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VSC-HVDC Bipolar Grid Based On Novel Distance Protection Scheme

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Abstract: Mostly distance protection is widely used in HVAC system no practical implementation is done for HVDC system. It is essential to measure accurately difference in internal fault from external correctly in distance protection at the zone boundary. The smoothing reactor in HVDC system is present at two ends and it can be considered as the operating boundary of distance protection. Considering these feature this paper introduce distance protection method for HVDC transmission line. Current and voltage at end-point are planned accurately using those at the relay point, based on distributed parameter model. The line between the fault point and end point is simplified as RL model lumped parameter and differential equations obtain fault distance. In this way, accuracy of calculation at the zone boundary is attained, that contributes to the improvement in operation of protection. Simulation results show that proposed method is used as primary protection for HVDC transmission and is capable of protecting the whole line with high rapidity.

Keywords: HVDC transmission line; Primary protection; Distance protection; Distributed parameter model.

I. INTRODUCTION

HVDC transmission system has significant advantages in long distance bulk power transmission and interconnection between large isolated HVAC systems [1]. Prominent faults frequently occur on HVDC transmission lines, which is a major cause of DC outages that are caused due to the long-distance, variance in weather and geographical conditions. To ensure the security and reliability of HVDC transmission lines, worthy protection is needed [2-5].

The fault should be effectively cleared by the HVDC line protection. Recently, the HVDC transmission line uses traveling wave and voltage derivative protection as primary protection [6-9]. Traveling wave protection is used to protect whole system. The main principle of travelling wave protection is the voltage change rate dv/dt which is sensitive to the change of fault resistance to a high fault resistance, the rejecting act of traveling wave protection perhaps occurs [6]. Traveling-wave protection has backup protection i.e. under voltage protection and the voltage change rate criteria are the same as traveling wave protection [7].

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So, backup protection is limited to travelling wave protection. The differential protection is designed as the backup of traveling wave protection and under-voltage protection [8-9]. Furthermore, for present HVDC transmission line protection there is no definite setting principle. The setting parameters depend on simulations and test system, which brings much inconvenience to engineering application. So, a new type of protection is required to be introduced which is desirable protection for the HVDC transmission line. For the further improvement of protection performance, unfortunately there is no practical application of distance protection for HVDC transmission line. But in HVAC power system it has been widely applied for its many merits such as immune to operation model, invariable operation scope and easy to setting calculation, etc [10]. The nonlinear relationship between actual fault distance and measured distance is lead by the distributed parameters of long line, which frequently results in over reach or under reach at the end point fault and this is the main problem with distance protection in the HVDC [11].

Instead of detecting the fault location accurately the main function of distance protection is to differentiate internal fault from external correctly. Therefore, for distance protection some measurement error are allowed and the measurement error varies which are allowable in dissimilar location and is increased proportionally from the end-point to start-point. As long as calculation error is less than the difference between the fault distance and the setting distance, distance protection can operate correctly.

HVDC transmission line is set with smoothing reactor at both ends, for practical operational condition and it has evident boundary characteristic, which offers other useful conditions for protection system [12-13]. This paper puts forward a distance protection method for HVDC transmission line which is capable of enhancing the measurement accuracy greatly at end-point fault and effectively improves the operating behavior of line protection based on these factors. The protection of full line is done by distance protection and this alternative is also suitable for primary protection for HVDC transmission line.

II. SYMMETRICAL COMPONENTS FAULT ANALYSIS

It is required to examine the HVDC system operating under faulty conditions to design HVDC line protection scheme. A symmetrical component provides such a function. Every pole vector voltage v_a and v_b, or line currents i_a and i_b is determined into the sum of two components i.e. zero sequence component and positive-sequence component.

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The zero and positive sequence networks connected in a choice of ways depending on the fault type which is represented by bipolar HVDC system.

A. Symmetrical Components

Consider a random set of two phasors that is v_a and v_b, that can be represented in equation (4) following symmetrical components in equation (1).

$$\begin{Bmatrix} v_a = v_{a0} + v_{a1} \\ v_b = v_{b0} + v_{b1} \end{Bmatrix} \quad ....(1) \qquad \begin{Bmatrix} v_{a0} = v_{b0} \\ v_{b1} = -v_{a1} \end{Bmatrix} \quad ....(2)$$

V_{a0} and V_{b0} are zero and V_{a1} and V_{b1} are positive sequence voltages. The properties of zero & positive sequence sets are shown in equation (2). The general rule is that V_{a0} and V_{a1} are preferred as the independent variables and the remaining is then expressed in terms of the self-governing variables. Applying equation (2) to (1) and in order to keep the electric power invariant under transformation, equation (3) expressed as-

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} v_{a0} \\ v_{a1} \end{bmatrix} \tag{3}$$

For calculating the symmetrical components from phasors, the equations are as follows,

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} v_{a0} \\ v_{a1} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} v_{a0} \\ v_{b1} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \end{bmatrix} \tag{5}$$

The voltage at every point of the line is close to its normal rated value at the normal condition operating HVDC bipolar system & magnitude can be taken in equation (6). where, V_{dc}- & V_{dc}+ represents the rated voltage of HVDC system i.e. -500 kV & +500 kV. With constant -α the rectifier is on and with constant-γ mode the inverter is on, where α is the firing angle of rectifier & γ is the angle of extinction for inverter, and the pole voltages are assumed constant for steady-state operation. According to equations (2) & (5), at the fault point the pre fault components sequence can be calculated as shown in equation (7):

$$\begin{Bmatrix} v_b = v_{dc-} \\ v_b = v_{dc+} \end{Bmatrix} \quad ....(6) \qquad \begin{Bmatrix} v_{a1} = \sqrt{2}v_{dc} - \\ v_{b1} = \sqrt{2}v_{dc} + \\ v_{a0} = 0 \\ v_{bo} = 0 \end{Bmatrix} \quad ....(7)$$

From equation (7), it is clearly noted that under normal conditions only positive-sequence components exist.

B. Symmetrical Components Analysis: Faulty Condition

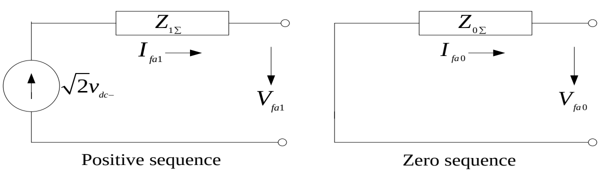

Fig.1. Sequence network

The superposition principle states that two symmetrical two-phase networks can be replaced by the faulted network each of them may be analyzed by considering a sequence network. The relationship between the current and voltage is described by basic equations as shown in Fig. 1 and are stated by the following equations, respectively

$$\sqrt{2}v_{dc(-)} - i_{fa1}Z_{1\Sigma} = v_{fa1} \tag{8}$$

$$0 - i_{fa0}Z_{0\Sigma} = v_{fa0} \tag{9}$$

In equation (8) & (9), $Z_{1\Sigma}$ and $Z_{0\Sigma}$ are positive and zero sequence impedance of thevenin's equivalent, observing into system at fault location equal to zero sequence and positive sequence impedances of HVDC transmission line respectively.

Single-Line-to-Ground (SLG) Fault:

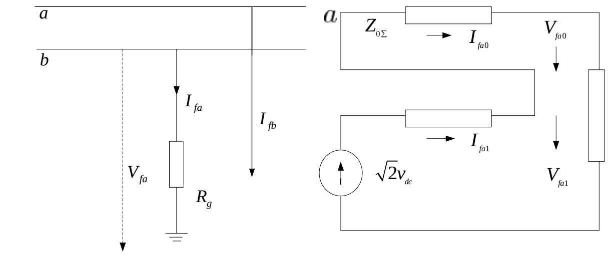

Fig. 2. Sequence network connection for SLG fault

Assuming the grounding resistance is R_g as shown in Fig. 2 of the single-line to grounding fault. The instantaneous boundary conditions are -

$$\begin{Bmatrix} i_{fb} = 0 \\ v_{fa} = i_{fa}R_g \end{Bmatrix} \tag{10}$$

Then sequence components are

$$\begin{Bmatrix} i_{fa0} - i_{fa1} = 0 \\ v_{fa0} + v_{fa1} = (i_{fa0} + i_{fa1})R_g \end{Bmatrix} \tag{11}$$

Combining equation (8) and (9) the voltage sequence components can be solved

$$\begin{Bmatrix} v_{fa0} = \dfrac{\sqrt{2}v_{dc} + Z_{0\Sigma}}{Z_{1\Sigma} + Z_{0\Sigma} + 2R_g} \\ v_{fa1} = \dfrac{\sqrt{2}v_{dc} - (Z_{0\Sigma} + 2R_g)}{Z_{1\Sigma} + Z_{0\Sigma} + 2R_g} \end{Bmatrix} \tag{12}$$

III. NOVEL DISTANCE PROTECTION

It is important to measure end-point fault accurately and correct identification of internal or external fault. At the M point the relay is placed as shown in Fig. 4. If the relay is located at point N instead of M and when fault occurs at F point, the distance from the fault point to the relay point will be shortened and control of distributed capacitance on distance protection will be moderately weak.

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As the distance becomes long and the control is strong; when fault point is at a distance from the end-point, correspondingly the accuracy of measurement becomes comparatively low. As a result, the measurement accuracy of fault distance is comparatively high. As the distance increases proportionally the measurement error also increases.

As mentioned previously the allowed measurement error at the end-point is small and high measurement accuracy is required.

Therefore, this method is favorable to the performance of line protection and in accordance with the characteristic of distance protection. The novel distance protection with its fundamental principle can be described by as follow.

Fig. 3 shows Bergeron transmission line model which is adapted to simulate the HVDC transmission line. For line parameters R=0.01330 Ω/km, L=0.8470 mH/km, C=0.012970 µF/km and l = 500 km. Based on this, the current and voltage (v', i') at the end-point N can be calculated accurately with (v_m, i_m) at the relay point M. The relationship of them is shown in equations (13) and (14).

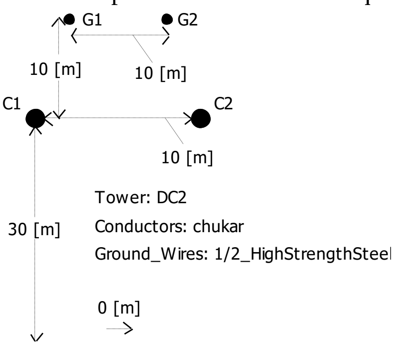

Fig.3. Bergeron transmission line model

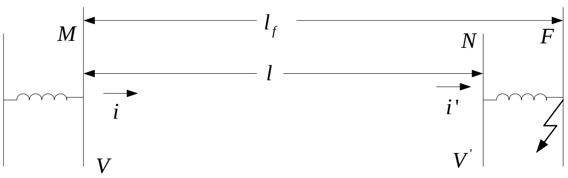

Fig. 4. Protection principle

$$i' = \frac{1}{2Z_c}\left(\frac{Z_c + Rl/4}{Zc}\right)[v_m(t+l/v) - i_m(t+l/v)(z_c + Rl/4)] - \frac{1}{2Z_c}\left(\frac{Z_c - Rl/4}{Z_c}\right).[v_m(t+l/v) + i_m(t+l/v)(z_c + Rl/4)] - \frac{1}{2Z_c}\cdot\frac{Rl}{2Z_c}[v_m(t) - i_m(t)(Rl/4)] \quad (13)$$

$$v' = \frac{1}{2}\left(\frac{Z_c + (Rl/4)}{Z_c}\right)^2 [v_m(t+l/v) - i_m(t+l/v)(z_c + Rl/4)] + \frac{1}{2}\left(\frac{Z_c + (Rl/4)}{Z_c}\right)^2 [v_m(t-l/v) + i_m(t-l/v)(z_c - Rl/4)] - \left(\frac{(Rl/4)}{Z_c}\right)^2 v_m(t) - \frac{Rl}{4}\left(\frac{Z_c + (Rl/4)}{Z_c}\right).\left(\frac{Z_c + (Rl/4)}{Z_c}\right) i_m(t) \quad (14)$$

where l & R are length & resistance of line in per km respectively. V and Z_c are wave speed and characteristic impedance respectively. The line between the F (fault point) and N (end point) is simplified as lumped parameter RL model, and the differential equation obtains the length of that part line easily. With LSM (Least Square Method) the fault distance can be calculated. Assuming that fault occurs at a distance of l_f from the relay point as follows,

$$v' = (l_f - 1)(R_i' + l\frac{di}{dt}) = R_f' i_g' \quad (15)$$

where, i' is the current fault component and R_f is the equivalent transition resistance. Finally, the external or internal fault is famed. The fault identification criterion is expressed as follows,

$$l_f \le l_{set} \quad (16)$$

For distance protection it is positive to use the smoothing reactor as operating boundary detecting external or internal fault as a smoothing reactor is about 300 mH, equivalent to the value of HVDC transmission lines upto 200 km around. Assume smoothing reactor and transmission line is alike in terms of inductance. With the high reliability for full line protection, the length of the total line must be less than the setting distance. On the other hand, for external fault selectivity guaranty, the setting distance should be less than sum of line and smoothing reactor as shown in equation (17),

$$l_{set} \le l + \frac{1}{2} l_{eq} \quad (17)$$

Equations (16) and (17) constitute the full-line tripping distance protection criterion of the for HVDC line. The protection will not operate if the external fault is detected and equation (17) is true. Otherwise, the internal fault is detected and the protection will immediately operate to trip.

The observation point at the end-point rather than the relay point is located by this method, shortening the distance from the observation to the fault point when fault arise at the line end, which is capable of calculating the fault distance accurately at boundary fault and preventing protection from incorrect action.

$$v(i_f) = \frac{1}{2}\left(\frac{Z_c + R(l_f - 1)/4}{Z_c}\right)^2 [v(t + (i_f - l)/v] - i'(t + (l_f - l)/v)(Z_c + R(l_f - l)/4) + \frac{1}{2}\left(\frac{Z_c - R(l_f - 1)/4}{Z_c}\right)^2 [v'(t - (l_f - 1)/v) + i'(t - (l_f - l)/v)(Z_c - R(l_f - l)/4] - \left(\frac{R(l_f - l)/4}{Z_c}\right)^2 v'(t) - \frac{R(l_f - l)}{4}\left(\frac{Z_c + R(l_f - l)/4}{Z_c}\right).\left(\frac{Z_c + R(l_f - l)/4}{Z_c}\right) i'(t) \quad (18)$$

Metallic short-circuit fault occurs, namely v(l_f) = 0, making laplace transform to (18), in terms of fault distance the measurement impedance is acquired as below,

$$Z = \frac{v'(s)}{i'(s)} = \frac{A^2.c.[Z_c + R(l_f - l)/4] - B^2.D.[Z_c - R(l_f - l)/4] - R(l_f - l)/2.A.B}{A^2.c + B^2.D - 2.[\frac{R(l_f - l)/4}{Z_c}]^2} \quad (19)$$

where,

$$A = \frac{Z_c + R(l_f - l)/4}{Z_c}, B = \frac{Z_c - R(l_f - l)/4}{Z_c}$$
$$C = e^{s(l_f - l)/v}, D = e^{-s(l_f - l)/v}$$

with fault distance x measurement impedance can also be obtained as;

$$Z = \frac{v'(s)}{i'(s)} = (R + sL)(x - l)$$

(20)

Therefore, the relation between fault error and measurement error is,

$$E_r = [x - l_f] = \frac{A^2 c.[Z_c + R(l_f - l)/4] - B^2.D.[Z_c - R(l_f - l)/4] - R(l_f - l)/2.A.B}{A^2.c + B^2.D - 2.[\frac{R(l_f - l)/4}{Z_c}]^2.\frac{1}{R+sL} + l - l_f} \quad (21)$$

According to above equation, the relation between measurement error and fault distance under different frequencies can be calculated.

IV. SIMULATION

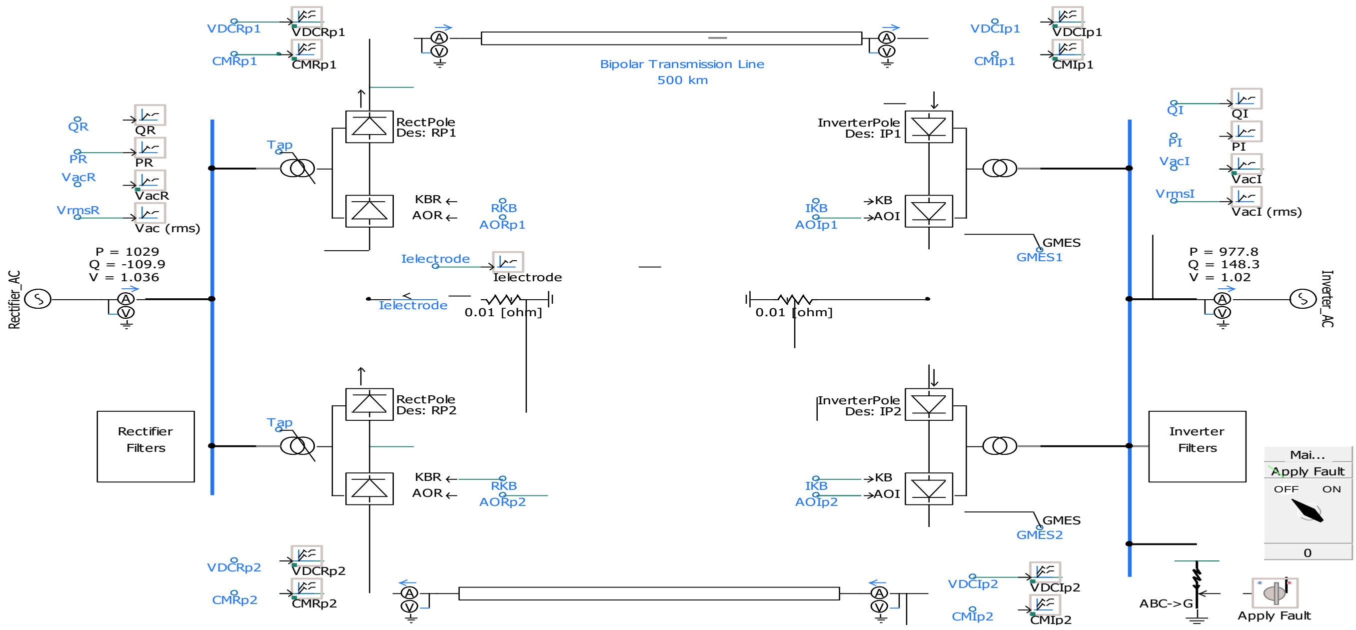

Fig. 5. VSC based HVDC bipolar system

Based on the simulation model as shown in Fig. 5 to verify the proposed technique, extensive simulations are preformed. The length of VSC bipolar transmission line of ±500kV is 500 km and that of smoothing reactor length is equivalent to 200 km. For HVDC transmission line fault simulation PSCAD is used. The pole current and voltage measured on converter side are obtain with PSCAD data output function. Mode transformation matrix calculates the mode quantities at the relay point, and so does at the end-point, with which the current & voltage in each pole can be obtained from mode anti-transform matrix. The consequent operation behavior and fault distance of protection are evident. The l_{set} is 600 km and full data window time is equal to 20 ms.

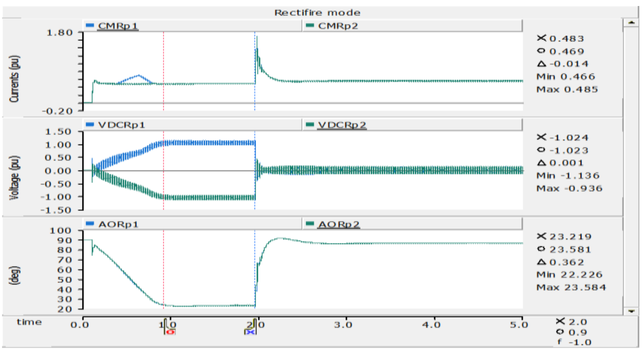

Fig. 6. Rectifire mode with controlling parameter

An HVDC link consists of a rectifier and inverter connected together. Power flows from the rectifier to the inverter and is in effect transferred from the rectifier AC side to the inverter AC side. The rectifier voltage plays the role of the dc source, required for inverter operation as discussed above. The magnitude of the inverter and rectifier voltages is determined by the firing angle.

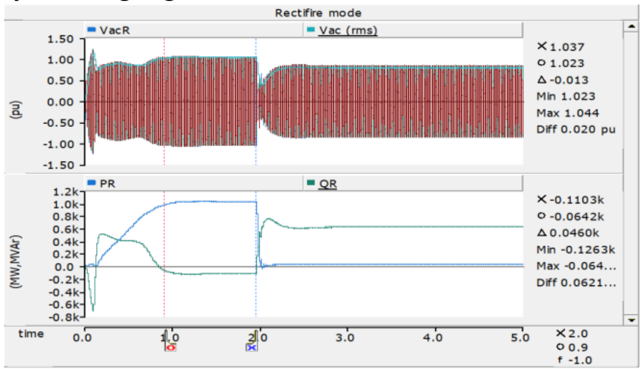

Fig. 7. Rectifier mode with active and reactive power

Current can be changed by changing the magnitude of either or both voltages. Since they are constraints on the maximum value of delay angles for inverter, so in practice current is controlled by controlling the rectifier dc voltage. Since the magnitude of the dc side voltages are dependent only on AC side voltage magnitudes, delay angles and power flow is not dependent on AC side system frequency or phase angle at either end.

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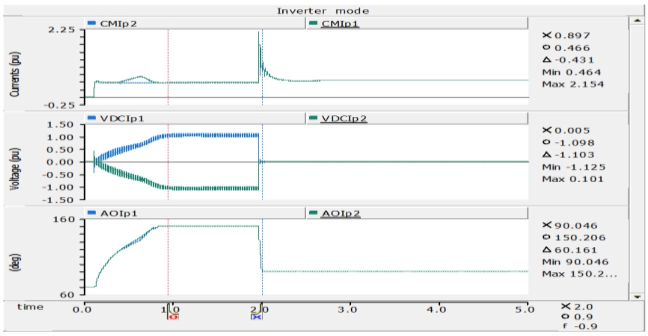

Fig.8. Inverter mode with controlling parameter

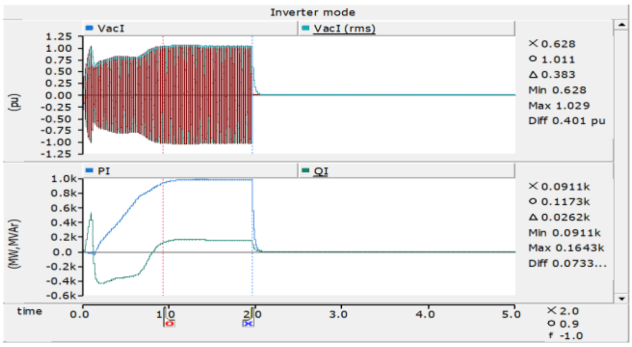

Fig.9. Inverter mode with active and reactive power

From Fig. 6-9, it is shown that the performance of rectifier and inverter of HVDC system in different modes. The fault occurs at 1.9 sec there is a change in results in voltage and current at 1.9 sec.

To verify the validity of equation (15) to (21) and proposed algorithm, different faults inside and outside the line is taken into account at different points.

Table 1: Internal fault

Fault distance (km)	Transition resistance (Ω)	Measuring Distance (km)	Setting distance (km)	Operating behavior
0	0	172.6	600	+
	15	171.1		+
	30	161.8		+
50	0	175.3	600	+
	15	170.4		+
	30	120.4		+
100	0	154	600	+
	15	130.3		+
	30	132.5		+
150	0	138	600	+
	15	125		+
	30	110		+
200	0	194.2	600	+
	15	167.3		+
	30	140.6		+
250	0	246.2	600	+
	15	220.3		+
	30	190.2		+
300	0	291.4	600	+
	15	294		+
	30	282.6		+
350	0	345	600	+
	15	332		+
	30	314		+
400	0	387.9	600	+
	15	379.9		+
	30	373.9		+
450	0	443	600	+
	15	430		+
	30	425.6		+
500	0	496.7	600	+
	15	483		+
	30	493.7		+

The (+) sign means that internal fault is detected and the protection will trip to operate, while the (–) sign indiactes that the external fault is detected as the external fault is located outside the smoothing reactor at end point of transmission line and the protection doesn't operate. Table 1 and 2, respectively represent operating behavior and calculation results of the distance protection

Table 2: External fault

Fault distance (km)	Transition resistance (Ω)	Measuring distance (km)	Setting distance (km)	Operating Behavior
Smoothing reactor at end point	0	759	600	-
	15	810		-
	30	858		-

From Table 1, it is clear that this method improves the measurement precision of fault distance deeply when a fault is present at the end-point. Example, consider that measuring distance is 194.9 km and 291.4 km respectively when the fault distance actually is 200 km & 300 km at zero transition resistance. When the fault is away from the end-point, the measurement error of fault distance is high. For the measurement error border is comparatively high at these locations, the inaccuracies can't result in the fake action of the protection. From Table 2, distance protection shows that it is an external fault and it will not operate when a fault occurs outside the line. Table 1 and 2 shows, there is poor control on the measurement results of distance due to presence of transition resistance. Particularly, this method has ability to stand upto some extent transition resistance and prevent protection from incorrect action.

V. CONCLUSION

Distance protection is used for AC transmission line; however, there is no application of it for HVDC transmission line. A time domain distance protection scheme is presented by taking advantage of the boundary characteristic of smoothing reactor in HVDC transmission line. This method can improve the measurement precision of fault distance deeply at end-point faults, which enhance the act of line protection and ease the setting calculation. PSCAD simulations indicate the proposed method is able to discriminate internal fault from external properly. In addition, a very short data casement is passable for this method to function. Therefore, this method can be used as primary protection for HVDC transmission line to protect the full line with high speediness.

REFRENCES

1. Wanjun Zhao, HVDC transmission engineering technology. Beijing: China Electric Power Press, pp.91-114, 2004.
2. Naidoo and N. M. Ijumba, "A protection system for long HVDC transmission lines", *IEEE Power Engg. Society Inaugural Conf. and Exp. in Africa*, pp.150-155, 2005.
3. Naidoo, "HVDC line protection for the proposed future HVDC systems," *Proc., IEEE PowerCon Conf.*, Singapore, pp.1327-1332, 2004.
4. Yaozhong, "New types of protective relaying and fault location theory and techniques" *Xian China:Xian Jiaotong Univ. Press,* pp. 185–206, 2007.
5. Xinming Gao, Peng Zhang, et.al, "HVDC transmission line protection behaviour analysis," *Automation of Electric Power Systems*, vol.29, no.14, pp.96-99, 2005
6. Xiaolei Liu, Osman, A. H. Malik, "Hybrid traveling wave/boundary protection for monopolar HVDC line," *IEEE Trans. on Power Deliv.,* vol. 24, pp.569-578, 2009.
7. Shuxin Luo, "A Non-unit protection principle based on travelling wave for HVDC transmission lines," IEEE Trans *on Power Deliv.*, vol. 21, pp.400-407, 2008.
8. Shuxin luo, Xinzhou Dong, Shenxing Shi, Bin Wang, "Directional protection scheme for HVDC transmission lines based on reactive energy" *IEEE Power and energy general meeting,* 2016.
9. Shuxin luo, xinzhou Dong, Shenxing Shi, "Directional protection scheme for HVDC transmission lines based on reactive energy" IEEE Trans. vol. 31, no.2, pp. 1003-1009, 2016.
10. Yuchao liu, "Research on AC line distance relay in the presence of modular multilevel converter based HVDC" IEEE conf. 2016.
11. Mohammad shahidepour,"Robust distance protection for bulk AC power system considering effect of HVDC interfaced offshore wind unit", *IEEE system Jour*., vol. 12, pp. 370-379, 2018.
12. Cheng Lv, Nengling Tai, "Protection principle for MMC HVDC DC lines based on boundary signal," *The journal of engineering*, vol. 10, pp. 17-22, 2017.
13. J. Suonan, S. Gao, and G. Song, "A novel fault-location method for HVDC transmission lines," *IEEE Trans. Power Del.*, vol. 25, no.2, pp. 1203-1209, Apr. 2010.
14. Huidong Guo; Shuyong song; Rui Li, "Simulation study on line protection of HVDC transmission system" *IEEE 2nd Int. conf. on power and Renewable Energy*, 2017.
15. Zhao Zhao, Duan jiandong, Liu Jing, "VSC HVDC transmission line protection based on current natural frequency" IEEE Conf. pp. 1938-1948, 2016.
16. Xiaofu Xiong, yongni leo, "Analysis of distance protection operation characteristics of power system based on VSC-HVDC interconnection" *IEEE conf. on Energy internet,* pp.1-6, 2017.

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