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HVDC Transmission Line Protection Based on Transient Power

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Abstract

This paper presents a new protection method for High Voltage Direct Current (HVDC) system based on transient power. Behavior of the HVDC system during fault is studied. Variation of transient power and the relation between various parameters of the line are analyzed during each fault. Based on that the protection principle is developed. Transient power is obtained by measuring the voltage and current at the two terminals of the line. Identification of internal and external faults as well as location of DC lone fault can be done correctly and quickly from transient power. The test system is modeled using MATLAB - SIMULINK based on first CIGRE HVDC benchmark system.

Keywords: High voltage direct current transmission, transients, fault location and identification

1. Introduction

With the ever increasing demand for electrical power, there is a need for increased power transmission capacity over long distances. Implementing the increased power generation into an existing power system is a challenge for the AC networks. To overcome this challenge, increased interconnection of load centers with the use of high voltage direct current (HVDC) has been proposed as an efficient and economical solution.

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The HVDC transmission system has obvious advantages in long-distance bulk power transmission and interconnection between bulk HVAC systems [1]. Most HVDC lines are used for transmission of power over long distance, inevitably passing through complex terrain and operating under harsh weather conditions. Therefore, faults frequently occur on the line which is a major cause of HVDC outages.

Presently, traveling-wave-based protection and voltage derivative protection are usually used as the main protection for HVDC transmission lines, while backup line protections are composed of dc under-voltage protection and current differential protection [2]–[4]. However, traveling-wave-based protection and voltage derivative protection are sensitive to fault transition impedance. Undervoltage protection is low in reliability and current differential protection operates with time delay up to hundreds of milliseconds [4]. Unnecessary HVDC system outages caused by the shortcomings of the present protections in operation have been reported in [3].Given this background, novel HVDC transmission-line protection, which has better performance than the presently used protection, is developed in this paper.

The new method is based on the transient power data. Modeling of the system is done in MATLAB based on first CIGRE HVDC Benchmark system.

2. Principle of Protection

In Fig.1 the main structural diagram of the typical HVDC transmission system is shown [5], [6]. Protection devices are installed at points X at the rectifier side and Y at the inverter side. I_X and I_Y are dc currents, V_X and V_Y are dc voltages at X and Y. The positive directions of currents and voltages are defined in the diagram.

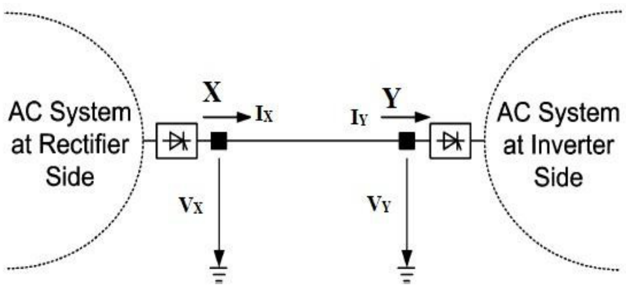

Fig.1. Typical structural diagram of HVDC transmission line

The power at the two points is given by,

$$\left.\begin{aligned} P_X &= V_X I_X \\ P_Y &= V_Y I_Y \end{aligned}\right\} \quad (1)$$

The increment of the transient power during any disturbance is given by,

$$\left.\begin{aligned} \Delta P_X &= \Delta V_X \Delta I_X \\ \Delta P_Y &= \Delta V_Y \Delta I_Y \end{aligned}\right\} \quad (2)$$

Thus, the increment of transient power in the dc line is

$\Delta P = \Delta P_X - \Delta P_Y (3)$

At steady state condition, $\Delta P_X = \Delta P_Y = 0$. Then, $\Delta P = 0$. When a fault occurs difference in transient power will no longer be zero. The value of ΔP will depend on the type of the fault.

2.1. External Fault

The lumped parameter model of dc transmission line is shown in Fig. 2. Here leakage conductance is neglected

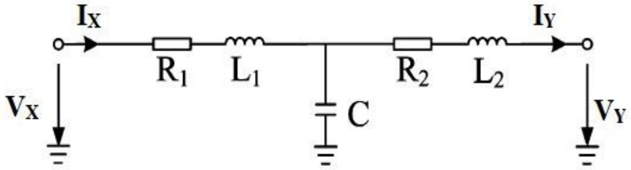

Fig.2. Lumped parameter model of DC transmission line

The increment of voltage and current caused by the distributed parameters of the transmission line can be described as follows

$$V_L = R_1 I_X + R_2 I_Y + L_1 \frac{dI_X}{dt} + L_2 \frac{dI_Y}{dt} \quad (4)$$

$$I_C = C \frac{dV_C}{dt} \quad (5)$$

Where,

$$V_L = V_X - V_Y$$

v_L-voltage drop in dc overhead line, i_C-charging current by the equivalent shunt capacitance in the dc overhead line, R_1,R_2- resistance of the dc overhead line, L_1,L_2- self-inductance of the dc overhead line, C- line-to-ground capacitance of the dc overhead line, v_C-capacitor voltage by equivalent shunt capacitance.

The series inductance of dc transmission line has an effect on the protective relay during the external fault at the inverter side. It is shown in Fig. 3.

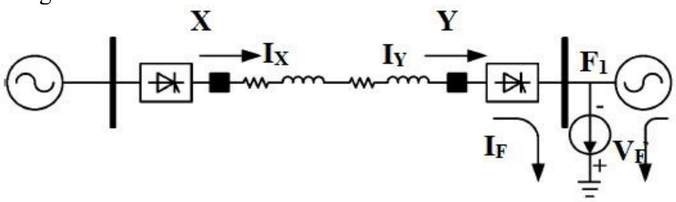

Fig.3. Effect of series inductance

The equivalent system impedance varies with fault F_1 and becomeslesser than the value at normal operation. Therefore, a rapid drop in voltage occurs at two ends of the dc transmission line.

A superimposed fault current I_F can be seen in Fig.3. Now the transient currents under fault F_1 at two ends of the dc transmission line can be obtained as follows

$$\left.\begin{aligned} I'_X &= I_X + I_F \\ I'_Y &= I_Y + I_F \end{aligned}\right\} \quad (6)$$

Substitute (6) in (4), then

$$v_L = R_1 I_X + R_2 I_Y + (R_1 + R_2) I_F + L_1 \frac{dI'_X}{dx} + L_2 \frac{dI'_Y}{dx} \quad (7)$$

And

$$V'_X - V'_Y = V_L$$

Before F_1, there is

$$V_X - V_Y = R_1 I_X + R_2 I_Y$$

It means

$$\Delta V_X - \Delta V_Y = (R_1 + R_2) I_F + L_1 \frac{dI'_X}{dt} + L_2 \frac{dI'_Y}{dx}$$

So there are,

$$\left.\begin{aligned} &\Delta V_X < 0 \text{ and } \Delta V_Y < 0 \\ &|\Delta V_X| < |\Delta V_Y| \end{aligned}\right\} \quad (8)$$

Shunt capacitance of the dc transmission line also has an effect on its protection. There is always shunt capacitance between the overhead dc line and ground during normal operating conditions. Effect of shunt capacitance during an external fault is shown in Fig. 4.

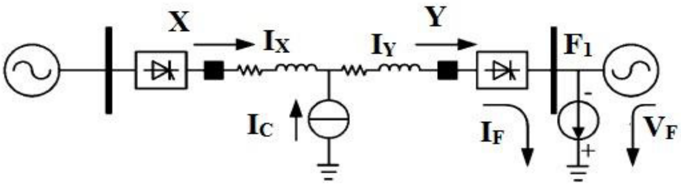

Fig.4. Effect of shunt capacitance

With the fault F_1 capacitance current is discharged from the shunt capacitance to the dc line. Discharging current of the equivalent capacitor under transient state condition is substituted by an equivalent current source and is shown in Fig. 4.

The equivalent discharge current of the dc line is given in (5). Under the fault F_1, the transient currents in the dc lines are,

$$\left.\begin{aligned} I'_X &= I_X + I_F - \frac{1}{2} I_C \\ I'_Y &= I_Y + I_F + \frac{1}{2} I_C \end{aligned}\right\} \quad (9)$$

Increments in two transient currents are,

$$\left.\begin{aligned} \Delta I_X &= I_F - \frac{1}{2} I_C \\ \Delta I_Y &= I_F + \frac{1}{2} I_C \end{aligned}\right\} \quad (10)$$

It is clear that $I_F > I_C$, so from (9) and (10) there is

$$\left.\begin{aligned} &\Delta I_X > 0 \text{ and } \Delta I_Y > 0 \\ &|\Delta I_X| < |\Delta I_Y| \end{aligned}\right\} \quad (11)$$

Now from (2) the increment in power will be,

$$\left.\begin{aligned} &\Delta P_X < 0 \text{ and } \Delta P_Y < 0 \\ &|\Delta P_X| < |\Delta P_Y| \end{aligned}\right\} \quad (12)$$

Substituting (12) in (3), then

$$\Delta P > 0$$

A similar conclusion can be obtained by analyzing the ac fault at the rectifier side based on the aforementioned procedures. External fault includes ac fault at the rectifier as well as inverter side. From the above analysis we can conclude that the difference of transient power between two ends of the dc line is positive under external faults.

2.2. Internal fault

With the internal fault, the voltages at two ends of the dc line drop sharply. Fig. 5 shows the superimposed circuit of the HVDC transmission system. V_F and I_F are the additional fault voltage source and the additional fault current respectively. Therefore it is clear that in this condition, the current I_X always ascends while I_Y descends.

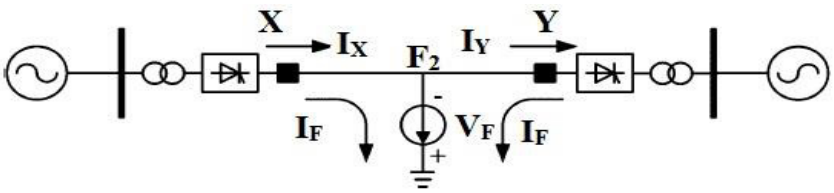

Fig.5.Internal fault

The increment of transient voltage and current will be as follows

$\Delta V_X < 0, \Delta V_Y < 0, \Delta I_X > 0, \Delta I_Y < 0$

Substituting these in (2), we get

$$\Delta P_X < 0$$

$$\Delta P_Y < 0$$

On substituting these relations in (3) it is obvious that

$$\Delta P < 0$$

It can be concluded as the difference of transient power between two ends of the dc line is negative under internal faults.

3. Location of DC line fault

Location of dc line fault is necessary since HVDC systems are usually employed for long distance power transmission. After simulating the CIGRE system for different transmission distance, a parameter can be found out which is related to the transmission distance. The transient power data is used to find out the fault location. The parameter which gradually decreases with increase in transmission distance is found to be P_Y. P_Y is the transient power at the inverter side. A lookup table is created with P_Y, from which the fault distance can be located. Table-I shows the values of the transient power at the inverter side, P_Y, used to create the lookup table.

Table – I
LOOKUP TABLE

Lookup table data	
P_Y(kw)	Distance(km)
0.9117	200
0.5176	400
0.2456	600
0.1132	800
0.05034	1000
0.02354	1200
0.01802	1400
0.01393	1600
0.006083	1800

4. MATLAB model of CIGRE system

Modelling of HVDC system is done in MATLAB based on first CIGRE HVDC benchmark system. The system is a mono-polar 500-kV, 1000-MW HVDC link with 12-pulse converters on rectifier and inverter sides. It is connected to weak ac systems. Damped filters and capacitive reactive compensation are also provided on both sides. Total length of the transmission line is 2000km [7]-[10]. System frequency is 50 Hz. AC filters are added to absorb the harmonics generated by the converter as well as to supply reactive power to the converter. MATLAB/SIMULINK model of HVDC system is shown in Fig. 6.

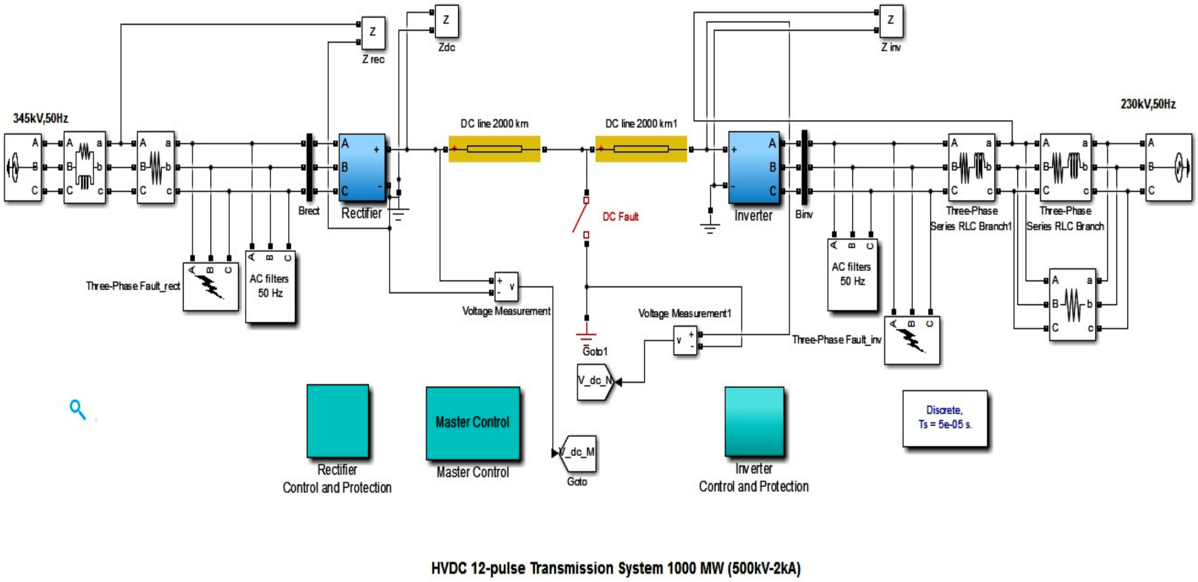

Fig. 6. MATLAB model of first CIGRE HVDC benchmark system

5. Results

5.1. Identification of fault

The fault at the inverter starts at 0.7 s. It is a three phase fault. I_X and V_X in the dc line are near to the rectifier, I_Y and V_Y in the dc line are near to the inverter.

When fault occurs at 0.7 s, big disturbance of the ac system causes a sudden increase in the dc current I_X and I_Y. During the transient process the shunt capacitance has an effect on the two dc currents. Due to thisI_X is lower than I_Y. Variation of current is shown in Fig: 7.

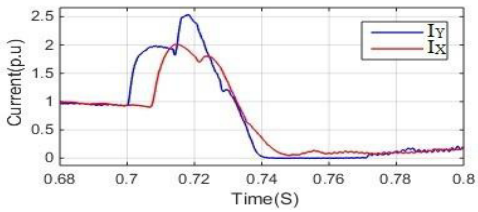

Fig: 7. Current response during inverter DC side fault.

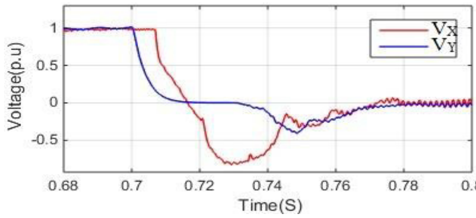

Fig: 8. Voltage response during inverter dc side fault

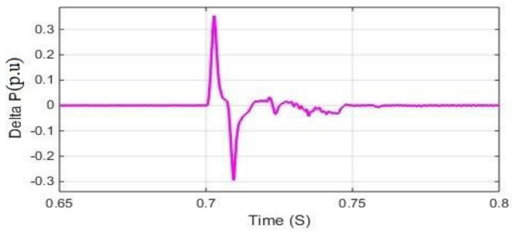

Fig: 9. Transient power response during inverter fault

The dc voltage V_X and $V_Y$slump during any fault at the inverter ac side. Obviously the voltage V_X is higher than V_Y at that time, as shown in Fig: 8.

There is a transient power difference between two terminals of the dc transmission line due to the difference in voltage and current. The value of transient power difference is positive at the initiation of the fault as shown in Fig.9. So the external fault can be identified easily by the proposed method.

The rectifier ac side fault occurs at 0.7 s. It is also a three phase to ground fault. The dc currents I_X and I_Y will drop as soon as the fault is initiated. The currents drop is in such a way thatI_X is smaller than I_Y. It is because of the presence of equivalent shunt capacitance. Current response during this transient period is shown in Fig: 10.

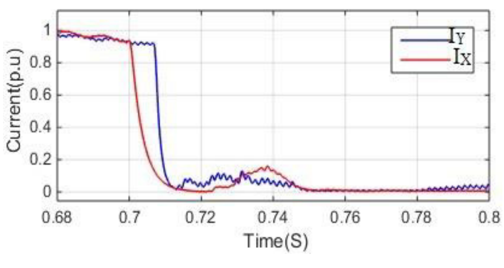

Fig: 10. Current response during rectifier DC side fault.

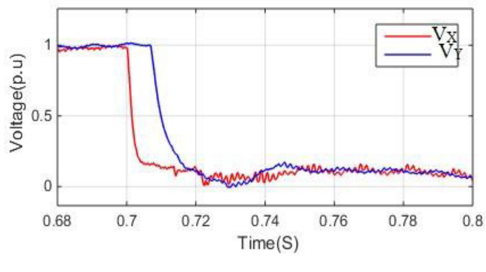

Fig: 11. Voltage response during rectifier side DC fault

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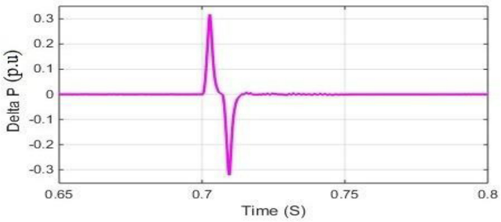

Fig: 12. Transient power response during rectifier fault

When the fault starts, the two dc voltages decline such that voltage V_Y decreases slower than V_X. This variation of voltage happens because of the effect of equivalent series inductance. It is shown in Fig: 11.

Due to the variation in voltage and current, there is transient power difference in the line. The value of transient power is positive at the initiation of the fault as shown in Fig: 12. Thus the external fault is identified by the proposed method.

The dc line fault is a pole to ground fault, occurs at 0.7 s. Fault occurs at the middle of the line. As soon as the fault occurs, dc current I_Y drops and I_X increases suddenly as shown in Fig: 13.

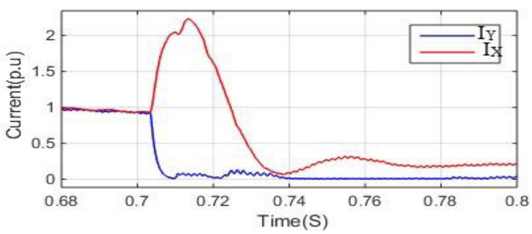

Fig: 13. Current response during DC line fault

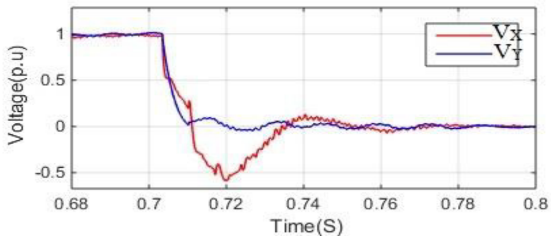

Fig: 14. Voltage response during DC line fault.

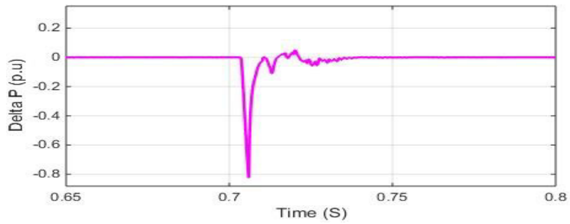

Fig: 15. Transient power difference during DC line fault

When a dc line fault occurs the voltages V_X and V_Y decrease immediately as shown in Fig: 14.

Due to the variation of voltage and current there will be a change in transient power in the dc line. And the value is negative. It is shown in Fig: 15. So the internal fault can be easily identified by the proposed method.

5.2. Fault location

Table-II shows the difference between measured distance and actual distance. The error in measurement is very small.

By inspecting the error table, it is clear that the proposed method is an effective method to find out the dc fault location in the transmission line. The main advantage of this method is that, the processing time is very less. Since transient power is monitoring continuously, the system identifies the fault correctly and quickly. If the fault is internal then the fault distance is located simultaneously and accurately by this method.

Table-II
ERROR TABLE

Error Table		
Actual Distance(km)	Measured Distance(km)	Percentage Error(%)
100	99.79	0.21
300	300	0
350	350	0
400	400.1	-0.01
450	450.5	-0.111
800	800.5	-0.111
850	851.9	-0.223
1050	1051	-0.0009
1200	1200	0
1300	1300	0
1450	1451	-0.0009
1500	1500	0
1700	1707	-0.00411
1850	1856	-0.0032
1950	1950	0

6. Conclusion

A novel Algorithm for fault identification and location, based on transient power is proposed for HVDC transmission lines. This method is found to be better than the commonly used travelling wave methods. Because it eliminates the disadvantages of travelling wave methods and gives output with minimum time possible. Test system is modelled in MATLAB based on CIGRE HVDC benchmark system. All the fault conditions were simulated and the result obtained is found to be accurate. The proposed method is simple, reliable and fast.

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