Protection of HVDC Transmission Line based on Distributed Parameters using Transient Energy

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Abstract—Protection of the HVDC transmission line is one of the major concerns in the present power system as HVDC is preferred more than HVAC due to its leading advantages over HVAC system. In this paper a novel transient energy protection principle is proposed. Behaviour of the HVDC system during internal and external fault is studied. And according to that the variation of the transient energy and the relation between the parameters of the dc transmission is analyzed during internal and external fault conditions, based on that the transient energy protective principle is developed. It is based on distributed parameters of the transmission line model and the transient energy distributed over the line is obtained by measuring voltage and current at both the terminals and fault can be identified from the calculated value of transient energy. The test system is modeled in MATLAB software and it is based on CIGRE (Counseil International des Grands Reseaux Electriques) benchmark by considering distributed parameters of the transmission line.

Index Terms-HVDC, Transient energy, Transmission line.

I. INTRODUCTION

HVDC transmission system has advantages over HVAC system such as long distance, flexible and fast control, low losses, large capability of power transmission [1]-[3]. Due to the rapid development of power electronics and encouraging means for improving the stability, HVDC transmission system plays a vital role in the complex power systems.

The older protective system for the HVDC transmission line uses the voltage and its rate of change to identify ground fault in the dc line. It is found that it is sensitive to fault impedance. Due to the increasing advance of microelectronics technology and microcomputer, traveling wave theory has been implemented in the HVDC transmission lines protection [4].Traveling wave methods has disadvantage such as it is easily affected by noise lacking mathematical tools to represent the traveling wave [5]-[7].

A novel protection scheme was proposed for UHVD based on the characteristics of low frequency differential transient energy at the two terminals of dc transmission line. But this paper considered lumped parameters of the transmission line. We know that the characteristic of HVDC transmission system is the long distance, distributed parameter effect cannot be neglected and that may cause the mis-operation of relay protection [8]-[10].

The system is monopolar 500kv, 1000MW HVDC link. It has 12 pulse converters on both rectifier and inverter side and is connected to weak ac system. Damping filters and capacitive reactive compensators are provided on both sides.

The power circuit consists of the following subcircuits [11], [12].

A. AC side
AC side of the HVDC system consists of Supply source, converter transformer, AC filters.

i) Supply Voltage source:
Three phase ac voltage source is supplied to rectifier and inverter side.
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ii) Converter Transformer:
Two transformers are connected on rectifier side. They are three phase, two winding transformers. One is with grounded Wye-Wye connection and other with grounded Wye-delta connection. Similar transformers are connected to inverter side.

iii) AC Filters:
Damped filters are provided to reduce harmonics and compensate reactive power.

B. DC Side
Smoothing reactors are connected at both rectifier and inverter side. The dc transmission is represented by T network.

C. Converters
Converters are of 12 pulse configuration. Two six pulse converters are connected in series and configuration of 12 pulses is obtained. It consists of built in RC snubber circuits for each thyristor.

i) Rectifier Control:
Constant Current Control technique is used for rectifier control. The reference for current limit is taken from inverter side. This is done to ensure the protection of the converter during fault when inverter does not have sufficient dc voltage support and during load rejection it does not have sufficient load requirement. The reference current used for rectifier control depends on inverter side voltage. DC current on the rectifier side is passed through filters before they are compared to produce the error signal. Further the error signal is passed through PI controller that produces firing order α.

ii) Inverter Control:
On the inverter side both extinction angle control (γ control) and current control have been implemented. The constant current control has been used with Voltage dependent Current Order Limiter (VDCOL) through PI controller. The reference limit for the current control is obtained by comparing the external reference and VDCOL (implemented by lookup table) output. Further the measured current is subtracted from reference limit to produce an error signal which is sent to the PI controller to produce the required angle order. In order to produce gamma angle order for the inverter the γ control uses another PI controller. The two angle orders are compared with each other and the minimum of two is used to calculate the firing instant.

III. TRANSIENT ENERGY PROTECTIVE PRINCIPLE

Fig. 2 is the main structure diagram of the typical HVDC transmission system. \( i_M, i_N, u_M, u_N \) are dc currents and dc voltages. The positive directions of the mentioned electrical vectors are defined in the diagram [13]-[15].

The transient energy from \( t_1 \) to \( t_2 \) is

\[
E_M = \int_{t_1}^{t_2} P_m(t) \, dt
\]

(1)

\[
E_N = \int_{t_1}^{t_2} P_n(t) \, dt
\]

The increase in the transient energy is described as

\[
\Delta E_M = \int_{t_1}^{t_2} \Delta P_m(t) \, dt
\]

(2)

\[
\Delta E_N = \int_{t_1}^{t_2} \Delta P_n(t) \, dt
\]

Where \( P_m(t) \) and \( P_n(t) \) are the instantaneous power and their increments are \( \Delta P_m(t) \, dt \) \( \Delta P_n(t) \, dt \). Converting equation (2) to discrete time form by substituting \( n \Delta t \) for continuous period from \( t_1 \) to \( t_2 \). As shown in equation (3) \( \Delta t \) is the sampling interval and \( n \) is the time index. Further the increase in dc voltage and dc current is expressed as \( \Delta u_M, \Delta i_M, \Delta u_N, \Delta i_N \) so the increase in transient energy is given as follows :

\[
\Delta E_M = \sum_{i=1}^{n} \Delta P_m(i) \Delta t
\]

(3)

\[
\Delta E_N = \sum_{i=1}^{n} \Delta P_n(i) \Delta t
\]

That means

\[
\Delta E_M = \sum_{i=1}^{n} \Delta u_M(i) \Delta i_M(i) \Delta t
\]

(4)

\[
\Delta E_N = \sum_{i=1}^{n} \Delta u_N(i) \Delta i_N(i) \Delta t
\]

Therefore the increase of transient energy in the dc transmission line is

\[
\Delta E = \Delta E_M - \Delta E_N
\]

(5)

In steady state operating condition,

\[
\Delta E_M = \Delta E_N = 0
\]

(6)
Transient energy difference is negative during steady state.

A. External fault

\[ u_L = R_1 i_{M1} + R_2 i_{N1} + L_1 \frac{di_{M1}}{dt} + L_2 \frac{di_{N1}}{dt} \]

And

\[ u_{M1} - u_{N1} = u_L \]

Before the fault has occurred, we have

\[ u_M - u_N = R_1 i_M + R_2 i_N \]

It means

\[ \Delta u_M - \Delta u_N = (R_1 + R_2) i_f + L_1 \frac{di_{M1}}{dt} + L_2 \frac{di_{N1}}{dt} \]

Hence there are

\[ \Delta u_M < 0 \text{ and } \Delta u_N < 0 \]

Shunt capacitance of the dc transmission line affects the dc protection of the dc line. Shunt capacitance between the overhead dc line and ground is present during normal operating conditions.

Therefore, with the fault \( F_1 \) the capacitance current is discharged from the shunt capacitance. Equivalent capacitance \( C \) and the discharging current \( i_c \) are represented in Fig. 4(a), and an equivalent current source that is used to substitute for the discharging current under the transient state condition is shown in Fig. 4(b). According to (9) the equivalent discharge current of the dc line is

\[ i_c = C \frac{du_c}{dt} \]

Hence the transient current of the dc line during the fault \( F_1 \) is obtained as,

\[ i_{M1} = i_M + i_f - \frac{1}{2} i_c \]

\[ i_{N1} = i_N + i_f + \frac{1}{2} i_c \]

and increase in two transient currents are

\[ i_{M1} = i_M + i_f - \frac{1}{2} i_c \]

\[ i_{N1} = i_N + i_f + \frac{1}{2} i_c \]
\[ \Delta i_M = i_f - \frac{1}{2}i_C \]

(19)

\[ \Delta i_N = i_f + \frac{1}{2}i_C \]

(20)

We know, \( i_f > i_C \)

During this condition the current \( i_M \) always ascends and \( i_N \) descends. So increase of transient voltage and current is

\[ \Delta u_M < 0 \]

\[ \Delta u_N < 0 \]

\[ \Delta i_M > 0 \]

\[ \Delta i_N < 0 \]

Substituting these relations into (4)

\[ \Delta E < 0 \]

During internal fault the difference of transient energy between both ends of the dc line is negative.

\[ \Delta i_M > 0, \Delta i_N > 0 \]

(21)

\[ \left| \Delta i_M \right| < \left| \Delta i_N \right| \]

Substituting (16) and (21) in to equation (4) We get,

\[ \Delta u_M \Delta i_M < 0 \text{ and } \Delta u_N \Delta i_N < 0 \]

Substituting these relations in equations (5) We get

\[ \Delta E > 0 \]

Depending on the aforementioned procedures, analysis of the ac fault at the rectifier side can be done. During external fault the difference of transient energy between both ends of the dc line is positive.

**B. Internal Fault**

![Flowchart of the transient energy principle](image)

**IV. TEST RESULTS**

**i) Results for the balanced fault at the inverter side:**

In Fig. (8) four curves of the system responses are shown during L-L-L-G fault at the inverter side. Fault occurs at 0.5s. \( I_{m} \) and \( U_{m} \) are the dc current and dc voltage close to the rectifier. \( I_{n} \) and \( U_{n} \) are the dc current and voltage close to the inverter.

During ac fault at the inverter side the dc voltages \( U_{m} \) and \( U_{n} \) suddenly drops down. But current \( I_{m} \) and \( I_{n} \) increase rapidly. During that time constant current (CC) and constant extinction angle (CEA) activates and tries to make the dc system stable.
But large disturbance of the ac system makes dc current to increase on greater extent during that transient process. Due to the impact of shunt capacitor in the dc line, the dc current \( I_m \) is smaller than \( I_n \). And \( U_m \) is greater than \( U_n \) at that time. Hence, there is transient energy difference between both the terminals of the dc transmission line. And its value is positive. As a result external fault can be identified by the new scheme.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 8. System response during inverter fault. (a) Current under the inverter fault. (b) Voltage under the inverter fault.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 9. Angle order of the rectifier during balanced fault at inverter side.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 10. Angle order of the inverter during balanced fault at inverter side.

ii) Results for the balanced fault at the rectifier side:

In Fig. (11) four curves of the system responses are shown during L-L-L-G fault at the rectifier side. Fault occurs at 0.5 s.

During ac fault at the rectifier side, the dc voltage \( U_m \) and \( U_n \) decrease suddenly and dc currents \( I_m \) and \( I_n \) will decline. During that transient process due to the impact of the shunt capacitor in the dc line the current \( I_m \) is smaller than \( I_n \). Considering the influence of the equivalent series inductance at that time, the voltage \( U_n \) decreases slowly than \( U_m \). Hence, there is transient energy difference between both terminals of the dc transmission line. And its value is positive. As a result external fault can be identified by the new scheme.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 11. System response during the rectifier fault. (a) Current under the rectifier fault. (b) Voltage under the rectifier fault.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 12. Angle order of the rectifier during balanced fault at the rectifier side.

\[ \text{(a)} \]
\[ \text{(b)} \]
Fig. 13. Angle order of the inverter during balanced fault at the rectifier side.
iii) Results for the dc line fault:

In Fig (12) four curves of the system responses are shown during L-L-L-G fault at the dc line fault occurs at 0.5 s.

During dc line fault, dc voltages $U_m$ and $U_n$ drops down suddenly and dc current $I_n$ decreases and $I_m$ increases rapidly. So increase of transient energy at the rectifier side is negative and that at the inverter side is positive. Hence there is transient energy difference between both the terminals of the dc transmission line. And its value is negative so the internal fault is recognized by the proposed scheme.

![Fig. 14. System response during the dc line fault. (a) Current under the dc line fault. (b) Voltage under dc line fault.](image)

![Fig. 15. Angle order of the rectifier during dc line fault.](image)

![Fig. 16. Angle order of the inverter during dc line fault.](image)

### TABLE I

<table>
<thead>
<tr>
<th>Fault type</th>
<th>$\Delta E_m$/kW.ms</th>
<th>$\Delta E_n$/kW.ms</th>
<th>$\Delta E$/kW.ms</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier fault</td>
<td>0.1713</td>
<td>0.1210</td>
<td>0.0503</td>
<td>-</td>
</tr>
<tr>
<td>Inverter fault</td>
<td>-0.1329</td>
<td>-0.1807</td>
<td>0.4662</td>
<td>-</td>
</tr>
<tr>
<td>Internal fault</td>
<td>0.2629</td>
<td>0.2033</td>
<td>-0.4662</td>
<td>+</td>
</tr>
</tbody>
</table>

#### A. Effect of Fault Resistance

To check the sensitivity of the transient protection scheme, simulation of the CIGRE benchmark test system is carried out with a set of different fault resistances from 1 to 300 $\Omega$. Correct responses are given by the proposed protection scheme during various fault conditions that includes high ground resistance fault.

In table II the performance evaluation of the proposed transient energy protection scheme under different fault resistance is given.

### TABLE II

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault resistance/$\Omega$</th>
<th>$\Delta E_m$/kW.ms</th>
<th>$\Delta E_n$/kW.ms</th>
<th>$\Delta E$/kW.ms</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier fault</td>
<td>1</td>
<td>0.1795</td>
<td>0.1101</td>
<td>0.0694</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.1075</td>
<td>0.0566</td>
<td>0.0509</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.0284</td>
<td>0.0130</td>
<td>0.0155</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>0.0063</td>
<td>0.0023</td>
<td>0.0059</td>
<td>-</td>
</tr>
<tr>
<td>Inverter fault</td>
<td>1</td>
<td>-0.1086</td>
<td>0.1638</td>
<td>0.0551</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>-0.0581</td>
<td>-0.1027</td>
<td>0.0446</td>
<td>-</td>
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<tr>
<td></td>
<td>100</td>
<td>-0.0360</td>
<td>-0.0712</td>
<td>0.0352</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-0.0002</td>
<td>-0.0014</td>
<td>0.0012</td>
<td>-</td>
</tr>
<tr>
<td>DC line fault</td>
<td>1</td>
<td>0.2475</td>
<td>0.2400</td>
<td>-0.4875</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>-0.1750</td>
<td>0.1827</td>
<td>-0.3777</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-0.0872</td>
<td>0.0810</td>
<td>-0.1681</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>-0.0282</td>
<td>0.0284</td>
<td>-0.0565</td>
<td>+</td>
</tr>
</tbody>
</table>

#### B. Effect of Transmission Distance

To check the sensitivity of the transient protection scheme, simulation of the CIGRE benchmark test system is carried out by locating the fault at different transmission distances from 100 to 2000 km. Proposed protection gives correct responses under different transmission distances.

In table III the performance evaluation of the proposed scheme under different transmission distance is given.
TABLE III
Performance Evaluation of Transient Energy Protection Scheme under Different Transmission Distances during Internal Fault

<table>
<thead>
<tr>
<th>Transmission Distance/Km</th>
<th>ΔE0 /kW.ms</th>
<th>ΔE1 /kW.ms</th>
<th>ΔE2 /kW.ms</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-0.2853</td>
<td>0.3234</td>
<td>-0.6087</td>
<td>+</td>
</tr>
<tr>
<td>300</td>
<td>-0.2477</td>
<td>0.2295</td>
<td>-0.4743</td>
<td>+</td>
</tr>
<tr>
<td>500</td>
<td>-0.2628</td>
<td>0.2034</td>
<td>-0.4661</td>
<td>+</td>
</tr>
<tr>
<td>1000</td>
<td>-0.1750</td>
<td>0.1827</td>
<td>-0.3070</td>
<td>+</td>
</tr>
<tr>
<td>1500</td>
<td>-0.1429</td>
<td>0.1640</td>
<td>-0.3070</td>
<td>+</td>
</tr>
<tr>
<td>2000</td>
<td>-0.1558</td>
<td>0.1263</td>
<td>-0.2821</td>
<td>+</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A novel transient energy protection method for the HVDC transmission line is proposed. This method is better than travelling wave protection method. Modeling of the CIGRE HVDC benchmark system is done using MATLAB software and the system is tested under various faults. According to the transient energy protection scheme, during external fault the transient energy is positive and negative during internal fault. Repetitive test studies shows that transient energy protection scheme satisfactorily works during internal and external fault conditions also it can respond to high ground resistance fault. Also the proposed protection scheme is not affected by the transmission distance.

APPENDIX

Rectifier ac system SCR= 2.5@84.0deg 354.0 kV 50 Hz.
Rectifier
\[ R_i = 261.87 \ \Omega \ , \ R_2 = 83.32 \ \Omega \ , \ R_o = 29.76 \ \Omega \]
\[ L_1 = 0.1364H \ , \ L_2 = 0.136H \]
\[ C_{i1} = 6.685 \ \mu F \ , \ C_{i2} = 6.685 \ \mu F \ , \ C_{i3} = 3.342 \ \mu F \ , \ C_{i4} = 0.1364 \ \mu F \]

Inverter ac system SCR= 2.5@75.0deg 230 kV 50 Hz.
Inverter
\[ R_i = 116.38 \ \Omega \ , \ R_2 = 37.03 \ \Omega \ , \ R_o = 13.23 \ \Omega \]
\[ L_1 = 0.0606 H \ , \ L_2 = 0.0061 H \]
\[ C_{i1} = 15.04 \ \mu F \ , \ C_{i2} = 15.04 \ \mu F \ , \ C_{i3} = 7.522 \ \mu F \ , \ C_{i4} = 167.2 \ \mu F \]

Resistance of the transmission line is 0.04633 Ω/km.

REFERENCES


Deepali Suryawanshi was born in Maharashtra, India, in 26 October 1990. Received B.E degree in Electrical Engineering from Shivaji University in 2012 and pursuing M.Tech(Power System) from Rajaramarapu Institute of Technology, Maharashtra. Her research interests are the HVDC transmission system, Power system protection.

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