Abstract—HVDC transmission line protection is one of the major concerns in the present power system because HVDC is preferred more than HVAC due to its leading advantages over EHVAC system. Various techniques are being proposed for the protection of HVDC lines. During the occurrence of faults the transients are generated in the HVDC system. This paper deals with a transient energy protection scheme proposed for protection of HVDC lines. Behaviour of the HVDC system during internal and external fault is studied. 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 voltages and currents at both the terminals and fault can be identified from the calculated value of transient energy. The test system is modelled in MATLAB software based on CIGRE 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 and tremendous capability of power transmission [1]-[3]. Due to the rapid development of power electronics technology for making a better stability condition, HVDC transmission link plays a very important role in the complex power systems. The older protective system for the HVDC transmission line uses the voltage and its changing rate to detect ground faults in the dc line. It is found that it is sensitive to fault impedance. Due to the increasing advance of microelectronics technology and microcomputer, travelling wave theory has been implemented in the HVDC transmission lines protection [4]. Travelling wave methods has disadvantage such as it is easily affected by noise and lacking mathematical tools to represent the travelling waves in the simulation model [5]-[7].

A novel protection scheme was proposed for UHVDC based on the characteristics of low frequency differential transient energy at the two terminals of dc transmission line [8]. 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 mal-operation of relay protection [9]- [10].

A new transient energy protection principle based on the distributed parameters of the transmission line is presented in this paper considering the steady state transmission line equations. The increase in the transient energy in dc line is used to identify internal and external faults. Based on this, the test system is modeled.

This paper is organized as follows. In section II CIGRE HVDC benchmark test system is given. In section III the protection principle used is proposed. Test results are given in section IV and conclusion is given in section V.

II. CIGRE HVDC BENCHMARK SYSTEM

The system is mono-polar 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 sub-circuits [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.

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.

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 PROTECTION

PRINCIPLE

The main structural diagram of the typical HVDC transmission system is shown in fig. 2. \(i_M, i_N\) and \(u_M, u_N\) 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

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

(1)

The increase in the transient energy is described as

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

(2)

Where \(P_m(t)\) and \(P_n(t)\) are the instantaneous power and their increments are \(\Delta P_m(t)\) and \(\Delta P_n(t)\). Converting equation (2) to discrete time form by substituting \(n.\Delta t\) for continuous period from \(t_2\) 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:

\[
\Delta E_M = \sum_{n=1}^{n} \Delta P_m \Delta t \\
\Delta E_N = \sum_{n=1}^{n} \Delta P_n \Delta t
\]  

(3)

That means

\[
\Delta E_M = \sum_{i=1}^{n} \Delta u_M \Delta i_M \Delta t \\
\Delta E_N = \sum_{i=1}^{n} \Delta u_N \Delta i_N \Delta t
\]  

(4)

Therefore the increase of transient energy in the dc transmission line is
Protection of HVDC Transmission Line Using Transient Energy Protection Scheme

In steady state operating condition,

$$\Delta E_M = \Delta E_N = 0$$  \quad (6)$$

Transient energy difference is zero during steady state.

A. External fault

Fig. 3. Demonstration of line model

(a) Distributed parameter model
(b) Lumped parameter model with shunt capacitance [14]

Where $R_0$ is the series resistance $\Omega/km$, $L_0$ is the series inductance (H/km), $G_0$ is the shunt leakage conductance (S/km).

Equations of the transmission lines are:

$$\begin{align*}
\frac{\partial u}{\partial x} &= R\frac{\partial i}{\partial t} + L\frac{d^2 i}{dt^2} \\
\frac{\partial i}{\partial t} &= G\frac{\partial u}{\partial t} + C\frac{\partial u}{\partial t}
\end{align*}$$  \quad (7)$$

For simplicity the impact of leakage conductance is neglected in this paper. The dc line that has to be protected is replaced by a lumped parameter model considering the influence of shunt capacitance. The increase of voltage and current due to distributed parameters of the transmission line can be expressed as:

$$u_L = R(i_M + i_N) + L_1\frac{di_M}{dt} + L_2\frac{di_N}{dt}$$  \quad (8)$$

$$i_c = C \frac{du_C}{dt}$$  \quad (9)$$

Fig. 4(b) shows superimposed fault current $i_f$ from that we get transient current at both ends of dc transmission line during fault $F_1$.

$$\frac{d}{dt}\left[N_1\frac{di_M}{dt} + N_2\frac{di_N}{dt}\right] = \frac{d}{dt}\left(v_{M1} - v_{M2}\right)$$  \quad (10)$$

Substituting the relations (10) in equation (8) We get

$$\frac{d}{dt}\left[N_1\frac{di_M}{dt} + N_2\frac{di_N}{dt}\right] = \frac{d}{dt}\left(v_{M1} - v_{M2}\right)$$  \quad (11)$$

And

$$u_L = u'_{M} - u'_{N}$$

Before the fault has occurred, we have

$$u_M - u_N = R(i_M + i_N)$$  \quad (12)$$

It means

$$\Delta u_M = \Delta u_N = (R_1 + R_2)i_f + L_1\frac{di_M}{dt} + L_2\frac{di_N}{dt}$$  \quad (13)$$

Hence there are

$$\Delta u_M < 0 \text{ and } \Delta u_N < 0$$  \quad (14)$$

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. 5(a), and an equivalent current source that is used to substitute for the discharging current under the transient state condition is shown in Fig. 5(b), According to (9) the equivalent discharge
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.

\[
ic = C \frac{du_C}{dt}
\]

and two transient currents are obtained as below:

\[
i'M = iM + if - \frac{ic}{2}
i'N = iN + if + \frac{ic}{2}
\]

This gives increments of two transient currents

\[
\Delta iM = if - \frac{ic}{2}
\Delta iN = if + \frac{ic}{2}
\]

We know, \(i_f > i_c\).

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

\[
\Delta i_M < \Delta i_N
\]

Substituting (14) and (17) 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

\[
\Delta E > 0
\]

During internal fault as shown in Fig. 6(a), the dc voltages at both ends of the dc line drops down rapidly. Fig. 6(b) shows superimposed circuit of the HVDC transmission system where \(u_f\) is the additional fault voltage source and \(i_f\) is the additional fault current.

During this condition the current \(i_M\) always ascends and \(i_N\) descends. So increase in transient voltage & 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 the transient energy between both end of the dc line is negative.

The proposed algorithm for this protective principle is given blow in fig. 7.
IV. TEST RESULTS

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

Four curves of the system responses are shown in fig.8 during L-L-L-G fault at the inverter side. Fault occurs at 0.5s. Im and Um are the dc current and dc voltage close to the rectifier. In and Un are the dc current and voltage close to the inverter.

During ac fault at the inverter side the dc voltages Um and Un suddenly drops down. But current Im and In 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 Im is smaller than In. And Un 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.

ii) Results for the dc line fault:

Four curves of the system responses are shown in fig.10, during L-L-L-G fault at the inverter side the dc line fault occurs at 0.5s. During dc line fault, dc voltages Um and Un drops down suddenly and dc current Im decreases and In 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.

ii) Results for the balanced fault at the rectifier side

Four curves of the system responses are shown in fig.9 during L-L-L-G fault at the rectifier side. Fault occurs at 0.5 sec. During ac fault at the rectifier side, the dc voltage Um and Un decrease suddenly and dc currents Im and In will decline. During the transient process due to the impact of the shunt capacitor in the dc line the current Im is smaller than In. Considering the influence of the equivalent series inductance at that time, the voltage Un decreases slowly than Um. Hence there is the 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 new scheme.
Protection of HVDC Transmission Line Using Transient Energy Protection Scheme

CONCLUSION

A transient energy protection method for the HVDC transmission line is presented. Modeling of the CIGRE HVDC benchmark system is done using MATLAB software and the system is tested under various fault conditions. 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.

APPENDIX

REFERENCES