travelling wave as a base for the principle and criterion of travelling wave protection.

3.2.1 Propagating equation

3.2.1.1 Propagation equation for single pole transmission line

The equivalent power circuit of single pole HVDC transmission line is shown as in Figure 3-1[35, 36].

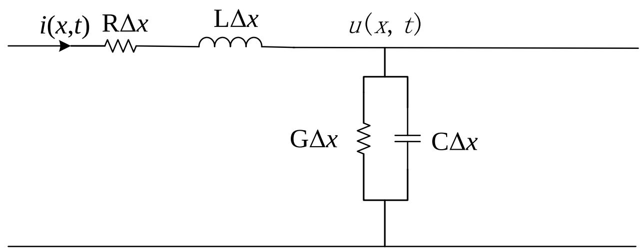


Figure 3-1 the equivalent power circuit of single pole HVDC transmission line

From the equivalent electric circuit, the differential equation is gained as:

$$\begin{bmatrix} \dfrac{\partial u(x,t)}{\partial x} \\ \dfrac{\partial i(x,t)}{\partial x} \end{bmatrix} = -\begin{bmatrix} Ri(x,t) + L\dfrac{\partial i(x,t)}{\partial t} \\ Gu(x,t) + C\dfrac{\partial u(x,t)}{\partial t} \end{bmatrix} \qquad (3\text{-}1)$$

Having Laplace transform and then partial derivative on the equation, equation (3-2) is get as:

$$\begin{cases} \dfrac{\partial^2 U(x,s)}{\partial x^2} = (R+sL)(G+sC)I(x,s) \\ \dfrac{\partial^2 I(x,s)}{\partial x^2} = (R+sL)(G+sC)U(x,s) \end{cases} \qquad (3\text{-}2)$$

From equation (3-2), the general solution is gained as:

$$\begin{cases} U(x,s) = F_1(s)e^{-\gamma(s)x} + F_2(s)e^{-\gamma(s)x} \\ I(x,s) = \left(F_1(s)e^{-\gamma(s)x} - F_2(s)e^{-\gamma(s)x}\right)/Z_C \end{cases} \qquad (3\text{-}3)$$

Where, $\gamma(s)$ ——propagating coefficient; Z_C——wave impedance ; $F_1(s)$, $F_2(s)$ —— coeffienct depedent on boundary. Moreover, $\gamma(s)$ and Z_C have the following relation:

$$\gamma(s) = \sqrt{(R+sL)(G+sC)} \qquad (3\text{-}4)$$

$$Z_C = \sqrt{(R+sL)/(G+sC)} \qquad (3\text{-}5)$$

Assuming s=jω, so

$$\gamma(j\omega) = \sqrt{(R+j\omega L)(G+j\omega C)} = \alpha(\omega) + j\beta(\omega) \qquad (3\text{-}6)$$

Where, $\alpha(\omega)$ ——attenuation coefficient, $\beta(\omega)$ ——phase shift factor.

According to the definition of phase, under certain frequency, voltage wave along the tranmissio line in time domain is get as:

$$\begin{aligned} u(x,t) &= \mathrm{Re}\{U(x,j\omega)\} = F_1(\omega)e^{\alpha(\omega)x}\cos(\omega t+\beta(\omega)x)+ \\ &F_2(\omega)e^{-\alpha(\omega)x}\cos(\omega t-\beta(\omega)x) = u_f(t+x/v)+u_q(t-x/v) \end{aligned} \qquad (3\text{-}7)$$

In the equation, u_f——backward voltage wave，u_q——forward voltage wave.

The propagating velocity of travelling wave is definited as the propagating velocity of constant phase face, the equatio of constant phase plane is as:

$$\omega t \pm \beta(\omega)\cdot x = const \qquad (3\text{-}8)$$

Having the derivative for equation(3-8), the propagating velocity is get as:

$$v = \frac{dx}{dt} = \frac{\omega}{\beta(\omega)} \qquad (3\text{-}9)$$

From equation (3-6) and (3-9), it can be seen that the propagating velocity and distortion of travelling wave is dependent on frequency.

As for lossless transmission line, R=0，G=0, so:

$$v = 1/\sqrt{LC} \qquad (3\text{-}10)$$

$$Z = \sqrt{L/C} \qquad (3\text{-}11)$$

As for undistorted transmission line, $G_a/C_a=R_a/L_a$, so:

$$\gamma(\omega) = \sqrt{R_a G_a} + j\omega\sqrt{L_a C_a} \qquad (3\text{-}12)$$

therefore，

$$\beta = \sqrt{R_a G_a}, v = 1/\sqrt{L_a C_a} \qquad (3\text{-}13)$$

$$Z_C = \sqrt{L_a/C_a} = \sqrt{R_a/G_a} \qquad (3\text{-}14)$$

In order to illustrate the essence of travelling wave and give the expression of propagation, for the following analysis the HVDC transmission line is considered as undistorted transmission line. But in the practical HVDC transmission project, due to the long transmission distance, the tranmission line is lossy and frequency-dependent definitly. So in chapter 2, the model for HVDC transmission line chooses frequency-depedent parameters.

Equation (3-7) indicates that voltage wave is composed by forward wave $u_f$and backward wave u_q, and they have the following relationship:

$$\begin{cases} u_f = -i_f \cdot Z_C \\ u_q = i_q \cdot Z_C \end{cases} \qquad (3\text{-}15)$$

From equation (3-7) and (3-15), the forward and back voltage wave are get as:

$$\begin{cases} Z_C i(x,t) + u(x,t) = 2u_q \\ Z_C\, i(x,t) - u(x,t) = -2u_f \end{cases} \qquad (3\text{-}16)$$

3.2.1.2 Double pole transmission line

In practical HVDC transmission system, there is usually double pole HVDC transmission line, which transfers to single pole transmission line only when fault occurring on transmission line. For double pole transmission line, due to the coupling effect, the non-fault transmission line can induce the fault signal. The equivalent electric circuit of HVDC transmission line is shown in Figure 3-2.

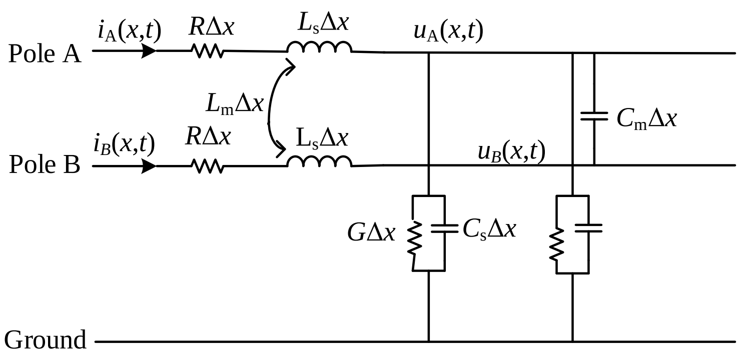


Figure 3-2 the equivalent electric circuit of HVDC transmission line

From the equivalent electric circuit of HVDC transmission line, derivative equation is get as:

$$\begin{bmatrix} \frac{\partial u_A}{\partial x} \\ \frac{\partial u_B}{\partial x} \end{bmatrix} = -\begin{bmatrix} L_s \frac{\partial}{\partial t} + R & L_m \frac{\partial}{\partial t} \\ L_m \frac{\partial}{\partial t} & L_s \frac{\partial}{\partial t} + R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} = -Zi \qquad (3\text{-}17)$$

$$\begin{bmatrix} \frac{\partial i_A}{\partial x} \\ \frac{\partial i_B}{\partial x} \end{bmatrix} = -\begin{bmatrix} C_s \frac{\partial}{\partial t} + C_m \frac{\partial}{\partial t} + G & -C_m \frac{\partial}{\partial t} \\ -C_m \frac{\partial}{\partial t} & C_s \frac{\partial}{\partial t} + C_m \frac{\partial}{\partial t} + G \end{bmatrix} \begin{bmatrix} u_A \\ u_B \end{bmatrix} = -Yu \qquad (3\text{-}18)$$

Where, L_s——distributed series inductance; C_s——distributed parallel capacitance; L_m——distributed coupled inductance; C_m——distributed capacitance between line.

In order to eliminate the coupling effect between poles, the sagami transforming method is used, which means exploiting sagami transforming matrix Q to convert quantity in time domain to mode domain, so quantity in time domain u and i has the following relationship with quantity in mode domain $\bar{u}$ and $\bar{i}$.

$$\begin{cases} u = Q\bar{u} \\ i = Q\bar{i} \end{cases} \tag{3-19}$$

Taking equation (3-19) into equation (3-17) and (3-18), the new derivative equation is get as:

$$\begin{cases} \dfrac{\partial \bar{u}}{\partial x} = -Q^{-1}ZQ\bar{i} = -\bar{Z}\bar{i} \\ \dfrac{\partial \bar{i}}{\partial x} = -Q^{-1}YQ\bar{u} = -\bar{Y}\bar{i} \end{cases} \tag{3-20}$$

Taking appropriate matrix Q to make $Q^{-1}ZQ$ and $Q^{-1}YQ$ as sysmetric matrix, so the coupling effect between poles can be eliminated. According to the calculation, the matrix Q meeting the requirements is not unique. Here the matrix Q is taken as:

$$Q = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{3-21}$$

Taking matrix Q into equation (3-20), the impedance and reactance in mode domian is get as:

$$\bar{Z} = \begin{bmatrix} L_0 \dfrac{\partial}{\partial t} + R & 0 \\ 0 & L_1 \dfrac{\partial}{\partial t} + R \end{bmatrix} \tag{3-22}$$

$$\bar{Y} = \begin{bmatrix} C_0 \dfrac{\partial}{\partial t} + G & 0 \\ 0 & C_1 \dfrac{\partial}{\partial t} + G \end{bmatrix} \tag{3-23}$$

Where, $L_0=L_s+L_m$, $L_1=L_s-L_m$, $C_0=C_s$, $C_1=C_s+2C_m$. Taking $\bar{Y}$ and $\bar{Z}$ into equation (3-20), a derivative eqaution similar to equation (3-1) can be get. Using the same method, the solution in mode domian is get as:

$$\begin{cases} Z_0 i_0(t) + u_0(t) = 2u_{q0} = a_0(t) \\ Z_0\, i_0(t) - u_0(t) = -2u_{f0} = b_0(t) \end{cases} \tag{3-24}$$

$$\begin{cases} Z_1 i_1(t) + u_1(t) = 2u_{q1} = a_1(t) \\ Z_1\, i_1(t) - u_1(t) = -2u_{f1} = b_1(t) \end{cases} \tag{3-25}$$

Where, Z_1——differential mode impedance，Z_0——common mode impedance.

Wave impdedance, attenuation coefficient and wave velocity of differential mode and common mode hace the same expression with that of single pole transmission line as:

$$\begin{cases} Z_1 = \sqrt{L_1/C_1} = \sqrt{(L_s - L_m)/(C_s + 2C_m)} \\ Z_0 = \sqrt{L_0/C_0} = \sqrt{(L_s + L_m)/C_s} \end{cases} \tag{3-26}$$

$$\begin{cases} v_1 = \sqrt{1/L_1C_1} = \sqrt{1/(L_s - L_m)(C_s + 2C_m)} \\ v_0 = \sqrt{1/L_0C_0} = \sqrt{1/(L_s + L_m)C_s} \end{cases} \tag{3-27}$$

As shown in equation (3-26) and (3-27), common mode impedance is greater than the differential mode impedance, and differential mode velocity is greater than common mode velocity.

3.2.2 Propagating characteristic under DC transmission line fault

3.2.2.1 Single pole transmission line

In the time of fault on DC transmisson line, the voltage at the fault point goes to zero suddenly. According to the superposition theory, the voltage at the fault point is superposed by normal operation part and fault operation part. The fault operation part is equivalent to the case with the voltage source at the fault point, which has the same voltage value to the voltage before fault but opposite polarity, and no system sources, as shown in Figure 3-3.

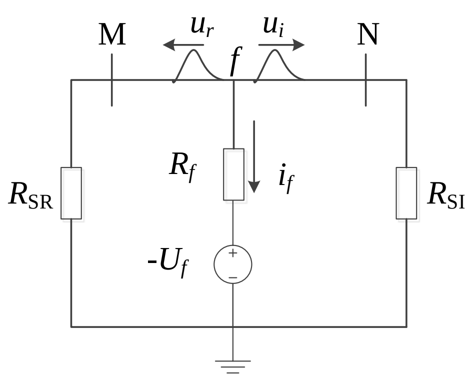


Figure 3-3 the transient electric circuit under fault on single pole transmission line

By analyzing the transient electric circuit, equations about the fault quantity are gained as:

$$i_f = i_r - i_i = U_f / R_f \qquad (3\text{-}28)$$

$$\begin{cases} i_r = -u_r / Z_C \\ i_i = u_r / Z_C \end{cases} \qquad (3\text{-}29)$$

Where, i_r——current from the fault point towards rectifier， i_i——current from the fault point towards inverter.

From equation (3-28) and (3-29), the amplitude of the first travelling wave is get in equation (3-30), which indicates that the amplitude is dependent on fault impedance, wave impedance and voltage before fault.

$$u_r = u_i = \frac{Z_C}{Z_C + 2R_f}\left(-U_f\right) = K\left(-U_f\right) \qquad (3\text{-}30)$$

From all the analysis before, the first voltage and current travelling wave at the protection equipment installed point M is get as:

$$\begin{cases} u_M = \left(1 + n(t)\right) \cdot K\left(-U_f\right) e^{-\alpha l} \cdot \varepsilon\left(t - \tau\right) \\ i_M = \left(-1 + n(t)\right) \cdot K\left(-U_f\right) e^{-\alpha l} \cdot \varepsilon\left(t - \tau\right) / Z_c \end{cases} \qquad (3\text{-}31)$$

Where, n(t)—refection coefficient dependent on boundary； l—distance from fault point to protection equipment installed point； τ—propagating time from fault point to protection equipment installed point.

From equation (3-31), the voltage and current travelling wave is dependent on frequency, and in the propagation process, the wave front would be distorted, which is travelling wave dispersion.

3.2.2.2 Double pole transmission line

Assuming there is fault occurring on pole *a* in Figure 2-1, the transient equation is get as:

$$\begin{cases} u_{fa} = -U_f + i_{fa} R_f \\ i_{fb} = 0 \end{cases} \qquad (3\text{-}32)$$

Where, u_{fa}——voltage at the fault point on pole *a*； i_{fa}——current at the fault point on pole *a*； u_{fb}——voltage at the fault point on pole *b*.

Using sagami transformation to get the equation in mode domain as:

$$\begin{cases} u_{f0} + u_{f1} = -U_f + 2 i_{f1} R_f \\ i_{f0} + i_{f1} = 0 \end{cases} \qquad (3\text{-}33)$$

Where, u_{f1}, i_{f1}——differential mode voltage and current at the fualt point; u_{f0}, i_{f0}——differential mode voltage and current at the fualt point.

For the first travelling wave, it has such equation as:

$$\begin{cases} i_{f0} = -2u_{f0}/Z_0 \\ i_{f1} = -2u_{f1}/Z_1 \end{cases} \tag{3-34}$$

From equation (3-33) and (3-34), the solution can be gained as:

$$\begin{cases} u_{f0} = -Z_0 U_f / \left(2R_f + Z_0 + Z_1\right) = -K_0 U_f \\ u_{f1} = -Z_1 U_f / \left(2R_f + Z_0 + Z_1\right) = -K_1 U_f \end{cases} \tag{3-35}$$

Therefore, the first differential mode and common mode of voltage at the protection equipment installed point M are as:

$$\begin{cases} u_{M1} = \left(1 + n_1(t)\right) \cdot K_1 \left(-U_f\right) e^{-\alpha_1 l} \cdot \varepsilon\left(t - \tau_1\right) \\ u_{M0} = \left(1 + n_0(t)\right) \cdot K_0 \left(-U_f\right) e^{-\alpha_0 l} \cdot \varepsilon\left(t - \tau_0\right) \end{cases} \tag{3-36}$$

Where, α_1, α_0——attenuation coefficient of differential mode and common mode corresponding; n_1, n_0——reflection coefficient of differential mode and common mode corresponding; τ_1, τ_0——propagating time of differential mode and common mode corresponding.

3.3 Travelling wave protection

3.3.1 Protection principle and criterion

The structure of HVDC transmission system based on 12 pulses converter is shown in Figure 3-4. This part will introduce the principle and criterion of travelling wave protection.

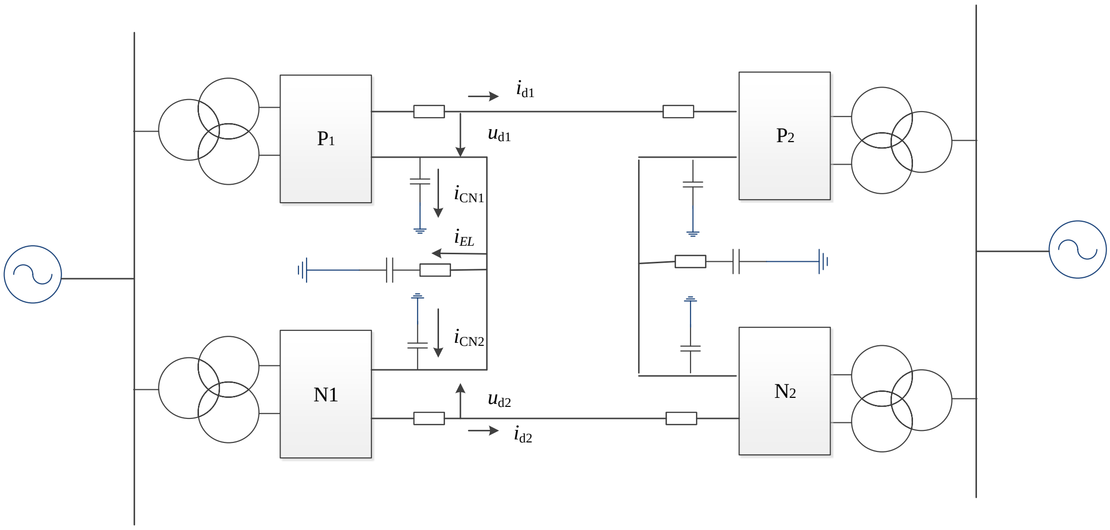


Figure 3-4 the structure of HVDC transmission system

3.3.1.1 Pole wave to detect fault on transmission line

In the fault moment, the travelling wave is generated in the fault point and propagates along the transmission line to converter in both sides. Protection equipment makes use of this transient travelling wave to form pole wave to detect fault on DC transmission line. The definition of pole wave is shown in equation (3-37).

$$P_i = Z_1 i_{dLi} - u_{dLi} \tag{3-37}$$

Where, Z_1——the differential mode impedance, i=1, 2; i_{dLi}—— the current on pole i; u_{dLi}——the voltage on pole i.

3.3.1.1.1 Single pole transmission line

Taking equation (3-31) into equation (3-37), the expression of pole wave is gained as shown in equation (3-38), which indicates that, the amplitude of pole wave is dependent on fault impedance and distance, and the pole front is dependent on attenuation coefficient.

$$P_M = i_M Z_c - u_M = 2K \cdot u_f e^{-\alpha l} \cdot \varepsilon\left(t - \tau\right) \tag{3-38}$$

From equation (3-38), when there is fault occurring on positive pole, the derivative and change of pole wave would be greater than a positive threshold, while with fault occurring on negative pole, the threshold would be negative. Therefore, by measuring the derivative and change of pole wave, the fault can be detected by protection equipment rapidly. When the fault occurs outside DC transmission line, as to the smoothing effect of DC filter and reactors, the wave front of pole wave becomes much smoother, so the derivative and change of pole wave under fault outside of DC transmission line is much smaller than that under fault on DC transmission line. In this way, pole wave can be applied to discriminate the fault on or outside DC transmission line.

As shown in equation (3-38), the essence of pole wave is backward wave of pole voltage, therefore, before the second wave arriving point M, the pole wave cannot be affected by the forward wave resulted from reflection of boundary equipment. Because of the opposite pole of forward wave and backward wave, the pole voltage, which is composed of forward and backward wave, has smoother wave front than pole wave. So pole wave has more obvious fault characteristic than pole voltage.

3.3.1.1.2 Double pole transmission line

Assuming pole *a* being the fault pole, the pole wave of pole *a* and *b* can be get as:

$$\begin{cases} P_a = Z_1 i_{dLa} - u_{dLa} \\ P_b = Z_1 i_{dLb} - u_{dLb} \end{cases} \tag{3-39}$$

By sagami conversion, the expression of pole wave in mode domain can be gained as:

$$\begin{cases} P_a = \left[K_0 e^{-\alpha_0 l}\varepsilon\left(t-\tau_0\right) + K_1 e^{-\alpha_1 l}\varepsilon\left(t-\tau_1\right)\right]U_f - i_{dL0}\left(Z_0 - Z_1\right) \\ P_b = \left[K_0 e^{-\alpha_0 l}\varepsilon\left(t-\tau_0\right) - K_1 e^{-\alpha_1 l}\varepsilon\left(t-\tau_1\right)\right]U_f - i_{dL0}\left(Z_0 - Z_1\right) \end{cases} \tag{3-40}$$

As shown in equation (3-40), pole wave is superposed by differential mode and common mode. Because common mode wave propagates slower than differential mode wave, for long fault distance, pole wave front is almost dependent only on differential mode. For this reason, pole *a* and *b* have the same derivative and change for pole wave, which makes it difficult to discriminate the fault pole. But common mode wave can solve this problem.

3.3.1.2 Common mode to discriminate fault pole

In the time of fault on DC transmission line, impulse current i_{CN1} and i_{CN2} are generated on grounding capacitor parallel to electrode bus. The definition of common mode wave is shown as:

$$G_{wave} = Z_0(i_{EL} + i_{CN1} + i_{CN2})/2 - (u_{dL1} + u_{dL2})/2 \tag{3-41}$$

Where, Z_0——the common mode impedance; i_{EL}——the current through grounding line; i_{CN1}, i_{CN2}——the impulse current through the grounding capacitor, which is shown in Figure 3-4.

During normal operation, the common mode wave is almost zero; under fault on positive pole (pole *a*), the common mode wave would be greater than a positive threshold; under fault on negative pole (pole *b*), the common mode wave is shorter than a negative threshold. In this way, protection device makes use of the common mode wave to discriminate the fault pole.

By defining the pole wave *P* and common wave G_{wave}, the criterion of pole wave protection is gained as shown in equation (3-42). In overall, the derivative of pole wave criterion is to distinguish the internal and external fault, because the DC filter and smoothing reactor can weaken the deepness of pole wave propagating from the external of the DC transmission line. In case that the disturbance causes the protection dis-operate, the change of pole wave ΔP_2, ΔP_5 and ΔP_7 are essential to be measured. If they all meet the criterion, it shows there is surely a fault on the transmission line. The common wave criterion is for distinguishing the fault pole.

$$\begin{cases} \mathrm{d}P_i/\mathrm{d}t > \Delta_1 \\ \Delta P_i > \Delta_2 \\ \Delta G_{wave} > \Delta_3 \end{cases} \quad (3\text{-}42)$$

3.3.2 Protection algorithm

Figure 3-5 is the schematic diagram of travelling wave front. Firstly, the derivative of pole wave is measured by difference method, which is carried out by calculating the difference between two samples. Then the difference ΔP is greater than the threshold, the criterion of pole wave change is active, then comparing the difference between the 2^{th}, 5^{th} and 7^{th} sample and sample before wave. If ΔP_2, ΔP_5 and ΔP_7 all are greater than the threshold, it is verified that there is fault on DC transmission line. Because common mode wave propagates slower than differential mode wave, and the delay time is difficult to determine, after fault detection ten samples need to be measured and added to get ΔG. When ΔG is greater than the threshold, the protection device can trip.

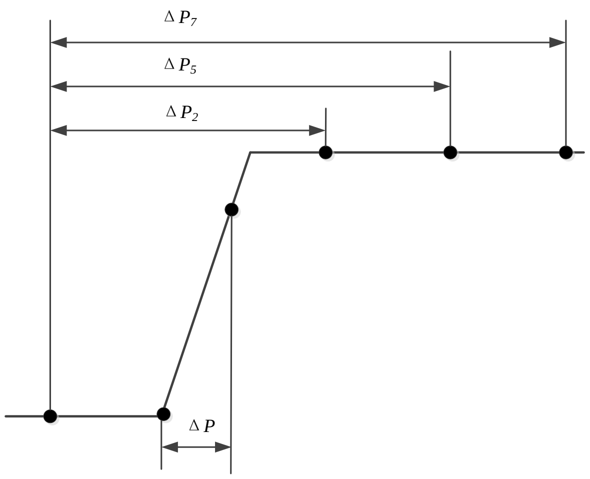


Figure 3-5 the schematic diagram of travelling wave front

Figure 3-6 shows the algorithm flowchart of travelling wave protection. When the pole wave criterion is greater than the threshold, the pulse will be broadened to 6ms, in which the common wave is measured.

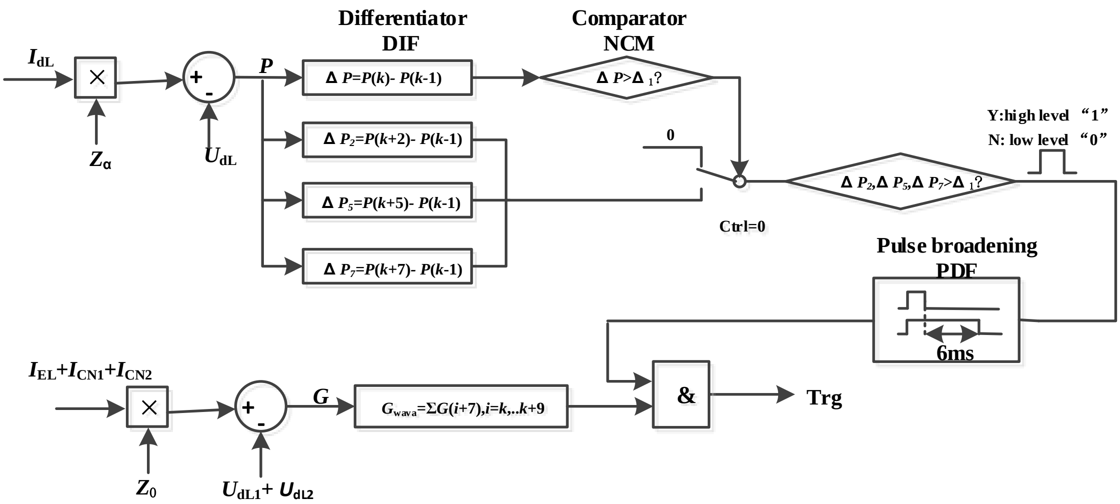


Figure 3-6 the algorithm flowchart of travelling wave protection

3.3.3 Setting principle for thresholds

3.3.3.1 Pole wave

According to the selectivity principle, the threshold of dP/dt should be set to not operate for the most serious fault outside the DC transmission line and, simultaneously, sensitive to operate for the lightest fault inside the DC transmission line. Equation(3-43) and equation(3-44) show the equation of threshold and sensitivity.

$$\left(\mathrm{d}P/\mathrm{d}t\right)_{set}=K_{rel}\cdot(\mathrm{d}P/\mathrm{d}t)_{\mathrm{out\_max}} \tag{3-43}$$

$$K_{sen}=\frac{\left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{in\_min}}}{\left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{set}}} \tag{3-44}$$

Where, $(\mathrm{d}P/\mathrm{d}t)_{\mathrm{max}}$——the maximum d$P$/d$t$ for fault outside the transmission line; $(\mathrm{d}P/\mathrm{d}t)_{\mathrm{in\_min}}$——the minimum d$P$/d$t$ for fault inside the transmission line; K_{rel}——the reliability coefficient, usually K_{rel}=1.2~1.3; K_{sen}——sensitivity coefficient, usually $K_{\mathrm{sen}}\geqslant$1.3~1.5.

3.3.3.2 Common wave

For different fault pole, the polarity of common wave is opposite, so the change of common wave should be set according to the lightest fault inside of the transmission line as shown in equation(3-45).

$$\Delta G_{set}=\Delta G_{\mathrm{in\_min}}/K_{\mathrm{sen.min}} \tag{3-45}$$

Where, $\Delta P_{\mathrm{in\_min}}$——the minimum$\Delta P$ for fault inside the transmission line; $K_{\mathrm{sen\_min}}$——the minimum sensitivity coefficient protection should meet.

3.3.4 Operating characteristic of travelling wave protection

Different fault condition has effect on the value of protection criterion, so in the following part the effect of fault impedance, fault distance, sampling frequency and boundary equipment on the protection criterion will be analyzed in detail.

3.3.4.1 Sampling frequency

In practical HVDC project, the highest sampling frequency of protection device is limited to 10 kHz. In order to know to how this technique limit affects the performance of protection device, fault cases under 10ckHz and 100 kHz sampling frequency are simulated. Simulation condition: simulation step 1μs, the fault occurs at 0.4s, the sampling frequency is 10 kHz and 100 kHz. Figure 3-7 shows the response curve of travelling wave protection. As shown in the figure, the wave front can be captured more clearly with higher sampling frequency; while with lower sampling frequency, few points of wave front are sampled. So under higher sampling frequency, travelling wave protection can have better performance.

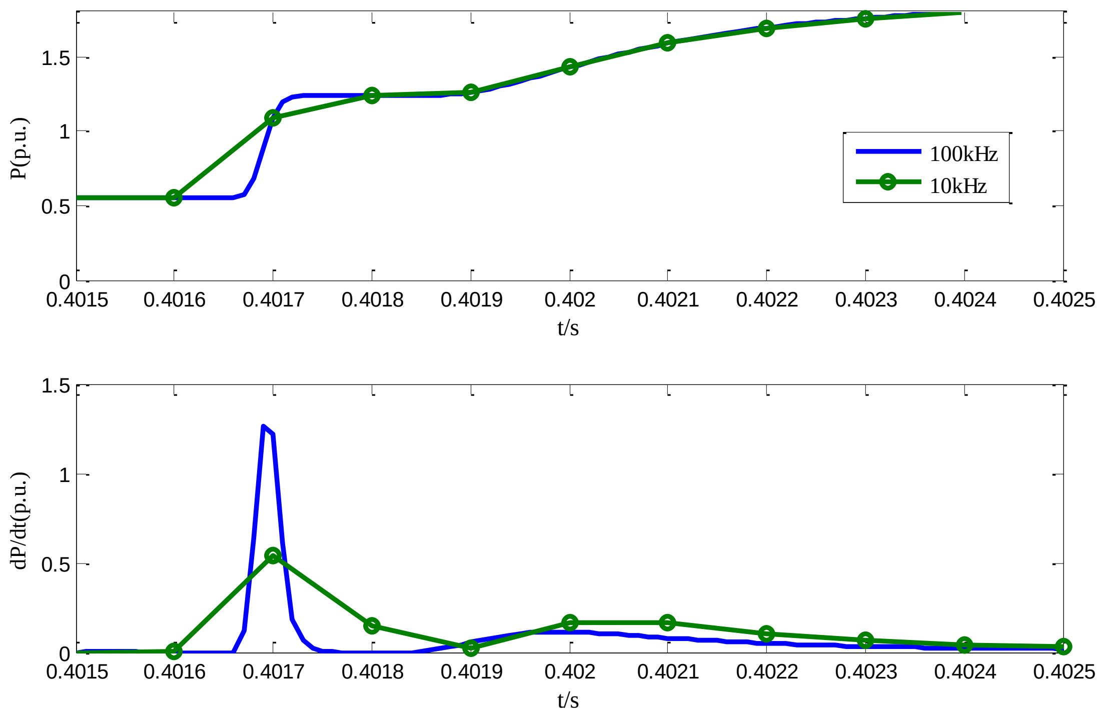


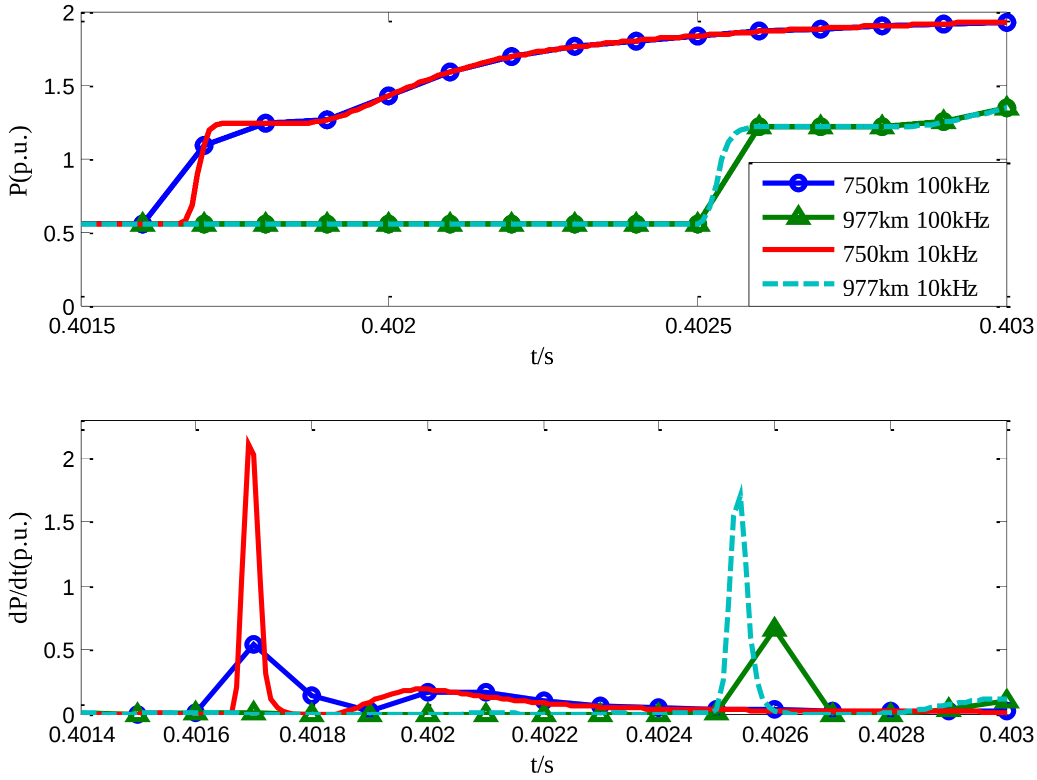
Figure 3-7 the response curve under different sampling frequency

3.3.4.2 Fault distance

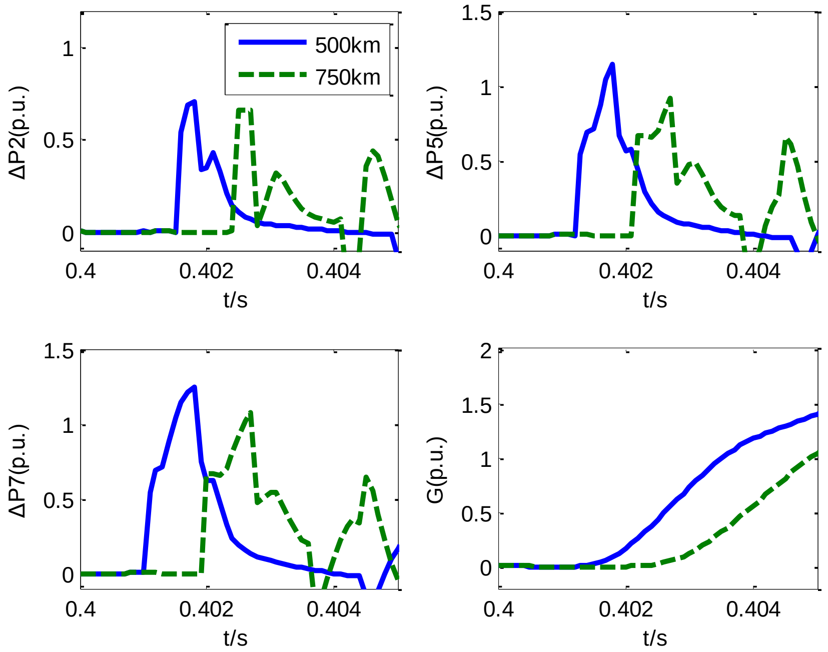
Simulation condition: simulation step 1μs, the fault occurs at 0.4s at point 750km and 977km far from rectifier. Because of the effect of sampling frequency, the simulation is carried out for 100 kHz and 10 kHz. Figure 3-8 shows the simulation result.

As shown in the figure 3-8(a), for 10 kHz sampling frequency, when the fault distance is 750km, the sampling point locates on the wave peak, so dP/dt is large; when the fault distance is 500km, the sampling point appears on the rising slope of pole wave, so dP/dt is small. Therefore, for 10 kHz sampling frequency, there is no regulation for pole wave with fault distance. For 100kHz sampling frequency, the protection device can samples the whole wave front, so dP/dt decreases with the increase of fault distance, for the loss of DC transmission line.

From figure 3-8(b), the change of pole wave and common wave is less affected by sampling frequency, they decrease with longer fault distance, since ΔP has lower requirement on sampling frequency and common mode wave has smooth wave front.



(a) Pole wave



(b) Common wave

Figure 3-8 the response curve under different fault distance

3.3.4.3 Fault impedance

Figure 3-9 shows the response curve for fault occurring at point 500km far from rectifier with zero impedance, 100 Ω and 200Ω corresponding. From the simulation result, the fault impedance merely has effect on the amplitude of pole wave and common wave. With higher fault impedance, the amplitude of pole wave and common wave is smaller.

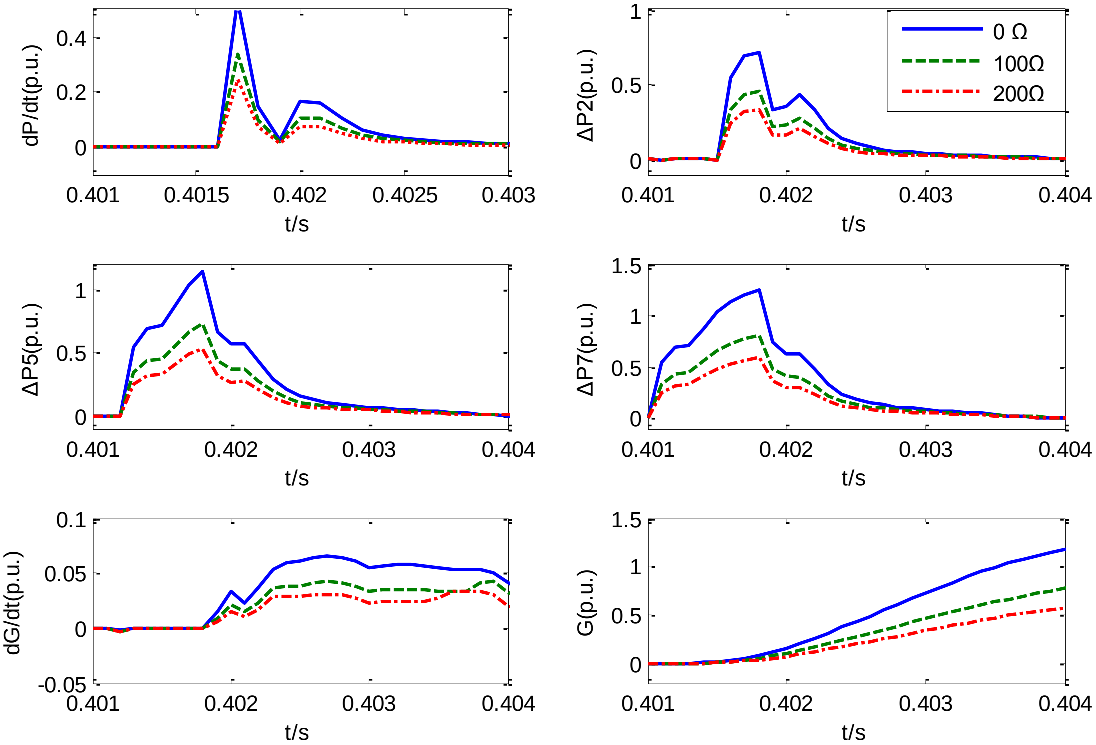


Figure 3-9 the response curve with different fault impedance

3.3.4.4 Boundary equipment

In order to find out the effect of boundary equipment on travelling wave, three kinds of boundary equipment is chosen: merely smoothing reactor; smoothing reactor and 6/12 dual tuner DC filter; smoothing reactor, 6/12 and 24/36 dual tuner DC filter, which are symbolized as boundary 1, boundary 2 and boundary 3. The fault occurs at 500km far from rectifier with no fault impedance. The simulation result is shown in Figure 3-10. From the simulation result, the boundary elements merely have effect on common wave, because the pole wave is in fact the backward travelling wave without superposition of forward travelling wave which is the reflection of backward wave. While, boundary equipment has large effect on common mode wave, but since common mode criterion is only used to discriminate the polarity, so in overall, the travelling wave protection is almost not affected by boundary equipment.

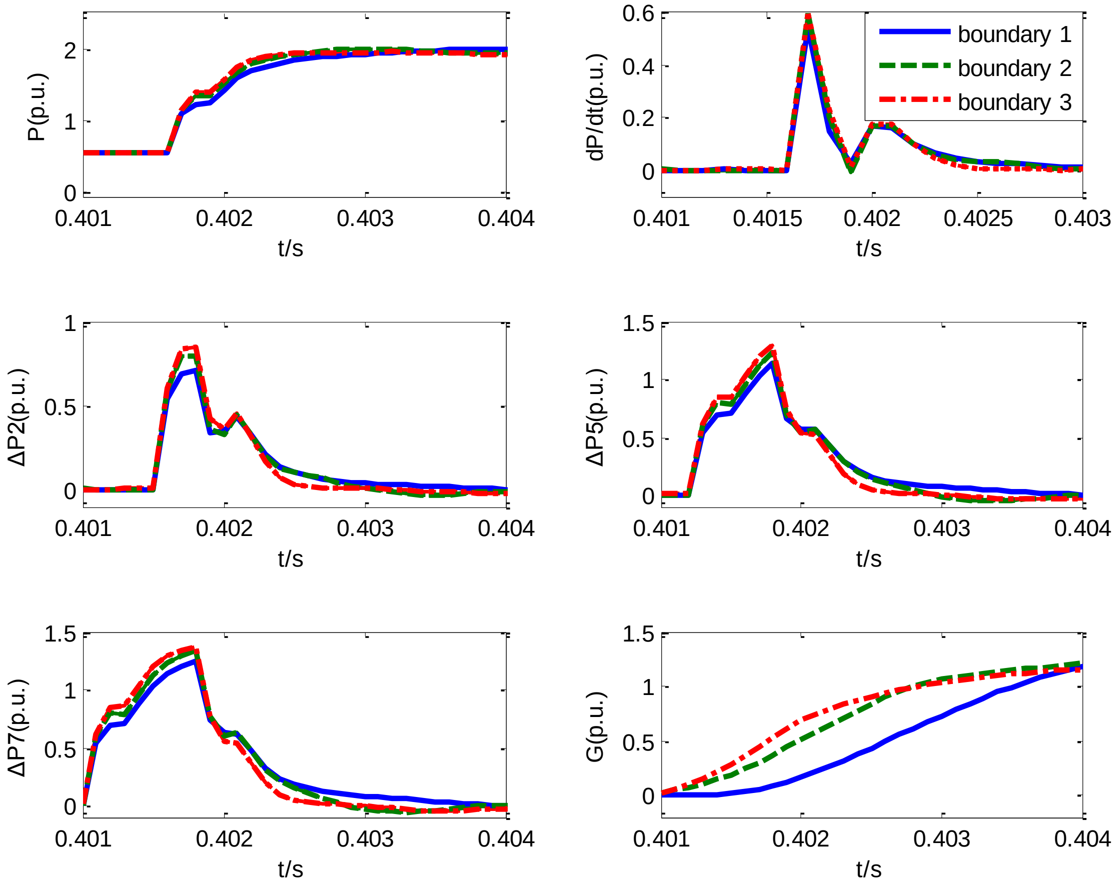


Figure 3-10 the response curve with different boundary equipment

3.4 Derivative and level protection

3.4.1 Protection principle and criterion

Derivative and level protection is the backup protection of travelling wave protection. Because the transient characteristic of DC voltage u_{dL} and current i_{dL} in the time of fault, DC voltage and current are used as criterion as shown in equation(3-46).

$$\begin{cases} \left|\mathrm{d}u_{\mathrm{dL}} / \mathrm{d}t\right| > \Delta_1 \\ \left|u_{\mathrm{dL}}\right| < \Delta_2 \\ \mathrm{d}i_{\mathrm{dL}} / \mathrm{d}t > \Delta_3 \end{cases} \tag{3-46}$$

Because of the smoothing effect of DC filter and smoothing reactor, the derivative of voltage for fault on the DC transmission line is much higher than that outside of DC transmission line. The level part are provided to prevent inadvertent operation due to voltage transients. Criterion di/dt is designed to distinguish the DC line fault and faults at

DC switch station, as that a high positive di/dt indicates the fault is located on the DC transmission line, while a high negative di/dt implicates a fault in the DC yard.

3.4.2 Protection algorithm

Figure 3-11 shows the algorithm flowchart of derivative and level protection. As shown in the figure, du/dt is calculated by differentiator, when it meets the criterion, one pulse signal is given, which would be broadened to 20ms by MOF module, in which the level and di/dt criterion are judged. If all the criterions meet the thresholds, the derivative and level protection would trip.

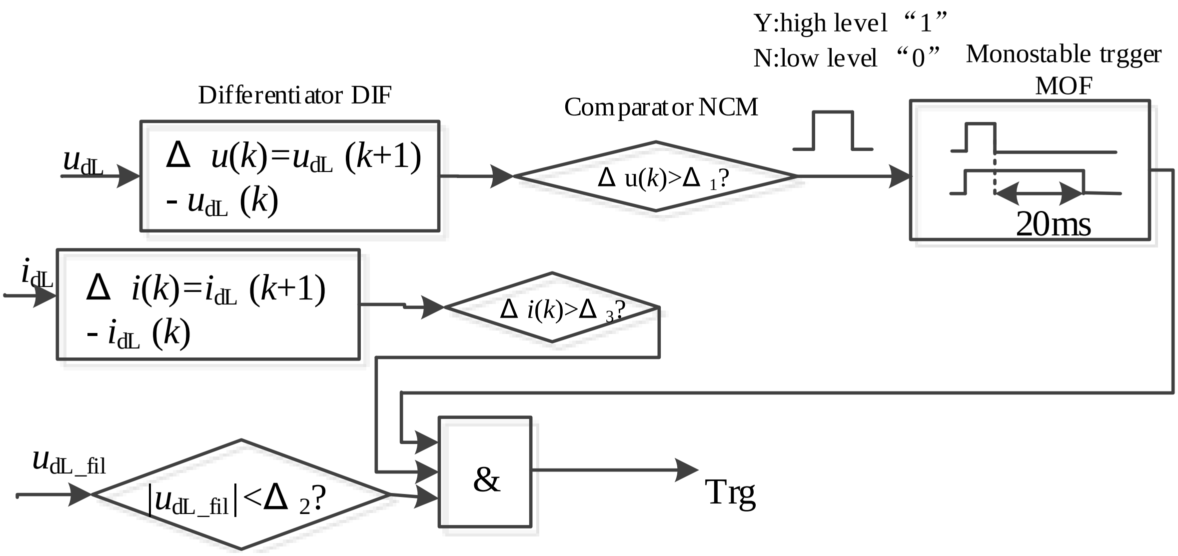


Figure 3-11 the algorithm flowchart of derivative and level protection

3.4.3 Setting principle of thresholds

3.4.3.1 du/dt

Similar to dP/dt, du/dt is designed to discriminate whether the fault occurs in or outside the DC transmission line. So the threshold is also determined according to the most serious fault outside the DC transmission line, as shown in equation(3-47). The sensitivity coefficient is dependent on the lightest fault inside DC transmission line and $(du/dt)_{set}$, as shown in equation (3-48).

$$(du/dt)_{set} = K_{rel} \cdot (du/dt)_{out\_max} \tag{3-47}$$

$$K_{sen} = (du/dt)_{in\_min} / (du/dt)_{set} \tag{3.48}$$

Where, $(\mathrm{d}u/\mathrm{d}t)_{out\_max}$——the maximum d$u$/d$t$ for all fault outside DC transmission line; $(\mathrm{d}u/\mathrm{d}t)_{in\_min}$——the minimum d$u$/d$t$ for all fault on DC transmission line; K_{rel}——the reliability coefficient, K_{sen}≥1.3~1.5; $(\mathrm{d}u/\mathrm{d}t)_{in\_min}$——minimum d$u$/d$t$ for all fault on DC tranmission line.

3.4.3.2 Voltage level

Voltage level is designed to prevent the disoperation of protection under transients and distinguish the fault pole, so the threshold of voltage level criterion is determined according to the minimum voltage level with fault on the opposite pole as shown in equation(3-49).

$$\left|u_{\mathrm{dl}}\right|_{\mathrm{set}} = K_{\mathrm{rel}} \cdot \left|u_{\mathrm{dl}}\right|_{\mathrm{out.max}} \tag{3-49}$$

Where, $|u_{dL}|_{out\_max}$——the minimum voltage level with fault on the opposite pole; K_{rel}——the reliability coefficient, $K_{rel}<1$. According to the running experience, $|U_{dL}|$ is given as 0.5p.u.

3.4.3.3 di/dt

On basis of function of di/dt criterion, the threshold of criterion di/dt is determined according to the minimum di/dt for the fault on DC line as shown in equation(3-50).

$$\left(\mathrm{d}i/\mathrm{d}t\right)_{\mathrm{set}} = \left(\mathrm{d}i/\mathrm{d}t\right)_{\mathrm{in\_min}} \big/ K_{\mathrm{sen\_min}} \tag{3-50}$$

Where, $(\mathrm{d}i/\mathrm{d}t)_{in\_min}$——the minimum d$i$/d$t$ with fault on DC transmission line; $K_{sen.min}$——the minimum sensitivity coefficient that meets requirement.

3.4.4 Operating characteristic

Similar to travelling wave, criterion of derivative and level protection is affected by fault condition. In the following part, the effect of fault distance, fault impedance, sampling frequency, boundary elements and control system on the criterion is analyzed.

3.4.4.1 Fault impedance

The fault occurs at 0.5s at the point on DC transmission line 580km far from rectifier with zero impedance, 100Ω and 500Ω fault impedance. The simulation step is 1μs. Figure 3-12 shows the simulation result, which indicates the fault impedance merely affects the amplitude of voltage and current.

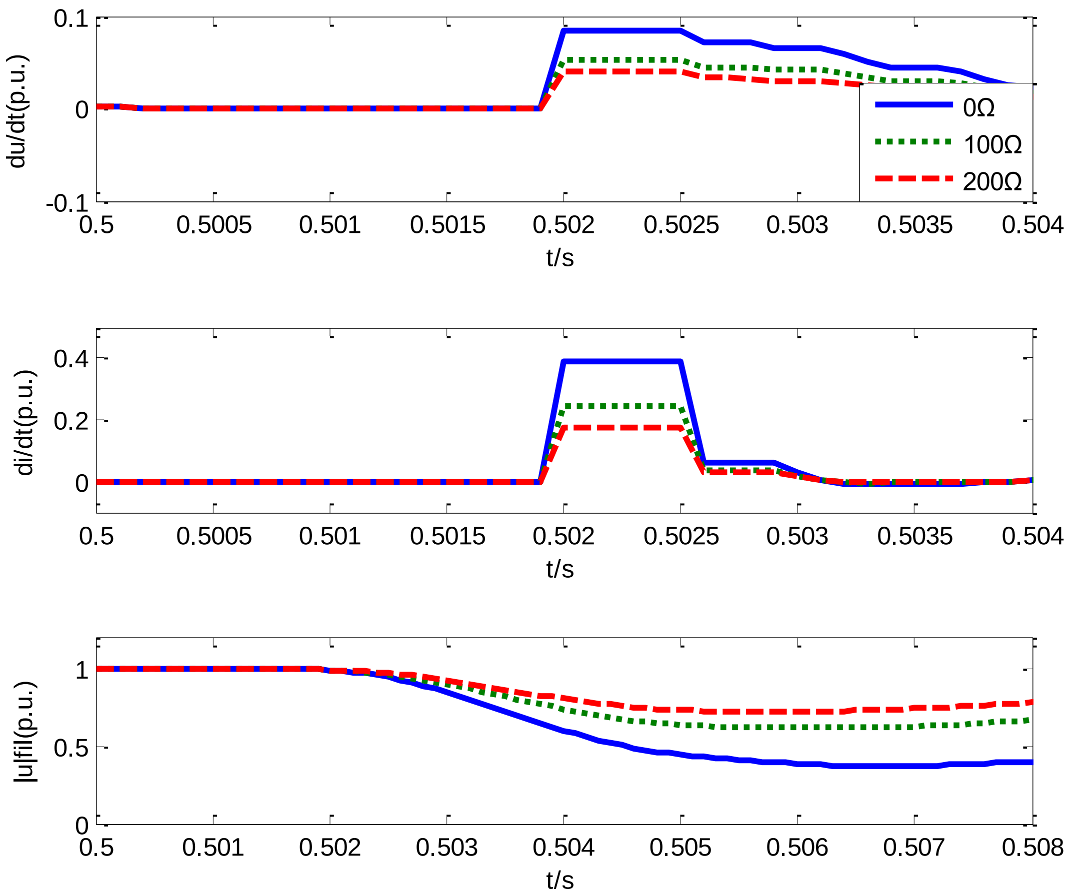


Figure 3-12 the response curve under different fault impedance

3.4.4.2 Sampling frequency

Similar to travelling wave protection, fault cases with10 kHz and 100 kHz sampling frequency are simulated to find out the effect of technique on protection. Simulation condition: single line grounded fault occurs at 0.4s at the point 977km far from rectifier under sampling frequency 100kHz and 10kHz. Figure 3-13 shows the simulation results. which indicates under higher sampling frequency, the voltage is more close to the real voltage and du/dt and di/dt are larger than the lower sampling frequency. Therefore, under higher sampling frequency, the derivative and level protection has better performance.

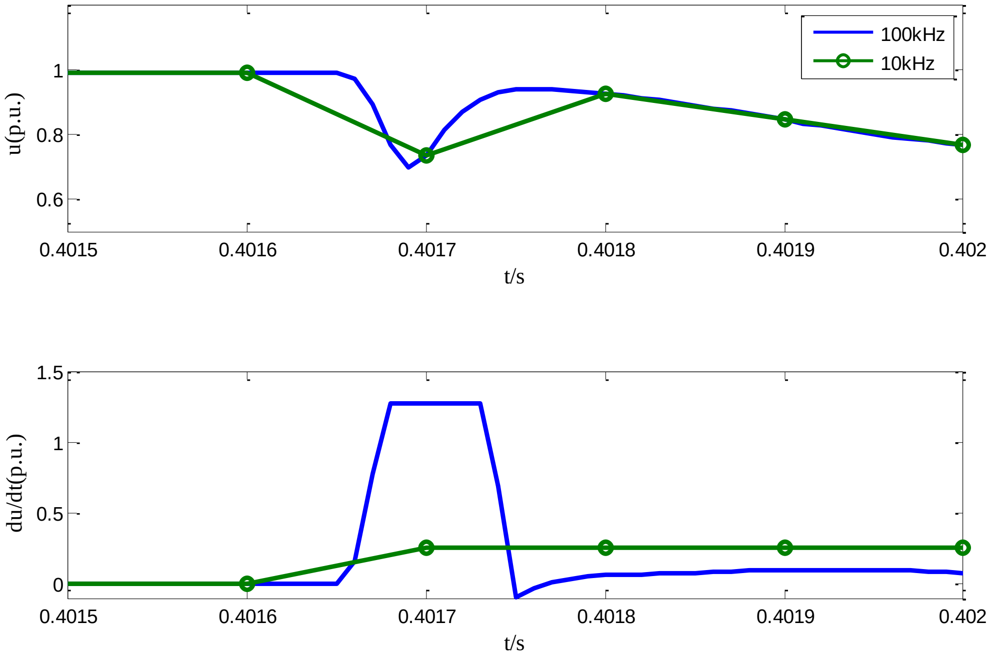


Figure 3-13 the response curve under different sampling frequency

3.4.4.3 Fault distance

Simulation condition: single line grounded fault occurs at 0.4s and at the point 750km and 977km far from rectifier under sampling frequency 100kHz and 10 kHz. Figure 3-14 shows the simulation results.

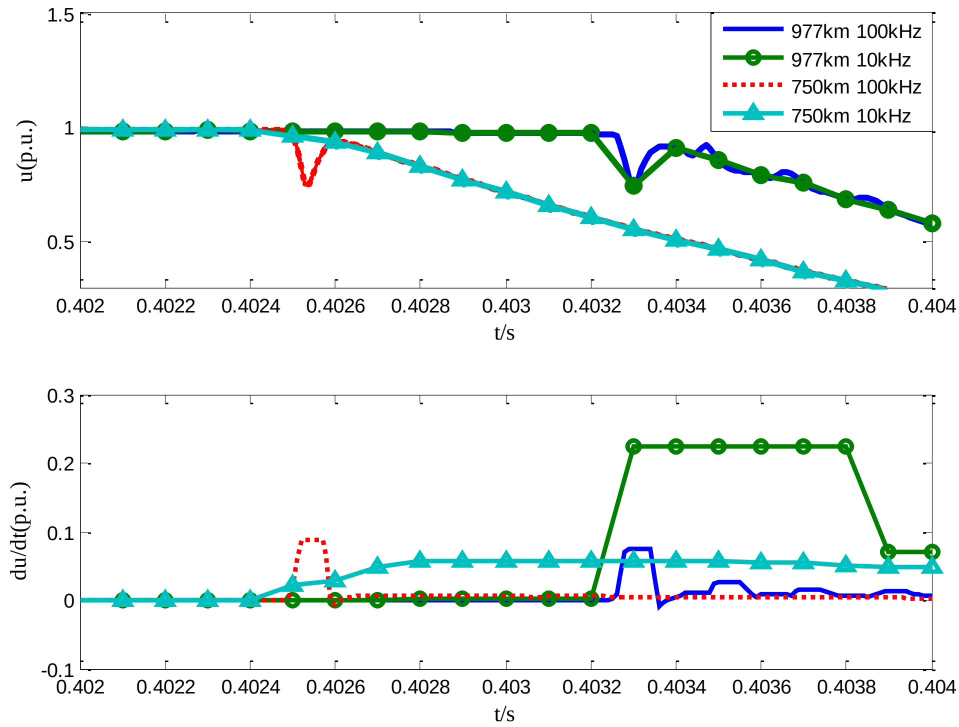


Figure 3-14 the response curve under different fault distance

From Figure 3-14, it indicates there is an overshoot just after fault which is because the delay of common wave compared to pole wave. Similar to travelling wave protection, under sampling frequency100kHz, the voltage decreases with the increase of fault distance, while under sampling frequency 10 kHz, there is no such regulation.

3.4.4.4 Control system

Simulation condition: direct to ground fault at the point 500km far from rectifier at 0.4s with VDCOL output as 0.55p.u. and 0.25 p.u which are symbolized as control mode 1 and control mode 2 correspondingly. Figure 3-15 shows the simulation result, which indicates that control system begin to operate at 6ms after fault, when derivative and level protection is acting. But d*u*/d*t* and d*i*/d*t* has achieved the highest value, so they are less affected by control system.

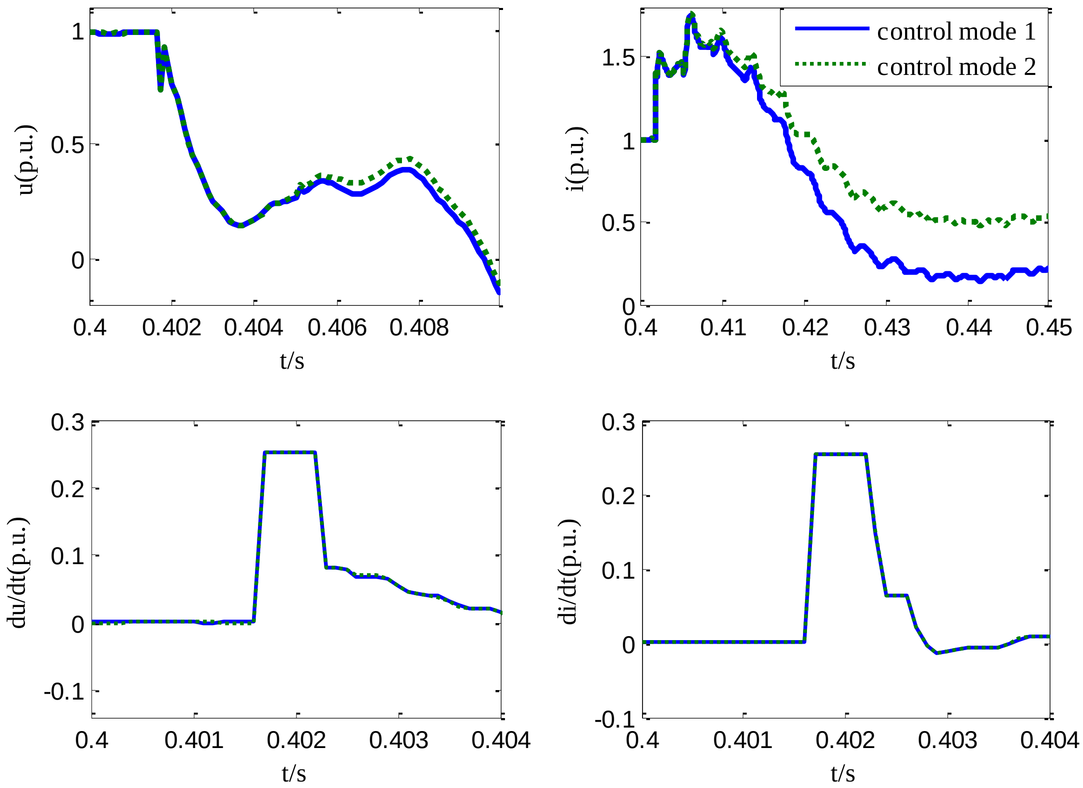


Figure 3-15 the response curve under different control system

3.4.4.5 Boundary equipment

The fault occurs at the point 500km far from rectifier with three kind of boundary elements: merely smoothing reactor; smoothing reactor and 6/12 dual tuner DC filter; smoothing reactor, 6/12 and 24/36 dual tuner DC filter, which are corresponding to the solid line, short dashed line and long dashed line in Figure 3-16. As shown in the figure, the protection criterion is largely affected by the boundary elements because the maximum of d*u*/d*t* and d*i*/d*t* appears near the first wave front. While the boundary equipment changes the spectrum of wave. For this reason, the boundary equipment has great impact on protection, and even the derivative and level protection cannot operate correctly.

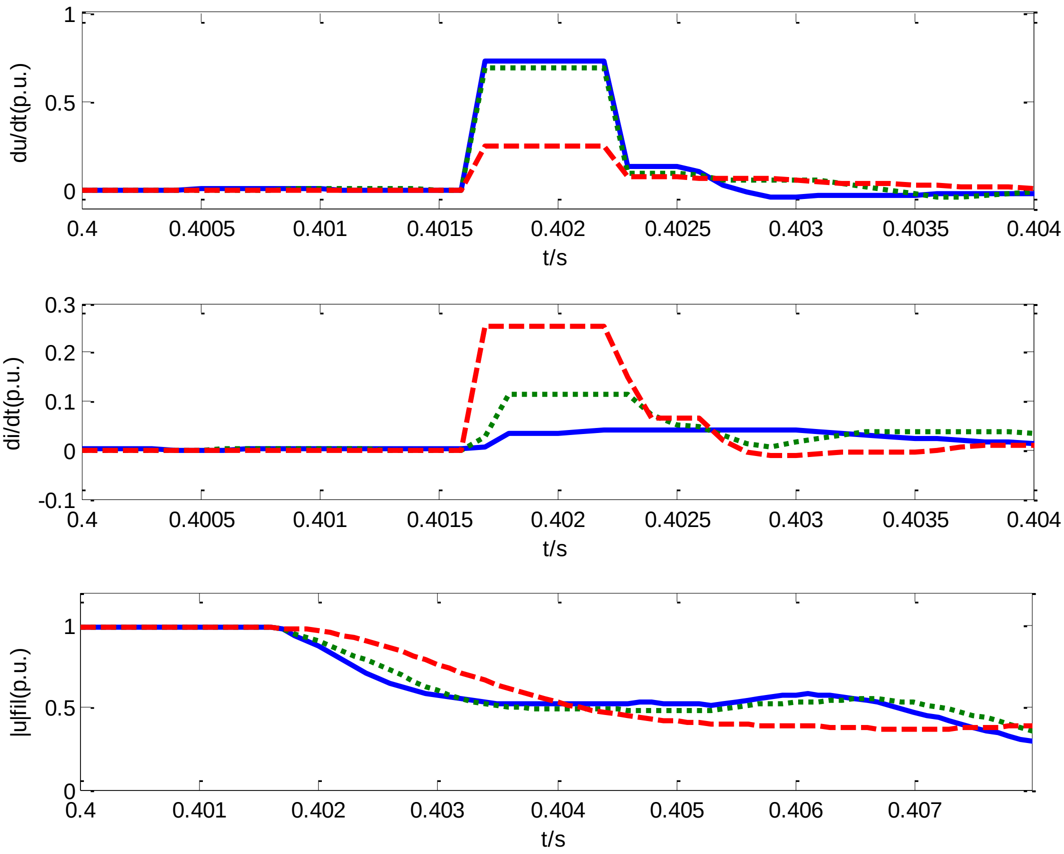


Figure 3-16 the response curve under different boundary equipment

3.5 DC line longitudinal differential protection

3.5.1 Protection principle and criterion

DC line longitudinal differential protection is the backup protection of travelling wave protection and derivative and level protection. The pole line current at both converters are measured and compared. The protection criterion is shown as in equation(3-51), i_{dL} is the DC current in one converter side, $i_{\mathrm{dL\_os}}$ is the DC current in the opposite converter side.

$$\left| i_{dL} - i_{dL\_os} \right| > \Delta \tag{3-51}$$

Under steady state operation or with fault occuring outside DC line, the pole line current at both converters are equal; under DC line fault, the pole line current at both converters are not equal anymore, so according to this transient feature, the differential current can be used to distinguish fault on DC line.

But as longitudinal differential protection criterion is mere the comparison of currents at both converters, not considering the effect of distributed capacitors of DC line, which discharges and adds current branches under transient disturbance. So, in order to eliminate the disoperation, the longitudinal differential protection can be used only after the transient period.

3.5.2 Protection algorithm

Figure 3-17 shows the algorithm flowchart of longitudinal differential protection. As shown in the figure, if the difference of current in both stations is greater than the threshold, the protection is blocked and can only activate and operate after 500ms delay. Because considering the effect of DC line transmission line, the current in rectifier side and its current after 65ms are compared. If the difference is greater than 3.5%, then the protection will be blocked for 600ms.

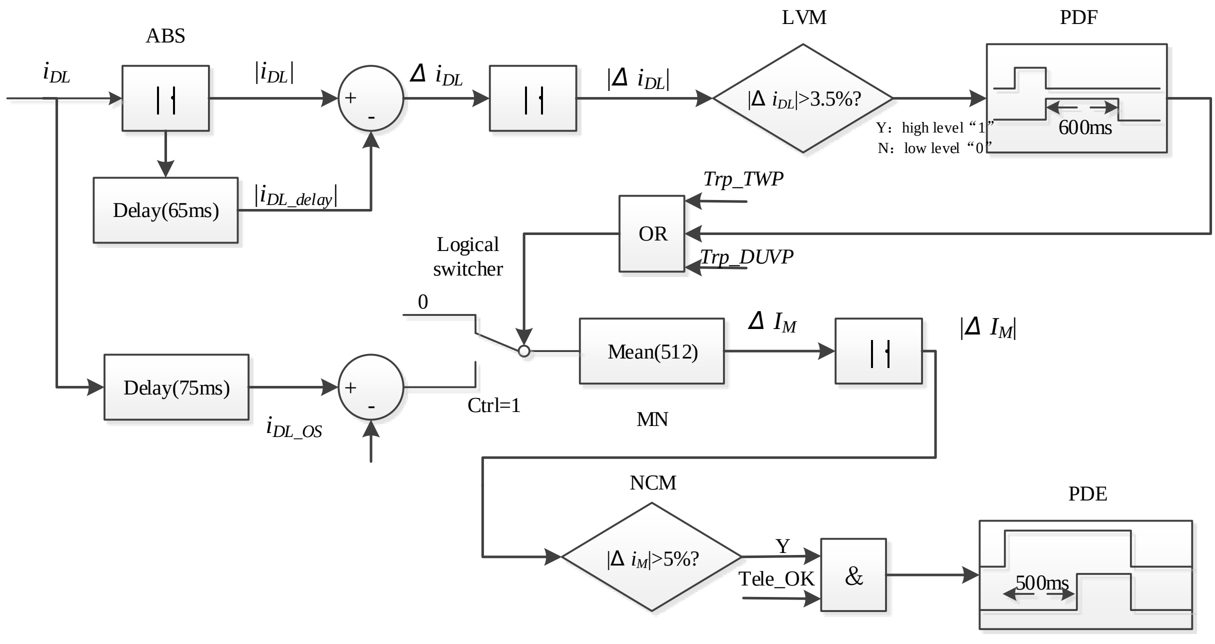


Figure 3-17 the algorithm flowchart of longitudinal differential protection

3.5.3 Setting principle for threshold

According to the different characteristic of ΔI under steady state and DC line fault, the threshold of Δi should be set for the purpose of not disoperation under any other transient state except DC line fault. So the threshold shoulder be greater than the maximum Δi under normal operation or fault outside DC transmission line as shown in equation(3-52).

$$\left|i_{\mathrm{dL}} - i_{dL\_os}\right|_{\mathrm{set}} > K_{\mathrm{rel}} \cdot \left|i_{\mathrm{dL}} - i_{\mathrm{dL\_os}}\right|_{\mathrm{out.max}} \qquad (3\text{-}52)$$

Where, $|i_{\mathrm{dL}}\text{-}i_{\mathrm{dL\_os}}|_{\mathrm{set}}$——maximum ΔI under normal operation or fault outside DC line，K_{rel}——reliability coefficient. according to running experience, $|i_{\mathrm{dL}}\text{-}i_{\mathrm{dL\_os}}|_{\mathrm{set}}$ =0.05p.u.。

3.5.4 Operating characteristic

Similar to travelling wave protection and derivative and level protection, the DC line longitudinal differential protection criterion is also affected by fault condition. In the following parts, by simulation, the effect of fault distance and fault impedance on protection criterion are analyzed.

3.5.4.1 Fault distance

Simulation condition: single line grounded fault at point 280km and 580km far from rectifier. Figure 3-18 shows the response curve under different fault distance. In the figure, from the top to bottom, the curves are pole line current, differential current, difference of current between 65ms and block signal correspondingly. As shown in figure, the effect of fault distance on differential current is very light. When the sampling frequency is high, the difference of current between 65ms is large, so the block signal is longer. But since the sampling frequency of longitudinal differential protection is low, so fault distance has limited effect on the protection.

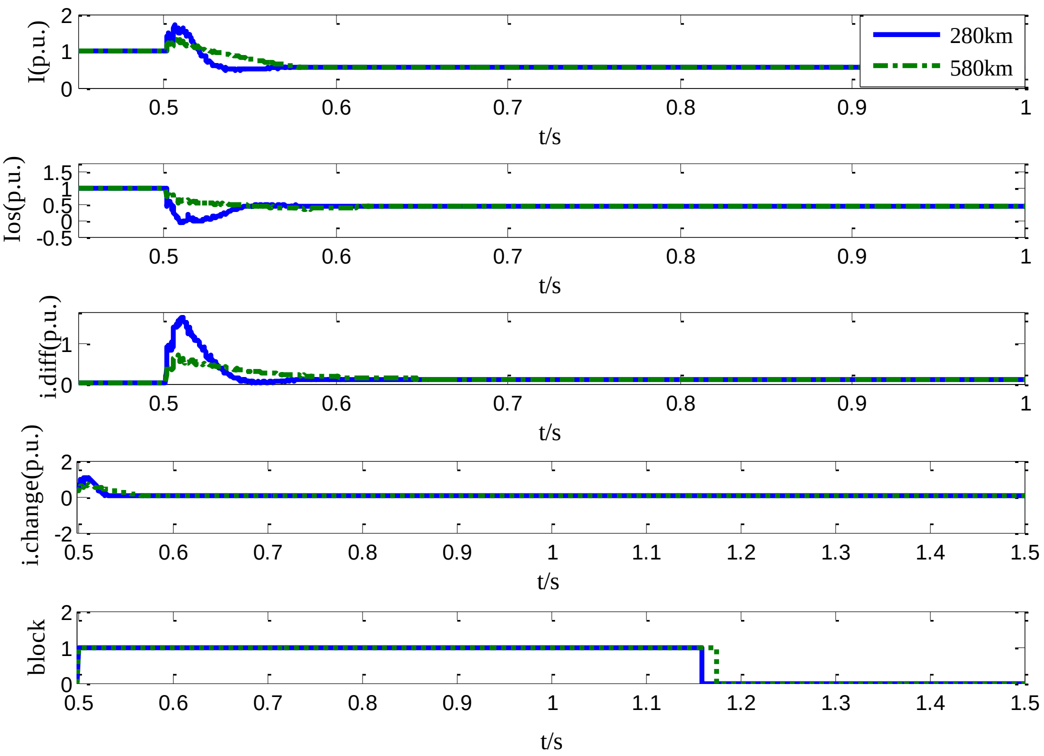


Figure 3-18 the response curve under different fault distance

3.5.4.2 Fault impedance

Figure 3-19 shows the response curve of protection under fault at point 580km far from rectifier with zero impedance and 200Ω fault impedance. As shown in the figure, the differential current increases with the decrease of fault impedance. And after the oscillating transient period, the differential current has the same stable value.

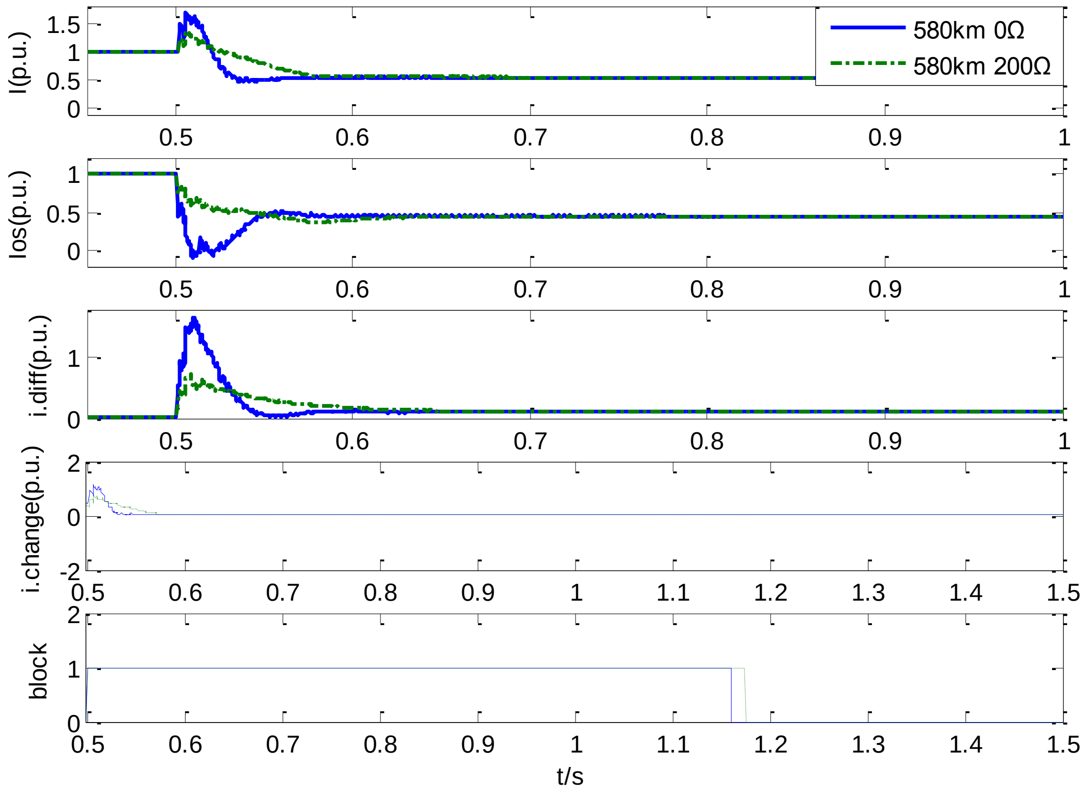


Figure 3-19 the response curve under different fault impedance

3.6 Conclusion

In this chapter, firstly, the principle, criterion and setting principle of each DC line protection are introduced in detail. Then, by simulation and analysis, the operating characteristic of each DC line protection is get:

3.6.1 Travelling wave protection

High sampling frequency can capture the wave front more accurately, so the derivative of pole wave is higher; under the high sampling frequency, pole wave increases with the decrease of fault distance, while under the low sampling frequency, there is no such regulation; fault impedance merely has effect on the amplitude of pole wave and common wave; boundary element merely have light effect on pole wave, while common wave is much more affected.

3.6.2 Derivative and level protection

High sampling frequency can capture the wave front more accurately, so the derivative of voltage is higher; under the high sampling frequency, voltage increases with the decrease of fault distance, while under the low sampling frequency, there is no such regulation; fault impedance merely has effect on the amplitude of voltage and current; voltage and current is highly affected by boundary equipment.

3.6.3 DC line longitudinal differential protection

Fault distance has light effect on differential current; differential current increases with the decrease of fault impedance, and after oscillating transient period, the differential current goes to the same stable value.

4 THE OVERALL OPERATING CHARACTERISITC OF HVDC TRANSMISSION LINE PROTECTION

The operating characteristic of DC transmission line protection embody on reliability, sensitivity and speed. Reliability means that the DC transmission line protection can be reliable to operate when there is fault on DC line, and reliable not to operate when without DC line fault. By setting the proper threshold, the reliability can be meet. In the following part, the sensitivity and speed of each DC transmission line protection and overall DC transmission line protection are be analyzed.

4.1 Travelling wave protection

4.1.1 Sensitivity

According to setting principle of threshold, the maximum dP/dt for fault outside of DC transmission line should be found. So fault outside DC transmission line are simulated. Since three phase grounded fault is the most serious fault for fault in AC system, the fault type in AC system is three phase grounded fault, as shown in Figure 4-1. By simulation, the maximum of dP/dt for several kinds of fault outside DC line are gained as shown in Table 4-1. From the simulation, the maximum dP/dt of the entire fault outside DC line is 0.064.

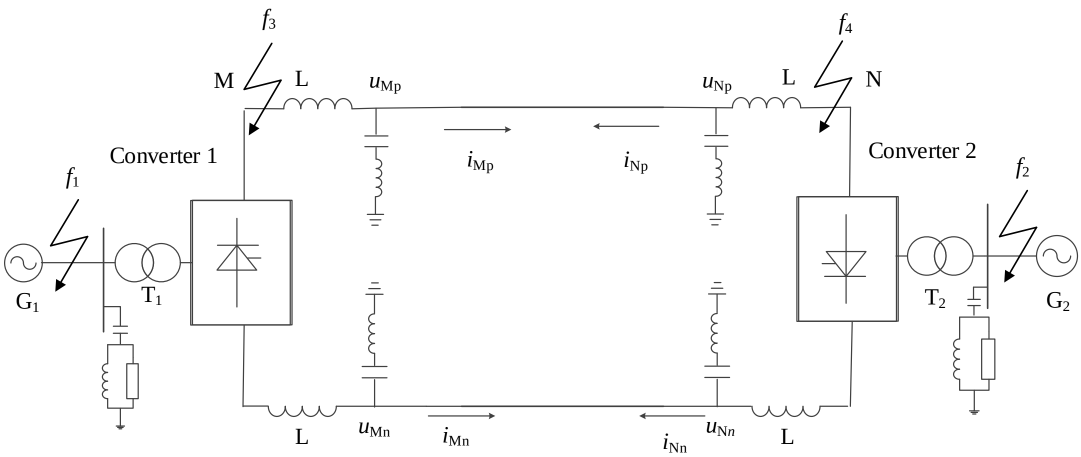


Figure 4-1 fault type outside DC transmission line

Table 4-1 the maximum d*P*/d*t* for fault outside of DC line

Fault type	f_1	f_2
(d*P*/d*t*)max/(p.u./(0.1ms))	0.0285	0.0365
Fault type	f_3	f_4
(d*P*/d*t*)max/(p.u./(0.1ms))	0.0285	0.064

Taking the reliable coefficient as K_{rel}=1.3, so the threshold for d*P*/d*t* is as:

$$\left(\mathrm{d}P/\mathrm{d}t\right)_{set} = K_{rel} \cdot (\mathrm{d}P/\mathrm{d}t)_{\mathrm{out\_max}} = 0.0963\mathrm{p.u.}/\left(0.1ms\right) \quad (4\text{-}1)$$

Assuming the required sensitivity for protection is K_{sen}=1.5, so the minimum d*P*/d*t* for DC line fault for which pole wave criterion can be met is as:

$$\left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{in\_min}} = K_{sen} \cdot \left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{set}} = 0.1445\mathrm{p.u.}/\left(0.1ms\right) \quad (4\text{-}2)$$

From the analysis of operating characteristic of travelling wave protection, fault in the end of the line with fault impedance has the lowest d*P*/d*t*. By setting different fault impedance and by simulation, d*P*/d*t* for fault in the end of DC line with 70Ω fault impedance is 0.1483. so the maximum fault impedance under which travelling wave protection can operate reliably is 70Ω。

By simulation of the fault in the end of DC transmission line with 70Ω fault impedance, the minimum Δ*G* for fault in the protection zone is gained as 0.1103 p.u. According to the setting principle for the threshold of common wave, taking the sensitivity as $K_{sen.min}$=2.5, so the threshold of common wave is shown in equation

$$\left(\Delta G\right)_{\mathrm{set}} = \Delta G_{in\_\min} / K_{sen} = 0.0441\mathrm{p.u.} \quad (4\text{-}3)$$

In overall, the threshold values and fault impedance travelling wave protection can detect can be concluded in Table 4-2.

Table 4-2 the threshold of common wave

Criterion	d*P*/d*t* (p.u./(0.1ms))	Δ*G* (p.u.)	Fault impedance(Ω)
Threshold	0.0963	0.0441	70

4.1.2 Speed

Fault in the end of the DC line under 70Ω fault impedance is the lightest fault in protection zone as it has the minimum pole wave and common wave, so under this fault type, the travelling protection has the longest operation time. By simulation, the response curve of lightest fault is shown in Figure 4-2. The time for protection to operate is calculated after the fault occurs. From the simulation result, it indicates that d*P*/d*t* meets the criterion after 3.3ms, its value is 0.1483p.u./（0.1ms）, and then calculate ΔP_2，ΔP_5，ΔP_7, the results are 0.4450p.u.，0.5568p.u.，0.5903p.u. correspondingly, which are greater than the threshold, so it indicates there is fault on the DC line. Then calculating ΔG, and because common wave propagates slower than the pole wave, so the accurate time for common wave to arrive the protection equipment is unknown. In practical project, 10 sampling points of the common wave are measured after the pole wave meets the criterion. From the simulation result, ΔG meets the criterion at 5ms, and its value is 0.1101p.u. So the time for travelling wave protection to operate is 5ms. Table 4-3 shows the corresponding response value of fault in the end of DC line with 70Ω fault impedance.

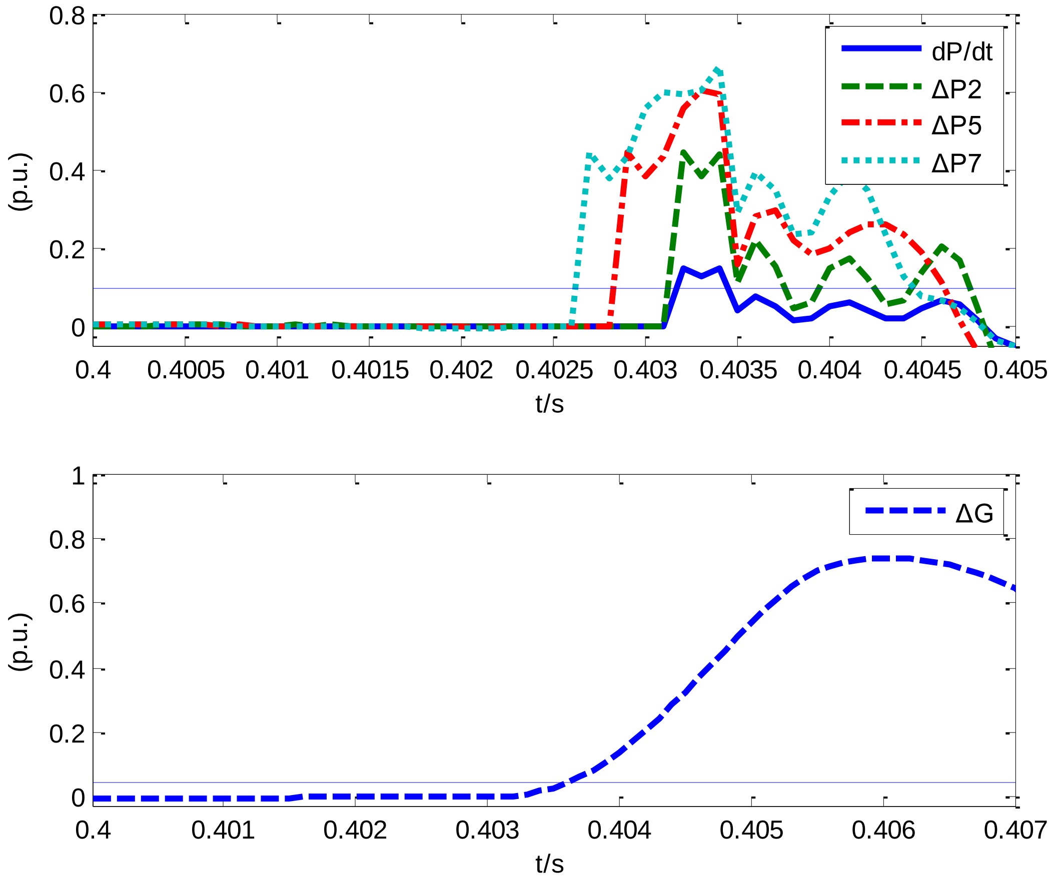


Figure 4-2 the response curve of fault in the end of DC line with 70Ω fault impedance

Table 4-3 the response value of fault in the end of DC line with 70Ω fault impedance

criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
time(ms)	3.3	4.0			5.0
Criterion value(p.u.)	0.1483	0.4450	0.5568	0.5903	0.1101
discrimination	1.5403	4.6208	5.7822	6.1302	2.4966

From the simulation, the conclusion can be drawn as：Travelling wave is speedy to operate within 5ms, but the sensitivity is low, the fault impedance it can detect is only 70Ω, so it relays on the backup protection to operate for fault with high fault impedance.

4.2 Derivative and level protection

4.2.1 Sensitivity

According to setting principle of threshold, the maximum du/dt for fault outside of DC line should be found. As seen in the Table 4-1, the fault at the DC switchyard in the inverter is the most serious fault for all fault outside the protection zone. By simulation, the maximum of du/dt is get as $(\mathrm{d}u/\mathrm{d}t)_{out\_max}$=0.0446(p.u./0.1ms). Taking the reliable coefficient K_{rel}=1.1, the threshold of du/dt is as:

$$\left(\mathrm{d}u/\mathrm{d}t\right)_{\mathrm{set}} = K_{\mathrm{rel}} \cdot \left(\mathrm{d}u/\mathrm{d}t\right)_{out\_\max} = 0.049\,\mathrm{p.u.}/\left(0.1\mathrm{ms}\right) \qquad (4\text{-}4)$$

Assuming the required sensitivity for protection is K_{sen}=1.3, so the minimum du/dt for DC line fault for which pole wave criterion can be met is $(\mathrm{d}u/\mathrm{d}t)_{in\_min}$=0.064p.u./ (0.1ms).

By setting different fault impedance and by simulation, du/dt for fault in the end of DC line with 50Ω fault impedance is 0.0657p.u./ (0.1ms). So the maximum fault impedance under which travelling wave protection can operate reliably is 50Ω。

According to the setting principle for the threshold of di/dt, taking the sensitivity as $K_{sen.min}$=2.5, so the threshold of di/dt is shown as:

$$\left(\mathrm{d}i/\mathrm{d}t\right)_{\mathrm{set}} = \left(\mathrm{d}i/\mathrm{d}t\right)_{\mathrm{sen.min}} \big/ K_{\mathrm{sen.min}} = 0.0238\,\mathrm{p.u.}/\left(0.1\mathrm{ms}\right) \qquad (4\text{-}5)$$

So the threshold for derivative and level protection is shown in Table 4-4.

Table 4-4 the threshold of derivative and level protection

Criterion	d*u*/d*t*	$\lvert U_{dL\_fil}\rvert$	d*i*/d*t*	Fault impedance
Threshold（p.u.）	0.049	0.5	0.0238	50Ω

4.2.2 Speed

Similar to travelling wave protection, the fault in the end of DC line with 50Ω fault impedance is simulated and analyzed to know the operating time of derivative and level protection. Figure 4-3 and Table 4-5 are the simulation result, which indicates that d*u*/d*t* meets criterion at 3.4ms, then a positive pulse is given, which is broadened to 20ms; d*i*/d*t* meets the criterion at 3.5ms; $\lvert U_{dL\_fil}\rvert$ meets criterion at 26.4ms, so the derivative and level protection operates at 26.4ms.

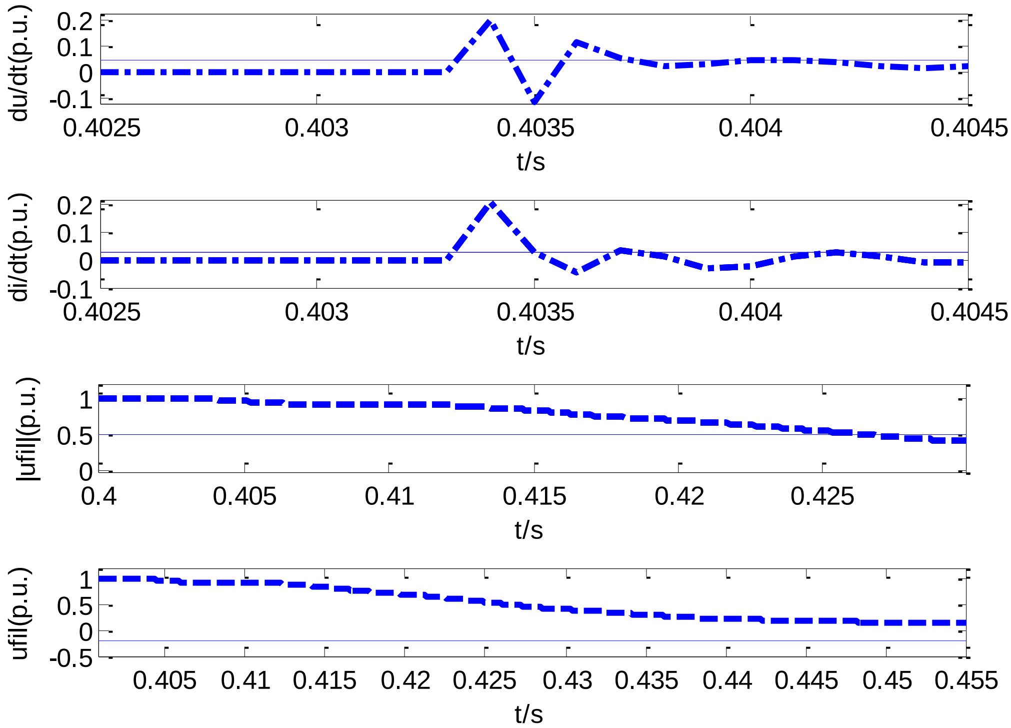


Figure 4-3 the response curve for fault in the end of DC line under 50Ω fault impedance

Table 4-5 the response value for fault in the end of DC line under 50Ω fault impedance

Criterion	d*u*/dt	d*i*/dt	$\lvert U_{dL\_fil}\rvert$
Time(ms)	3.5	3.8	10.3
Criterion value(p.u.)	0.0608	0.2178	0.2421

From the simulation result, the conclusion about the operating characteristic of derivative and level protection can be drawn as: it is not speedy as travelling wave protection, as its time to operate is 26.4ms; the sensitivity is low, as the fault impedance under which it can detect fault reliably is mere 50Ω, so it relays the DC line longitudinal differential protection to detect DC line fault.

4.3 DC line longitudinal differential protection

According to the running experience, the threshold of differential current is set as 0.05p.u.

4.3.1 Speed

For longitudinal differential protection, the fault impedance and fault distance has light effect. So the specific fault type is not needed to get the operating time. Simulation condition: single line grounded permanent fault at 0.5s at point 500km far from rectifier. Figure 4-4 shows the simulation result, which indicates that after fault the differential increases rapidly, then becomes greater than the threshold, but the current in rectifier between 65ms meets the block condition, so the protection states at block situation for 600ms, after which the differential current is still greater than the threshold, so the protection operates after 500ms delay. Therefore, the operating time of longitudinal differential protection is 1.1017s.

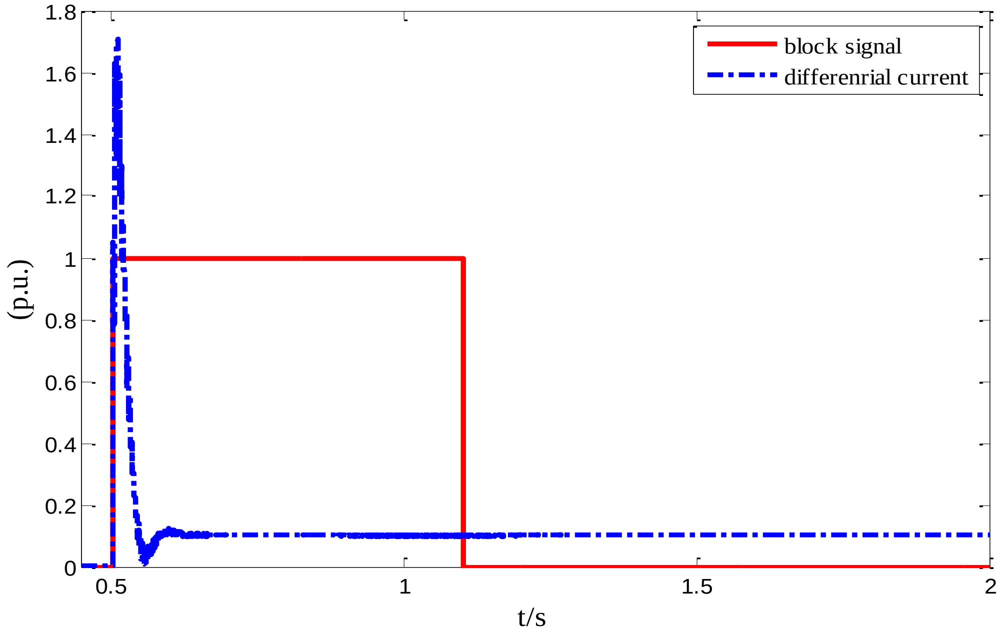


Figure 4-4 the response curve for direct to ground permanent fault on 500km point

4.3.2 Sensitivity

Simulation condition: permanent fault at point 500km far from rectifier under 500Ω impedance, the simulation result is as shown in Figure 4-5. As shown in the figure, in the beginning of fault, differential current decreases with the increase of fault impedance; in the steady state of fault, the converter in both sides goes into the constant current control, and the differential current is stable at 0.1p.u. Therefore, although under high fault impedance, the longitudinal differential protection still can operate. The sensitivity is shown in equation(4-6).

$$K_{sen} = \left| I_{\mathrm{dL}} - I_{\mathrm{dL\_os}} \right| / \left| I_{\mathrm{dL}} - I_{\mathrm{dL\_os}} \right|_{\mathrm{set}} = 2 \qquad (4\text{-}6)$$

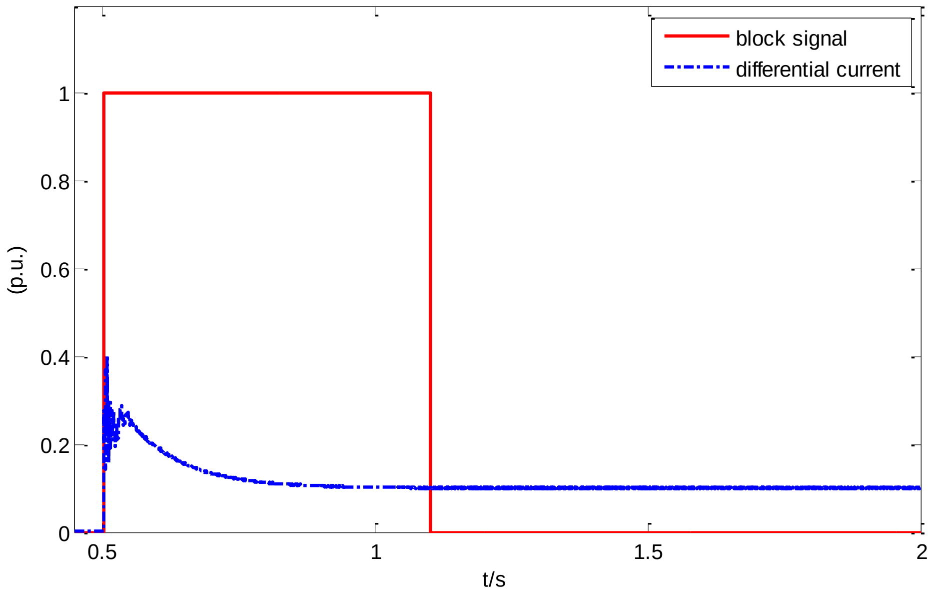


Figure 4-5 the response curve for fault on 500km point under 500Ω fault impedance

4.4 The overall operating characteristic of DC line protection

In the following parts, the operating characteristic of DC transmission line protection under DC line fault or fault outside the protection zone is analyzed.

4.4.1 Fault in the protection zone

Fault in the protection zone can be classified into several type of fault, in the following part, the operating characteristic of DC line protection under fault with different fault impedance and fault distance are analyzed.

4.4.1.1 Fault impedance

Simulation condition: simulation step 10μs, sampling frequency 10 kHz, fault occurs at 0.4s and 750km far from rectifier under 50Ω, 200Ω and 300Ω fault impedance.

4.4.1.1.1 50Ω

Table 4-6 is the operating results, which indicates that under such fault condition all DC line main protection and backup protection can operate. Operating time of travelling wave protection is 4.2ms, for derivative and level protection is 26.1ms, for longitudinal differential protection is 1.027s. so the fault is detected by travelling wave protection at 4.3ms.

Table 4-6 the operating results for fault on 750km under 50Ω impedance

Travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Acting Time(ms)	2.5	2.8	3.1	3.3	4.3
	Value(p.u.)	0.1711	0.5132	0.5417	0.7245	0.3117
	Discrimination	1.7763	5.3288	5.6253	7.5230	7.0686
Derivative and level protection	Criterion	du/dt	$\|u_{fil}\|$			di/dt
	Acting Time(ms)	2.6	26.1			2.2
	Value(p.u.)	0.0522	0.4988			0.0369
	Discrimination	1.0651	1.0023			1.5501
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time(ms)	0.0027				0.6027
	Value(p.u.)	--				0.5481
	Discrimination	--				10.9620

4.4.1.1.2 200Ω

Table 4-7 shows the operating results, which indicate that travelling wave protection operates at 4.3ms; while derivative and level protection cannot operate because du/dt and level do not meet the criterion; longitudinal differential protection operates at 1.1027s. so for this fault condition, the fault is detected at 4.3ms.

Table 4-7 the operating results for fault on 750km under 200Ω impedance

	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
Travelling wave protection	Acting Time(ms)	2.5	2.8	3.1	3.3	4.3
	Value(p.u.)	0.1014	0.3042	0.3247	0.4349	0.1872
	Discrimination	1.0531	3.1594	3.3715	4.5161	4.2455
Derivative and level protection	Criterion	du/dt	|u_{fil}|			di/dt
	Acting Time(ms)	--	--			2.2
	Value(p.u.)	--	--			0.0269
	Discrimination	--	--			1.1301
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time(ms)	0.0027				0.6027
	Value(p.u.)	--				0.4601
	Discrimination	--				9.2019

4.4.1.1.3 300Ω

Table 4-8 shows the operating results, which indicates that travelling wave protection and derivative and level protection cannot operate; longitudinal differential protection operates at 1.1027s. So for this fault condition, the fault is detected at 1.1027s.

Table 4-8 the operating results for fault on 750km under 300Ω impedance

	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
Travelling wave protection	Acting Time(ms)	--	--	--	--	--
	Value(p.u.)	--	--	--	--	--
	Discrimination	--	--	--	--	--
Derivative and level protection	Criterion	du/dt	|u_{fil}|			di/dt
	Acting Time(ms)	--	--			--
	Value(p.u.)	--	--			--
	Discrimination	--	--			--
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time(ms)	0.0027				0.6027
	Value(p.u.)	--				0.3160
	Discrimination	--				6.3208

From the simulation of fault in the protection zone with different fault condition, the conclusion can be drawn as:

a) Under low fault impedance, all DC line protection can operate, but with the increase of fault impedance, derivative and level protection is the first not to operate, then travelling wave protection.
b) When the fault impedance is shorter than 200Ω, traveling wave protection operates to clear transmission line fault, while the fault impedance is greater than 200Ω, longitudinal difference protection operates to clear DC transmission line fault.
c) Travelling wave protection can trip quite speedy.
d) Derivative and level protection has worse speed compared to travelling wave protection, and the fault impedance under which it can detect fault is low, which is the reason derivative and level protection cannot operate accurately.
e) Longitudinal difference protection has the poorest speed, but it can operate under such fault type with very high fault impedance.

4.4.1.2 Fault distance

Simulation condition: simulation step 10μs, sampling frequency 10 kHz, fault occurs at 0.4s under 100Ω fault impedance 100km and 900km far from rectifier.

4.4.1.2.1 100km

Table 4-9 shows the operating results, which indicate that under such fault condition all DC line main protection and backup protection can operate. Operating time of travelling wave protection is 2.1ms, for derivative and level protection is 12.3ms, for longitudinal differential protection is 1.1005s. so the fault is detected by travelling wave protection at 2.1ms.

4.4.1.2.2 900km

Table 4-10 shows the operating results which indicate that travelling wave protection operates at 4.8ms; while derivative and level protection cannot operate because du/dt and level do not meet the criterion; longitudinal differential protection operates at 1.1032s. So for this fault condition, the fault is detected at 4.8ms.

Table 4-9 the operating results for fault on 100km under 100Ω impedance

<table>
<tr><td rowspan="4">Travelling wave protection</td><td>Criterion</td><td>dP/dt</td><td>Δ P_2</td><td>Δ P_5</td><td>Δ P_7</td><td>Δ G</td></tr>
<tr><td>Acting Time(ms)</td><td>0.3</td><td>0.6</td><td>0.9</td><td>1.1</td><td>2.1</td></tr>
<tr><td>Value(p.u.)</td><td>0.2477</td><td>0.7432</td><td>0.9670</td><td>0.9950</td><td>0.6780</td></tr>
<tr><td>Discrimination</td><td>2.5725</td><td>7.7174</td><td>10.041</td><td>10.3321</td><td>15.3753</td></tr>
<tr><td rowspan="4">Derivative and level protection</td><td>Criterion</td><td>du/dt</td><td colspan="3">$|u_{\mathrm{fil}}|$</td><td>di/dt</td></tr>
<tr><td>Acting Time(ms)</td><td>0.3</td><td colspan="3">12.3</td><td>0.1</td></tr>
<tr><td>Value(p.u.)</td><td>0.0702</td><td colspan="3">0.4998</td><td>0.0600</td></tr>
<tr><td>Discrimination</td><td>1.4318</td><td colspan="3">1.0004</td><td>2.5192</td></tr>
<tr><td rowspan="4">Longitudinal differential protection</td><td>Criterion</td><td colspan="4">Block signal</td><td>i_{diff}</td></tr>
<tr><td>Acting Time(s)</td><td colspan="4">0.0005</td><td>0.6005</td></tr>
<tr><td>Value(p.u.)</td><td colspan="4">--</td><td>0.5483</td></tr>
<tr><td>Discrimination</td><td colspan="4">--</td><td>10.9655</td></tr>
</table>

Table 4-10 the operating results for fault on 900km under 100Ω impedance

<table>
<tr><td rowspan="4">Travelling wave protection</td><td>Criterion</td><td>dP/dt</td><td>Δ P_2</td><td>Δ P_5</td><td>Δ P_7</td><td>Δ G</td></tr>
<tr><td>Acting Time(ms)</td><td>3.0</td><td>3.3</td><td>3.6</td><td>3.8</td><td>4.8</td></tr>
<tr><td>Value(p.u.)</td><td>0.1138</td><td>0.3414</td><td>0.7302</td><td>0.4144</td><td>0.1542</td></tr>
<tr><td>Discrimination</td><td>1.1817</td><td>3.5451</td><td>3.6355</td><td>4.3027</td><td>3.4976</td></tr>
<tr><td rowspan="4">Derivative and level protection</td><td>Criterion</td><td>du/dt</td><td colspan="3">$|u_{\mathrm{fil}}|$</td><td>di/dt</td></tr>
<tr><td>Acting Time(ms)</td><td>--</td><td colspan="3">--</td><td>2.7</td></tr>
<tr><td>Value(p.u.)</td><td>--</td><td colspan="3">--</td><td>0.0300</td></tr>
<tr><td>Discrimination</td><td>--</td><td colspan="3">--</td><td>1.2598</td></tr>
<tr><td rowspan="4">Longitudinal differential protection</td><td>Criterion</td><td colspan="4">Block signal</td><td>i_{diff}</td></tr>
<tr><td>Acting Time(s)</td><td colspan="4">0.0032</td><td>0.6032</td></tr>
<tr><td>Value(p.u.)</td><td colspan="4">--</td><td>0.5966</td></tr>
<tr><td>Discrimination</td><td colspan="4">--</td><td>11.9318</td></tr>
</table>

From the simulation of fault on the protection zone with different fault condition, the conclusion can be drawn that with the increase of fault distance, du/dt and level of derivative and level protection cannot meet criterion; Sensitivity of travelling wave protection decreases; longitudinal differential protection can operate under long fault distance.

4.4.2 Fault outside protection zone

4.4.2.1 Fault on the opposite DC line

Table 4-11 shows the operating results which indicate that all DC line protection all cannot operate. For travelling wave protection, dP/dt meet the criterion, but the ΔP and ΔG do not meet the criterion; for derivative and level protection, di/dt meets the criterion, but du/dt and $|u_{fil}|$ do not meet the criterion; for longitudinal differential protection, the differential current do not meet the criterion.

Table 4-11 the operating results for fault on the opposite DC line

Travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Acting Time(ms)	0.8	1.2	--	--	--
	Value(p.u.)	0.2394	0.7182	0.0283	0.0783	-0.8353
	Discrimination	2.4860	7.4579	--	--	--
Derivative and level protection	Criterion	du/dt	$\|u_{fil}\|$			di/dt
	Acting Time(ms)	--	--			0.5
	Value(p.u.)	--	--			0.0626
	Discrimination	--	--			2.6319
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time(s)	0.001				--
	Value(p.u.)	--				0.0015
	Discrimination	--				0.0303

4.4.2.2 Fault in the DC switchyard of the inverter station

Table 4-12 shows the operating results of DC transmission line overall protection under fault in the DC switchyard of the inverter station. From the simulation results, all DC transmission line protection cannot operate, because the pole wave and common wave criterion of travelling wave protection, criterion du/dt and di/dt of derivative and level protection, criterion i_{diff} of longitudinal differential protection cannot meet the threshold.

Table 4-12 the operating results for fault in the DC switchyard of the inverter station

<table>
<tr><td rowspan="4">Travelling wave protection</td><td>Criterion</td><td>dP/dt</td><td>Δ P_2</td><td>Δ P_5</td><td>Δ P_7</td><td>Δ G</td></tr>
<tr><td>Acting Time (ms)</td><td>--</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Value(p.u.)</td><td>7.1562 e-004</td><td>0.0017</td><td>0.0027</td><td>0.0022</td><td>0.27998</td></tr>
<tr><td>Discrimination</td><td>0.0085</td><td>0.0108</td><td>0.0170</td><td>0.0138</td><td>0.5652</td></tr>
<tr><td rowspan="4">Derivative and level protection</td><td>Criterion</td><td>du/dt</td><td colspan="3">$|u_{\text{fil}}|$</td><td>di/dt</td></tr>
<tr><td>Acting Time (ms)</td><td>--</td><td colspan="3">6.1</td><td>--</td></tr>
<tr><td>Value(p.u.)</td><td>0.0089</td><td colspan="3">0.2399</td><td>5.3616e-004</td></tr>
<tr><td>Discrimination</td><td>0.1987</td><td colspan="3">1.0423</td><td>0.0032</td></tr>
<tr><td rowspan="4">Longitudin al differential protection</td><td>Criterion</td><td colspan="4">Block signal</td><td>i_{diff}</td></tr>
<tr><td>Acting Time (s)</td><td colspan="4">4.0</td><td>--</td></tr>
<tr><td>Value(p.u.)</td><td colspan="4">--</td><td>3.8325e-004</td></tr>
<tr><td>Discrimination</td><td colspan="4">--</td><td>0.0077</td></tr>
</table>

4.4.2.3 Fault in the AC switchyard of the inverter station

Table 4-13 shows the operating results of DC transmission line overall protection under fault in the AC switchyard of the inverter station. From the simulation results, all DC transmission line protection cannot operate, because the pole wave and common wave criterion of travelling wave protection, criterion du/dt and di/dt of derivative and level protection, criterion i_{diff} of longitudinal differential protection cannot meet the threshold.

4.4.2.4 Fault in the DC switchyard of the rectifier station

Table 4-14 shows the operating results of DC transmission line overall protection under fault in the DC switchyard of the rectifier station. From the simulation results, all DC transmission line protection cannot operate, because the pole wave and common wave criterion of travelling wave protection, criterion di/dt of derivative and level protection, criterion i_{diff} of longitudinal differential protection cannot meet the threshold.

Table 4-13 the operating results for fault in the AC switchyard of the inverter station

Travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Acting Time (ms)	--	--	-	-	--
	Value (p.u.)	7.1570e-004	0.0017	0.0027	0.0022	0.1750
	Discrimination	0.0085	0.0108	0.0170	0.0138	0.3532
Derivative and level protection	Criterion	du/dt	$\|u_{fil}\|$			di/dt
	Acting Time (ms)	--	--			--
	Value (p.u.)	0.0032	--			5.3859e-004
	Discrimination	0.0710	--			0.0032
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time (s)	0.065				--
	Value (p.u.)	--				0.0018
	Discrimination	--				0.0363

Table 4-14 the operating results for fault in the DC switchyard of the rectifier station

Travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Acting Time (ms)	--	--	--	--	--
	Value (p.u.)	0.0116	0.0363	0.0770	0.1045	1.1633
	Discrimination	0.1381	0.2303	0.4889	0.6638	2.3481
Derivative and level protection	Criterion	du/dt	$\|u_{fil}\|$			di/dt
	Acting Time (ms)	1.0	3.7			--
	Value (p.u.)	0.0458	5.5252e-017			-0.0223
	Discrimination	1.0245	4.5247e+015			-0.1331
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time (s)	0.764-2				--
	Value (p.u.)	--				1.6432e-004
	Discrimination	--				0.0033

4.4.2.5 Fault in the AC switchyard of the rectifier station

Table 4-15 shows the operating results of DC transmission line overall protection under fault in the AC switchyard of the rectifier station. From the simulation results, all DC transmission line protection cannot operate, because all criterions cannot meet the thresholds.

Table 4-15 the operating results for fault in the AC switchyard of the rectifier station

Travelling wave protection	Criterion	$\mathrm{d}P/\mathrm{d}t$	ΔP_2	ΔP_5	ΔP_7	ΔG
	Acting Time (ms)	--	--	--	--	--
	Value (p.u.)	0.0072	0.0220	0.0466	0.0628	0.4127
	Discrimination	0.0851	0.1397	0.2960	0.3987	0.8331
Derivative and level protection	Criterion	$\mathrm{d}u/\mathrm{d}t$	$\lvert u_{\mathrm{fil}}\rvert$			$\mathrm{d}i/\mathrm{d}t$
	Acting Time (ms)	--	--			--
	Value (p.u.)	-0.0219	0.4757			-0.0131
	Discrimination	-0.4895	0.5255			-0.0783
Longitudinal differential protection	Criterion	Block signal				i_{diff}
	Acting Time (s)	0.063-2				--
	Value (p.u.)	--				--
	Discrimination	--				--

From the simulation of the fault type outside the DC transmission line protection zone, the conclusion can be drawn as:

a) For fault outside the protection zone, all DC line protection cannot operate, so the DC line protection is reliable.

b) For fault on the opposite DC transmission line, because pole wave and common wave criterion of travelling wave, criterion $\mathrm{d}u/\mathrm{d}t$ and $\lvert u_{\mathrm{fil}}\rvert$ of derivative and level protection, criterion i_{diff} of longitudinal difference protection cannot meet the thresholds, DC transmission line do not trip.

c) For fault in the AC switchyard and DC switchyard of inverter, because pole wave and common wave criterion of travelling wave, criterion $\mathrm{d}u/\mathrm{d}t$ and $\mathrm{d}i/\mathrm{d}t$ of derivative and level protection, criterion i_{diff} of longitudinal difference protection cannot meet the thresholds, DC transmission line protection do not trip.

For fault in the AC switchyard and DC switchyard of rectifier, because pole wave and common wave criterion of travelling wave, criterion di/dt of derivative and level protection, criterion i_{diff} of longitudinal difference protection cannot meet the thresholds, DC transmission line protection do not trip.

4.5 Conclusion

In this chapter, by simulation, calculation and analysis, the operating characteristic of each DC line protection and overall protection is analyzed and concluded as:

4.5.1 Travelling wave protection

Travelling wave protection operates speedily within 5ms; while the fault impedance under which it can detect fault is low as 70Ω, so when there is DC line fault under high fault impedance, travelling wave protection will fail.

4.5.2 Derivative and level protection

The criterion of derivative and level protection is simple as it only usees voltage and current in one converter, which is easy to get, but the sensitivity and speed is not good. It takes more than 26.4ms to operate, and the fault impedance under which it can detect fault is only 50Ω.

4.5.3 Longitudinal differential protection

Longitudinal differential protection can operate under fault with very high fault impedance, but the speed is very poor: the time to operate is more than 1.1s, in which the protection in converter station operates and the pole will be blocked. Moreover, as the protection needs the current in the both side of converter, the accurate operation of protection largely relays on the communication channel.

5 IMPROVED TRAVELLING WAVE PROTECTION

5.1 Characteristic of travelling wave in mode domain

In order to give an improved travelling wave protection, the deep analysis on the criterion of traditional travelling wave protection is necessary, so this part will analyze the characteristic of pole wave, differential mode wave and common mode wave with fault occurring in and outside the DC transmission line protection zone.

5.1.1 Comparison in mode domain

In order to find out the influence of boundary equipment on differential mode and common, two fault cases which are fault in the end of DC transmission line and fault between smoothing reactor and inverter are simulated. The simulation result is as shown in Figure 5-1, in which the up and down figure show the waveform of common mode wave and differential mode wave corresponding. From the simulation result, both common mode and differential mode wave under fault outside DC transmission line protection zone have smooth front than that under fault in the end of DC transmission line. So both differential mode and common mode wave are influenced by boundary equipment, but the boundary equipment has more serious effect on differential mode than the common mode. The reason is that the travelling wave dispersion has large influence on common mode wave and can make it have more attenuation for the front, so although the fault occurs in the DC transmission line protection zone, the front of common mode is very smooth[37].

5.1.2 Fault in the DC transmission line protection zone

In order to know the difference between the velocity of pole wave, differential mode wave and common mode wave, the case with fault occurring in the end of DC transmission line is simulated. The simulation result is shown in Figure 5-2. As shown in the up figure, pole wave is super posited by differential mode and common mode, and differential common wave arrives the protection measurement point earlier than common mode wave, so before common mode wave arrives measurement point, pole wave is only determined by differential mode wave. As shown in the down figure, the maximum of pole wave appears before common mode wave arrives protection point, so the derivative of pole wave is determined by differential mode wave, and the maximum derivative of pole wave equals to the maximum derivative of differential mode wave.

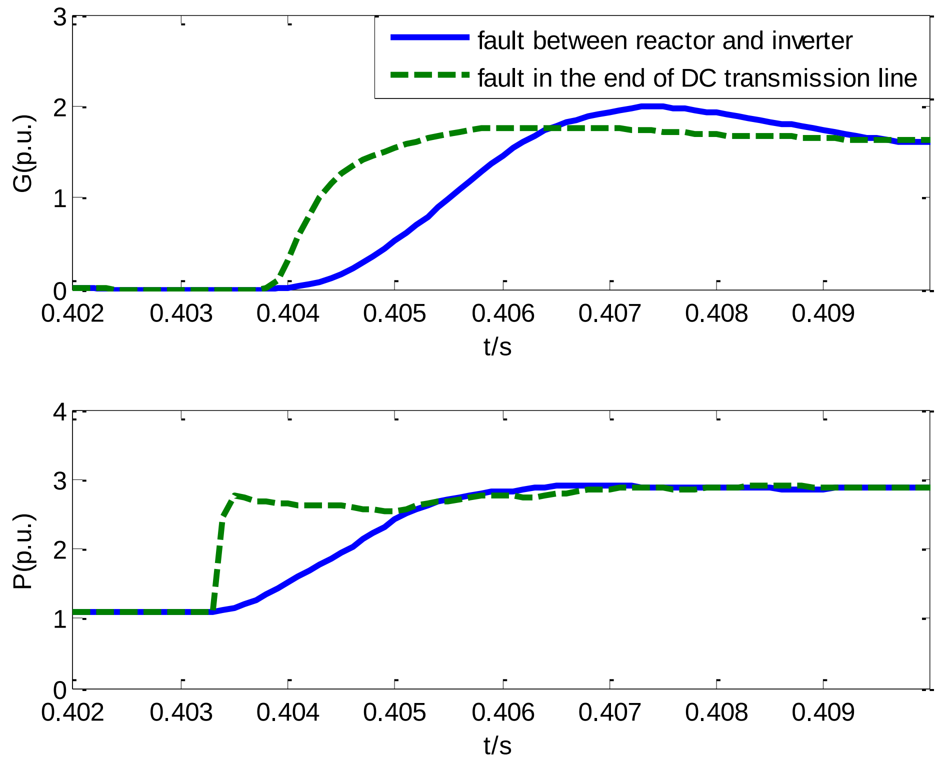


Figure 5-1 differential mode and common mode under fault in and outside DC line protection zone

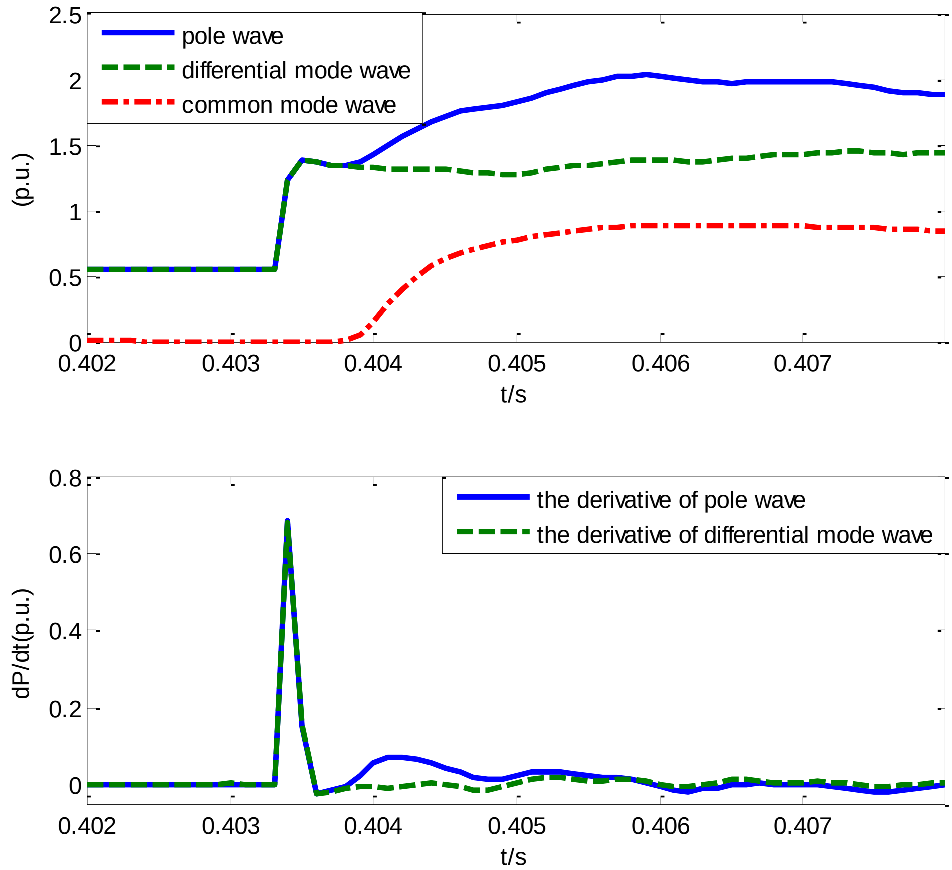


Figure 5-2 pole wave and mode wave under fault in the end of DC TL

5.1.3 Fault outside the DC transmission line protection zone

In order to know the relationship between pole wave and mode wave for fault outside the protection zone, the case fault occurring between smoothing reactor and inverter is simulated. Figure 5-3 shows the simulation result, which shows all pole waves, differential mode wave and common mode wave have smooth front, and the maximum derivative of pole wave appears after common mode wave arrives. Therefore, for fault outside the DC TL protection zone, the maximum derivative of pole wave is greater than the maximum derivative of differential mode wave.

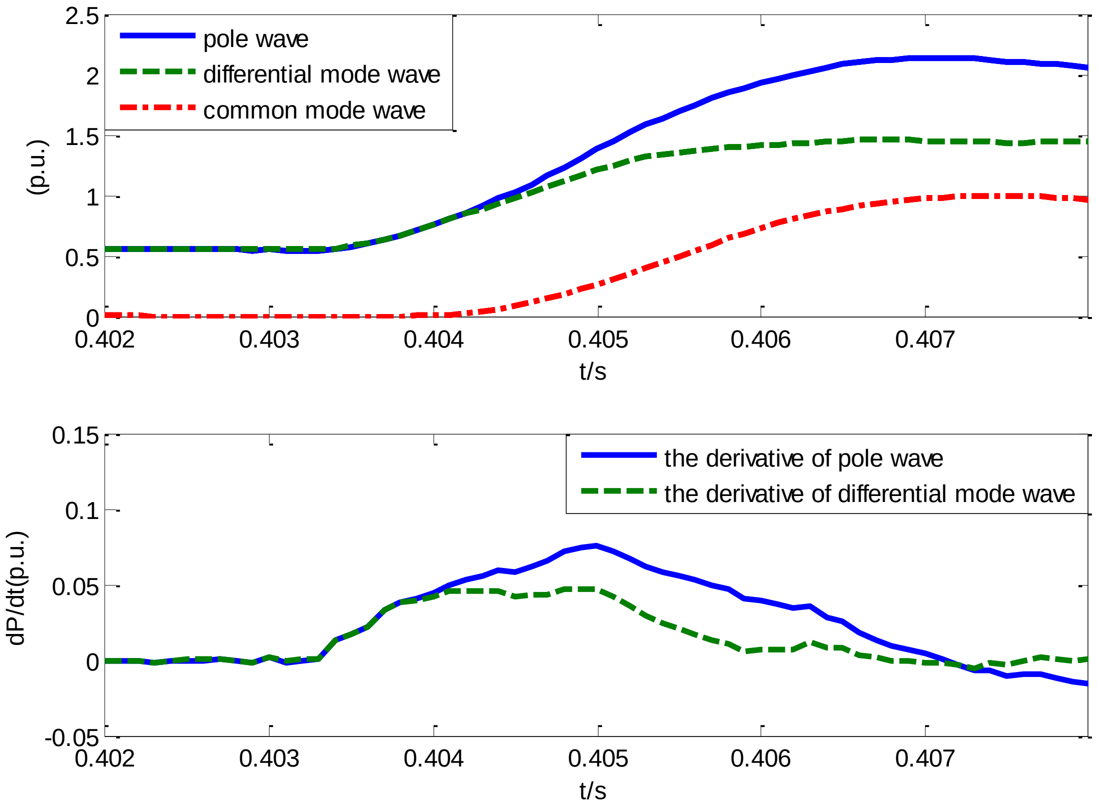


Figure 5-3 pole wave and mode wave under fault outside DC TL protection zone

5.2 Improved travelling wave protection

From above simulation result, for fault in the DC TL protection zone, the maximum derivative of pole wave is greater than that of differential mode wave, while for fault outside DC TL differential zone, the maximum derivative of pole wave is greater than that of differential come wave, so using only differential mode wave as criterion wound have higher sensitivity than pole wave. Moreover, as differential mode wave have higher propagation velocity than pole wave, when calculating the derivative of pole wave, the common mode wave has not arrived, while calculating the change of pole wave, the common mode wave has arrived, which is not good for setting of the threshold. For this reason, the improved pole wave protection uses only the differential mode wave as criterion to discriminate fault in or outside DC TL protection zone, and the definition of differential mode wave and common mode wave are shown as:

$$P = Z_1\left(i_{\mathrm{d1}} - i_{\mathrm{d2}}\right) - \left(u_{\mathrm{d1}} - u_{\mathrm{d2}}\right) \quad (5\text{-}1)$$

$$G = Z_1\left(i_{\mathrm{d1}} + i_{\mathrm{d2}}\right) - \left(u_{\mathrm{d1}} + u_{\mathrm{d2}}\right) \quad (5\text{-}2)$$

Where, P——pole wave；G——common mode wave；i_{d1}，i_{d2}——DC current of pole 1 and 2；u_{d1}，u_{d2}——DC voltage of pole 1 and 2.

Combining equation （3-19） and（3-36）, the expression of differential mode and common mode can be gained in equation（5-3）, which shows the concept of differential mode and common mode explicitly.

$$\begin{cases} P = 3(1+n_1(t))K_1 e^{-\alpha_1 l}\varepsilon(t-\tau_1)\cdot U_f \\ G = 3(1+n_0(t))K_0 e^{-\alpha_0 l}\varepsilon(t-\tau_0)\cdot U_f \end{cases} \quad (5\text{-}3)$$

Protection criterion is shown as:

$$\begin{cases} \mathrm{d}P/\mathrm{d}t > \Delta_1 \\ \Delta P > \Delta_1 \\ \Delta G > \Delta_2 \end{cases} \quad (5\text{-}4)$$

Since improved travelling wave protection has the similar criterion with traditional travelling wave protection, improved travelling wave also has similar algorithm and setting principle for thresholds.

5.3 Performance of improved travelling wave protection

5.3.1 Performance of improved travelling wave protection

5.3.1.1 Sensitivity

Since fault occurring between the smoothing reactor and inverter is the most serious fault case for fault outside DC TL protection zone, this fault case is simulated to gain the maximum derivative of differential mode wave for all the fault outside DC TL protection zone:

$$(\mathrm{d}P/\mathrm{d}t)_{\mathrm{out\_max}}=0.0948\ \mathrm{p.u./(0.1ms)}$$

Taking reliability coefficient as 1.3, so the threshold for dP/dt is:

$$\left(\mathrm{d}P/\mathrm{d}t\right)_{set} = K_{rel} \cdot (\mathrm{d}P/\mathrm{d}t)_{\mathrm{out\_max}} = 0.123\mathrm{p.u.}/\left(0.1ms\right) \qquad (5\text{-}5)$$

Taking the minimum sensitivity coefficient as K_{sen}=1.5, so the minimum dP/dt for fault in the DC TL protection zone which can be detected by protection is:

$$\left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{in\_min}} = K_{sen} \cdot \left(\mathrm{d}P/\mathrm{d}t\right)_{\mathrm{set}} = 0.184\mathrm{p.u.}/\left(0.1ms\right) \qquad (5\text{-}6)$$

By simulation of fault case in the end of DC TL with different fault impedance, the maximum fault impedance the protection can detect is 180Ω, whose (dP/dt)$_{\mathrm{max}}$ is 0.185p.u.

According the setting principle of common mode wave, the case for fault occurring in the end of DC TL with 180Ω fault impedance is simulated and its ΔG_{min}=0.384. Taking $K_{\mathrm{sen.min}}$=2.5, the threshold is gained as:

$$\Delta G_{set} = \Delta G_{\mathrm{min}} / K_{\mathrm{sen.min}} = 0.154\mathrm{p.u.} \qquad (5\text{-}7)$$

In overall, the thresholds and fualt impedace protection can detect is conclused in Table 5-1.

Table 5-1 the thresholds of improved travelling wave protection

Criterion	dP/dt(p.u.)	Δ G(p.u.)	Fualt impedance(Ω)
Threshold	0.123	0.154	180

5.3.1.2 Speed

Fault in the end of the DC line under 180Ω fault impedance is the lightest fault in protection zone as it has the minimum pole wave and common wave, so under this fault type, the travelling protection has the longest operation time. By simulation, the response curve of lightest fault is shown in Figure 5-4. The time for protection to operate is calculated after the fault occurs. From the simulation result, it indicates d*P*/d*t* meets the criterion after 3.3ms, and its value is 0.1858p.u./（0.1ms）, then calculateΔP_2，ΔP_5，ΔP_7, the results are 0.5573p.u.， 0.7214p.u.， 0.7510p.u. correspondingly, which are greater than the threshold, so it indicates there is fault on the DC line. Then, ΔG meets the criterion at 5ms, and its value is 0.3840p.u. So the time for travelling wave protection to operate is 5ms. Table 5-2 shows the corresponding response value of fault in the end of DC line with 180Ω fault impedance.

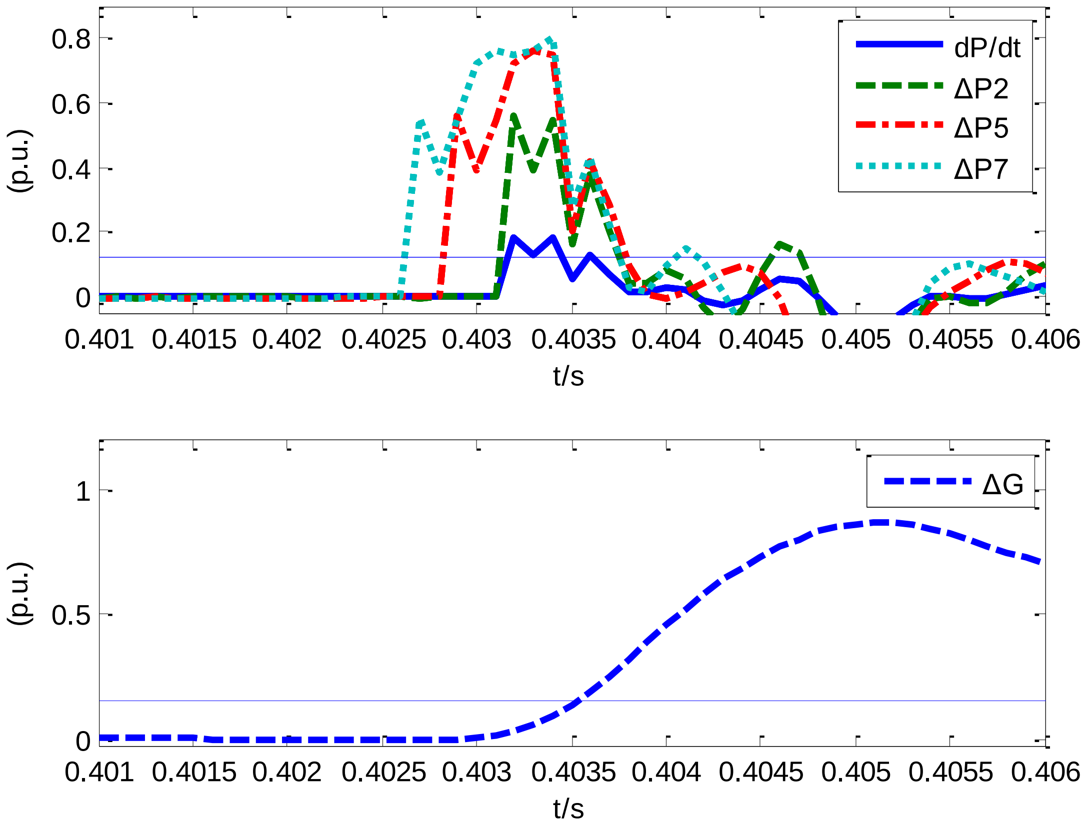


Figure 5-4 the response curve under fault in the end of DC TL with 180 fault impedance

Table 5-2 the response value under fault in the end of DC TL with 180 fault impedance

Criterion	d*P*/d*t*	ΔP_2	ΔP_5	ΔP_7	ΔG
Time (ms)	3.3	3.5	3.8	4.0	5.0
Value (p.u.)	0.1858	0.5573	0.7214	0.7510	0.3840
Discrimination	1.5104	4.5311	5.8650	6.1060	2.4936

5.3.2 Comparison between improved travelling wave protection and traditional travelling wave protection

In order to know whether the improved travelling wave protection has better performance than the traditional one, under the same fault case, performance of improved and traditional travelling wave protection is compared. The simulation condition: simulation step is 10us; fault occurs at 500km far from rectifier with 100Ω fault impedance. Table 5-3 shows the simulation result, and Figure 5-5 and Figure 5-6 show the response curve of traditional and improved travelling wave protection. From the simulation result, improved travelling wave protection has higher sensitivity than traditional travelling wave protection, and both protection have very good speed, as both protection can operate at 4.3ms after fault.

Table 5-3 the simulation result of improved and traditional travelling wave protection

Traditional travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Time (ms)	1.6	1.8	2.1	2.3	4.3
	Value (p.u.)	0.1138	0.3415	0.5636	0.7501	0.3603
	Discrimination	1.1820	3.5460	5.8521	7.7891	8.1704
Improved travelling wave protection	Criterion	dP/dt	ΔP_2	ΔP_5	ΔP_7	ΔG
	Time (ms)	1.6	1.8	2.1	2.3	4.3
	Value (p.u.)	0.2228	0.6685	0.8564	0.8517	1.2999
	Discrimination	1.8116	5.4349	6.9624	6.9239	8.4411

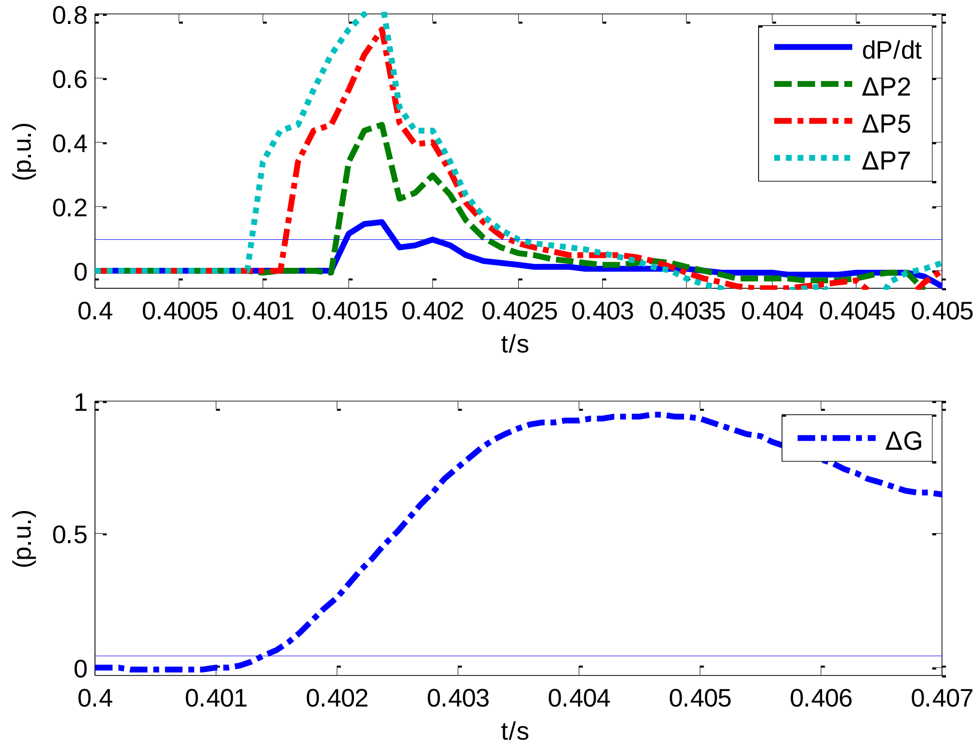


Figure 5-5 the response curve of traditional travelling wave protection

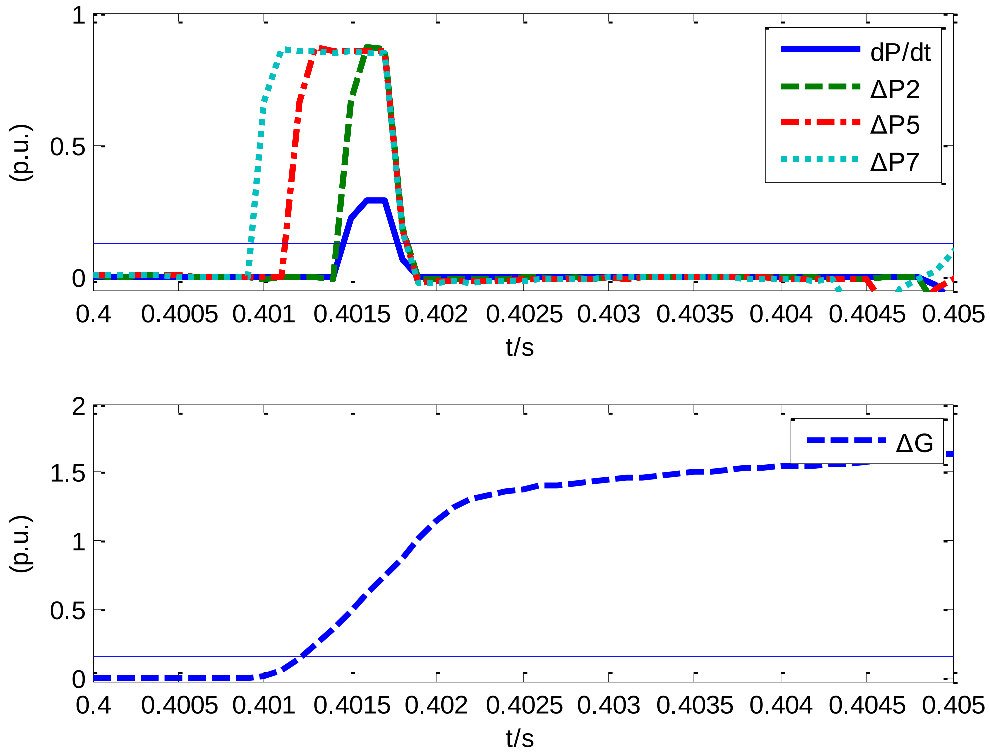


Figure 5-6 the response curve of improved travelling wave protection

5.4 Conclusion

In order to improve the fault impedance under which travelling wave protection can detect fault, this chapter substitutes pole wave with differential mode wave as criterion to discriminate fault inside or outside DC TL protection zone. Simulation result shows that improved travelling wave protection has higher sensitivity and fault impedance than the traditional travelling wave protection.

6 CONCLUSION

This paper built ±500kV HVDC transmission simulating model on PSCAD/EMTDC firstly. Then by simulation and calculation, the effect of fault impedance, fault distance, sampling frequency and boundary equipment on protection criterion is analyzed. Based on the analysis, the thresholds of protection criterion are gained. Moreover, Performance of HVDC transmission line protection are analyzed and concluded. Lastly, the improved traveling wave protection is proposed.

The conclusion of this paper can be drawn as:

6.1 Modeling of HVDC transmission system

±500kV HVDC transmission simulating model is built on PSCAD/EMTDC Microsoft. Due to the core components and parameter configuration, introduction are given in detail, especially 12 pulses converter, transformer and AC and DC filter. By simulation on the steady-state and transient- state operation, the HVDC simulating model is verified: the model can simulates the change of electrical quantity after fault, which offers the basis for the research on HVDC protection and control.

6.2 The operating characteristic of HVDC transmission line protection

By setting different fault condition, the operating characteristic of HVDC transmission line protection under different fault distance, fault impedance, sampling frequency and boundary equipment is analyzed: fault impedance and fault distance have influence on the amplitude of electric quantity, and fault in the end of transmission line under certain impedance is the lightest fault for all the fault occurring inside DC transmission line protection zone; boundary equipment has effect on waveform and therefore criterion, but as pole wave which is essentially backward wave is not affected by boundary equipment; sampling frequency has effect on the sampling of wave front, and under high sampling frequency, the criterion have higher sensitivity. Such analysis offers a basis for the optimization and setting calculation of HVDC transmission line protection.

6.3 The performance of HVDC transmission line protection

By simulation of different fault type inside and outside DC transmission line protection zone, the performance of HVDC transmission line main and backup protection is analyzed: travelling wave protection has the best speed, but it can operate under limit fault impedance; derivative and level protection has simple criterion, but its speed and fault impedance under which it can detect fault is poor; longitudinal differential protection can operate under high impedance, but its speed is poorest. Then the overall performance of HVDC transmission line protection is gained: for the fault inside DC transmission line protection zone, under serious fault, it is traveling wave protection to operate , and with the increase of fault impedance and distance, travelling wave protection and derivative and level protection cannot meet the criterion, so it needs longitudinal differential protection to operate; for fault outside DC transmission line protection zone, both HVDC transmission line main and backup protection cannot operate.

6.4 Improved travelling wave protection

In order to improve the fault impedance travelling wave protection can detect, considering the characteristic of differential mode and common mode wave, improved travelling wave protection is proposed which substitutes the pole wave with differential mode wave. By simulation, the improved travelling wave protection has better performance than travelling wave protection that improved travelling wave protection has higher sensitivity, and can operate under higher fault impedance.

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