Protection Scheme for AC Faults in HVDC Transmission System and Harmonics Reduction using Tuned Filters

K. G Visak[1], Vinod V[2]
[1]M. Tech Student
[2]Assistant Professor
[1,2]Dept. of EEE
Govt. Engg College Barton Hill

***Abstract*- HVDC transmission is the most economical and advanced method of efficient power transmission for long distances applications. It is free from those limitations imposed on HVAC transmission systems. Converters used may be either Voltage Source Converters (VSC) or Line commutated Converters (LCC) depending on the application and power rating of HVDC system. LCC based HVDC system is also known as Current Source Converter (CSC) based system. Most important feature of the HVDC system is the easy power control. The direction of power flow can be easily reversed by controlling the triggering of the converters. In this paper the main aim is to study the AC faults occurring in an HVDC system. Commutation failures caused by the AC faults and control method for its mitigation is analysed. Analysis of the HVDC system is carried out in the MATLAB Simulink software. THD analysis of the HVDC system is carried out using the tuned (single and double tuned) filters and comparison has been done to find the best out of the two.**

***Index Terms*- High Voltage Direct Current (HVDC), Commutation Failure Prevention (CFPREV), Voltage Dependent Current Order Limiter (VDCOL).**

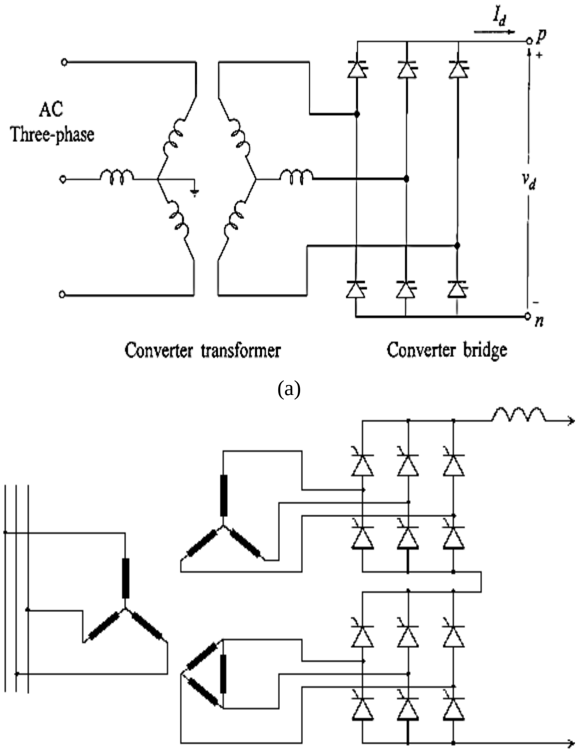
I. INTRODUCTION

Electrical power system plays a major role in the development of a nation by the proper conversion, transmission and utilisation of the electrical energy in the desired form. Electrical power system is mainly divided into following sub systems:

a) Generation system
b) Transmission system
c) Distribution system

Generation system deals with the electrical power generation from various sources like, Thermal power generation, Hydro-electric power generation and Nuclear power stations. which are far away from the power consumers. Hence the power generated has to be brought to the consumer many kilometres away via proper transmission system. Depending on various factors, the transmission systems can be classified into two types, High Voltage AC transmission (HVAC) and High Voltage DC transmission (HVDC). Of the two types of transmission systems HVDC transmission is more suitable for very long distance power transmission than the HVAC system due to its technical and economic merits. Choice of the type of transmission depends on various factors like, distance of power transmission, type of application, overall cost, types of interconnected systems etc.

HVDC system consist of two converter stations at both ends connecting the AC systems; one as rectifier and the other as inverter depending on the power flow direction. The converter circuit is 12-pulse converter which is implemented by connecting two 6-pulse converter circuits (Graetz circuit) in series. The figure shows the basic 6-pulse converter fig.1 (a) and the 12-pulse converter fig.1 (b) circuits.



(a)

(b)

Fig.1: Converter circuits

The paper mainly deals with the study of AC faults occurring in a High Voltage DC transmission system. The AC faults lead to commutation failure which causes short circuit in the converter circuit. The mitigation method for this commutation failure is studied. Then the harmonics

induced into the AC system due to the HVDC system is studied and filters for reduction of harmonics is also described. Further designing of Double tuned filter is also done which could be used to replace the conventional single tuned filter in the HVDC systems.
Analysis of the HVDC system is done with simulation experiments in MATLAB SIMULINK software. Various simulation study has been carried out to study the response of the system to various types of faults is also analysed. Then the analysis of THD in the system and reduction in the THD using single tuned and double tuned filters are also carried out.

II. AC FAULTS OCCURING IN AN HVDC SYSTEM

A. AC Fault

AC fault occurs in the AC grids of the HVDC system. This may occur in the AC grid on the rectifier side or inverter side. Faults on rectifier side AC grid cause less problems compared to that on the inverter side. In the inverter side, the AC faults cause the short circuit in the converter circuit. This is known as commutation failure in the HVDC system. Causes and mitigation method for this problem is described later.

AC faults are mainly of two types; L-G fault and three phase fault. Single line to ground fault (L-G fault) is the most commonly occurring type of fault. This causes an unbalanced current flow in the AC system. Whereas three phase fault is the rarest and the dangerous one. These cause commutation failure in the inverter station.

B. Commutation Failure Due to AC Faults

Commutation failures following AC system disturbances may occur in HVDC systems, mostly in the inverter station. The sensitivity of an HVDC inverter to commutation failure depends on the circuit design and on the control system. The commutation failures may happen during an AC system disturbance due to the voltage reduction. Repeated commutation failures generally cause overcurrent in the valves and also delay the restart time of the HVDC system after the fault clears. In a severe situation it might also cause the protection system to block the valves.

The equivalent circuit of the 6 pulse bridge converter at the instant of commutation is shown below. As shown in the fig. 2 thyristor valves 1 and 3 is conducting simultaneously. This cause a short circuit between phase A and B.

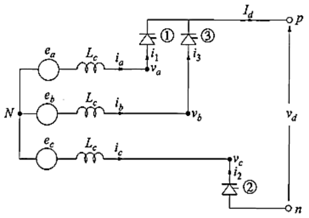


Fig.2: equivalent circuit of bridge converter during commutation

Since a converter transformer has inductance, the transformer current cannot change instantly. The transfer of current from one valve to another requires a finite commutation time. The volt time area required for the commutation is related to the commutating current. The higher the commutating current, the larger the volt-time area will be. A phenomenon in thyristor valves is that the internal stored charges produced during a forward conduction interval must be removed before the valve can establish a forward voltage blocking capability. This time is known as the de-ionisation time and the time from the instant when the valve current goes to zero to the time that the line-to-line voltage is zero is defined as the extinction angle (γ). If a thyristor becomes positively biased before complete de-ionisation occurs, this thyristor will regain current. Commutation failures in HVDC systems are mainly caused by voltage dips due to AC system faults. Voltage dips may affect the commutation in three ways:

Voltage magnitude reduction

Commutating AC line-to-line voltage decreases because of a voltage dip, as shown in fig. 3. Since the voltage magnitude has decreased, but the commutation area still remains the same, so the end of commutation will be delayed and the extinction angle will reduce γ.

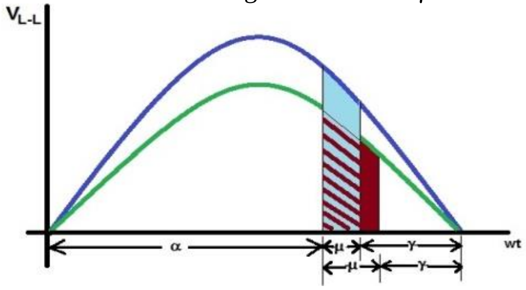


Fig. 3: Reduced commutation margin due to voltage magnitude reduction

Phase-angle shift

The backward phase-angle shift affects the commutating process negatively. If we assume that the firing instant does not change, although the volt-time area remains the same, the final extinction angle will be reduced. Fig. 4 illustrates how a voltage dip with backward phase-angle shift affects the commutation margin.

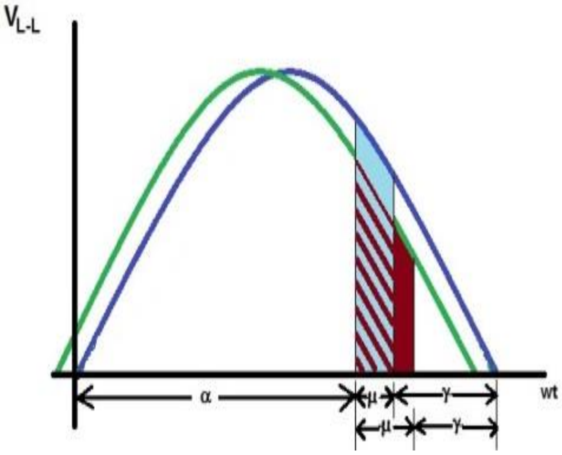


Fig. 4: Reduced commutation margin due to phase angle shift

Increased dc current.

The dc current increases on the initiation of the fault at the inverter. Since the volt-time area increases with the increased dc current, a relatively larger overlap μ will be needed to complete the commutation. This will in the end reduce γ.

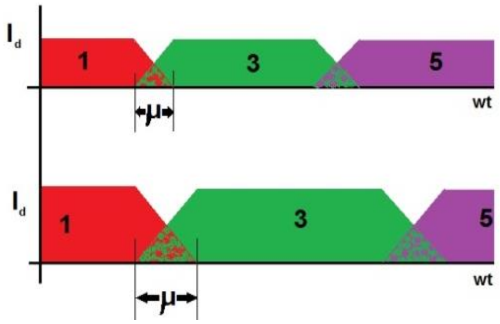


Fig. 5: Reduced commutation margin due to increase in DC current

All the above influences from, voltage dips reduce the extinction angle γ to a smaller γ. If γ is smaller than a certain value, the previously conducting valve will regain current, and will end up with a commutation failure.

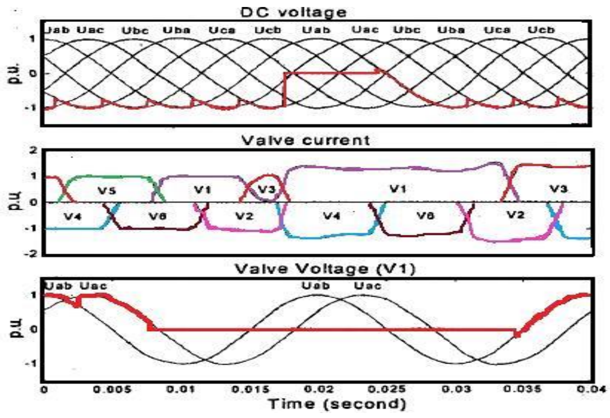


Fig. 6: DC voltage, valve current and valve voltage during commutation failure

Fig.6 gives an example plot with the dc voltage, valve current and the Valve 1 (VI) voltage when a commutation failure occurs. From fig.6, we can see that the commutation failure actually creates a short circuit on the dc side.

III COMMUTATION FAILURE PROTECTION SCHEME

As shown in fig. 3, fig. 4, and fig. 5, too small an extinction angle γ due to voltage dips in AC systems is the basic reason of commutation failures. To be able to keep a big enough γ, the control system should give an advanced firing instant on detection of the AC system disturbance. The flowchart in fig.7 shows how this function is designed. This control function includes two parallel parts.

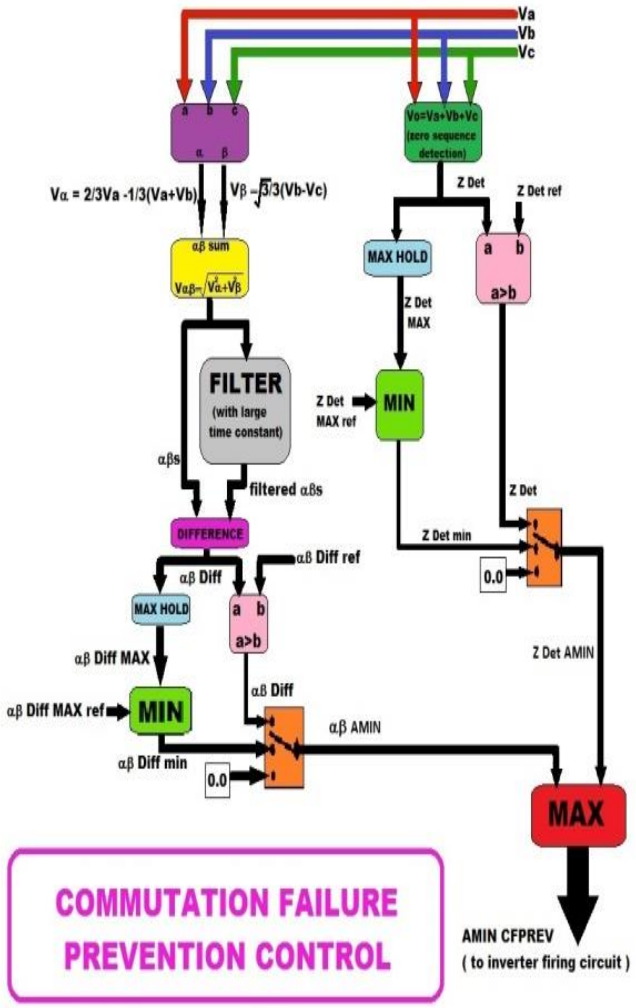


Fig. 7: flowchart of commutation failure prevention control

One is based on zero-sequence detection to detect single-phase faults, and the other one is based on abc- αβ transformation to detect three-phase faults. This control module is called CFPREV (Commutation Failure Prevention). Single-phase faults are the most frequently-occurring unbalanced faults experienced by the HVDC converter. The three-phase voltages at the converter bus usually contain zero sequence voltage during this type of fault. Z-Det AMIN is resulting signal obtained from the control part for line to ground fault. αβ-AMIN is the signal obtained as a result of the control scheme for three phase fault.

Although the two parts of the control module deal with different fault conditions, they might be activated at the same time. In such a situation, the maximum value of Z Det AMIN and αβ-AMIN will be chosen as the final output of the entire control module. The output AMIN-CFPREV value will be deducted from the final inverter firing control, advancing the firing instant and leaving a bigger commutation margin. Thus the commutation failure is mitigated at the instant of fault detection on the AC system at the inverter side.

IV HARMONICS AND DESIGN OF TUNED FILTER

Converters generate harmonic voltages and currents on both ac and dc sides. These harmonics may be of different orders and for the reduction of these tuned filters are implemented.

A. AC Side Harmonics

The converter circuit is composed of 12-pulse converter as described earlier. The resulting Ac current may be expressed as Fourier series.

$$i = \frac{2\sqrt{3}}{\pi} 2I_d \left(\sin\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t + \frac{1}{23}\sin 23\omega t + \cdots\right) \quad (1)$$

The harmonics of order 12*n*±1 (i.e., 11th, 13th, 23th, 25th, etc.) flow into the ac system. Their magnitudes decrease with increasing order; an *h*th order harmonic has magnitude *l/h* times the fundamental.

Filter circuits are designed for the reduction of harmonics in the AC system. Tuned filters capable of reducing certain order harmonics are used. Normally 2 single tuned filters are used; one for 11th order harmonics and other for 13th order harmonics. A high pass filter is also used for the reduction of higher harmonics.

B. Designing of Double Tuned Filter

Normally HVDC systems use single tuned filters for the harmonics reduction. Also these filters supply a part of the reactive power requirement of the system. A double tuned filter does the same function the two single tuned filters in parallel does. Also the cost of one double tuned filter is less than two single tuned filters. Hence use of double tuned filter will provide an economic advantage to the HVDC system.

For designing a double tuned filter two single tuned filters are designed. As described in the previous section HVDC system induce 11th and 13th harmonics and higher harmonics into the AC systems. Hence filters used must be capable of reducing these harmonics. Also a part of the reactive power has to be supplied by these filters.

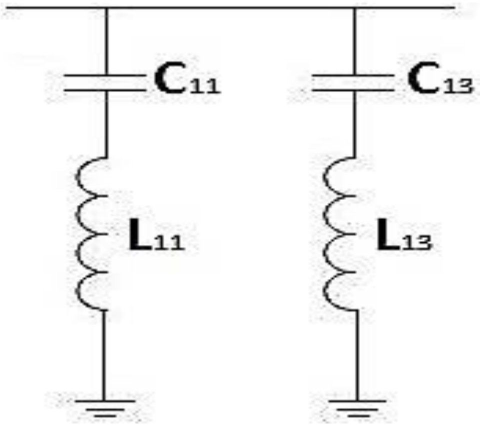


Fig. 8: single tuned filters in parallel

For a single tuned filter, tuned harmonic order,

$$n = \frac{f_n}{f} = \sqrt{\frac{X_C}{X_L}} \quad (2)$$

Reactive power at frequency f,

$$Q_C = \frac{V^2}{X_C}\frac{n^2}{(n^2-1)} \quad (3)$$

where, $X_C = \frac{1}{2\pi fC}$

$X_L = 2\pi fL$

f = fundamental frequency

f_n=tuning frequency

V= nominal line-line voltage

From these expressions the inductance (L) and capacitance (C) value of the single tuned filter can be obtained for each tuning frequency. For 11th harmonics inductance and capacitance values of the tuned filter are L_{11} and C_{11}. Similarly for 13th harmonics L_{13} and C_{13} respectively.

As stated earlier double tuned filter can be considered equivalent to two single tuned filters in parallel. The resonance frequencies can be expressed as

$$\omega_{11} = \frac{1}{\sqrt{L_{11}C_{11}}} \quad (4)$$

$$\omega_{13} = \frac{1}{\sqrt{L_{13}C_{13}}} \quad (5)$$

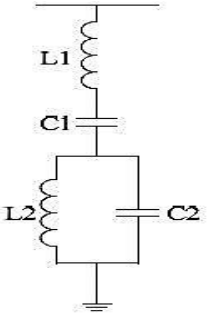


Fig. 9: double tuned filter

The impedance of two parallel single tuned filters can be expressed as:

$$Z_{ST} = \frac{\left(1-\frac{\omega^2}{\omega_{11}^2}\right)\left(1-\frac{\omega^2}{\omega_{13}^2}\right)}{j\omega C_{11}\left(1-\frac{\omega^2}{\omega_{13}^2}\right)+j\omega C_{13}\left(1-\frac{\omega^2}{\omega_{11}^2}\right)} \quad (6)$$

The double tuned filter has one series LC circuit and one parallel LC circuit connected in cascaded form. Series resonance circuit (L_1 and C_1) have resonance frequency

$$\omega_S = \frac{1}{\sqrt{L_1C_1}} \quad (7)$$

Parallel resonance circuit (L2 and C2) have resonance frequency

$$\omega_P = \frac{1}{\sqrt{L_2C_2}} \quad (8)$$

Impedance of the double tuned filter is expressed as

$$Z_{DT} = \frac{\left(1-\frac{\omega^2}{\omega_S^2}\right)\left(1-\frac{\omega^2}{\omega_P^2}\right)-\omega^2L_2C_1}{j\omega C_1\left(1-\frac{\omega^2}{\omega_P^2}\right)} \quad (9)$$

Analyzing the expressions for impedance of both single tuned and double tuned filters following expressions can be deduced.

$$\omega_{11}\omega_{13} = \omega_S\omega_P$$

$$C_1 = C_{11} + C_{13} \quad (10)$$

Parameter L_1 can be calculated as

$$L_1 = \frac{1}{C_{11}\omega_{11}^2 + C_{13}\omega_{13}^2} \quad (11)$$

Now series and parallel resonance frequencies can be obtained as

$$\omega_S = \frac{1}{\sqrt{L_1C_1}} \qquad \omega_P = \frac{\omega_{11}\omega_{13}}{\omega_S}$$

Parameter L_2 can be obtained as

$$L_2 = \frac{\left(1-\frac{\omega_{11}^2}{\omega_S^2}\right)\left(1-\frac{\omega_{11}^2}{\omega_P^2}\right)}{C_1\omega_{11}^2} \quad (12)$$

Parameter C2 is obtained as

$$C_2 = \frac{1}{L_2\omega_P^2} \quad (13)$$

Hence inductance and capacitance value for a double tuned filter equivalent to two single tuned filters can be obtained.

V. SIMULATION RESULTS AND DISCUSSION

A. Single Line to Ground Fault (L-G Fault)

For the analysis of the HVDC system under AC L-G fault a breaker is connected between one phase of the AC system at the rectifier end (AC system2) and ground. The fault is applied between t=0.7s and t=0.8s. The fault current of the system is shown below.

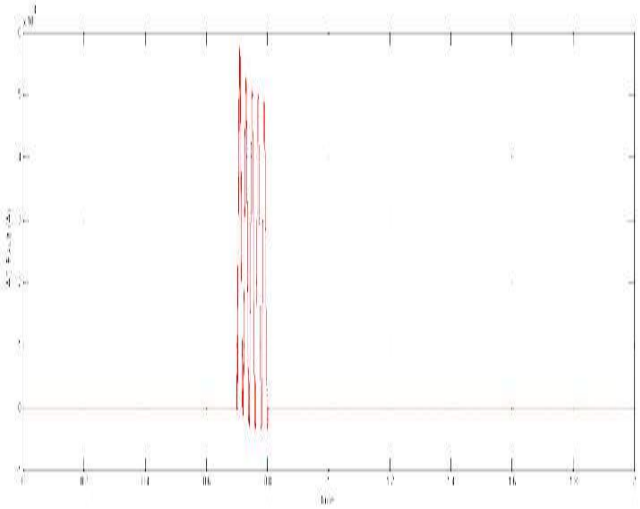


Fig. 10: L-G fault current

The effects of the fault on the AC system and the HVDC control system can be understood from the inverter scope data. When the fault is applied at t=0.7s the current increase to a value of 2pu. The VDCOL detects this rise in current value and reduces the reference current to 0.3 pu. The alpha ord in the rectifier increase above 100˚. Voltage also drops to a value less than zero. Thus rectifier now acts as an inverter and the energy stored in the line is returned back to the AC system leading to the fast extinction of the fault. After the fault is cleared at t=0.8s the reference current is ramped back to the normal value

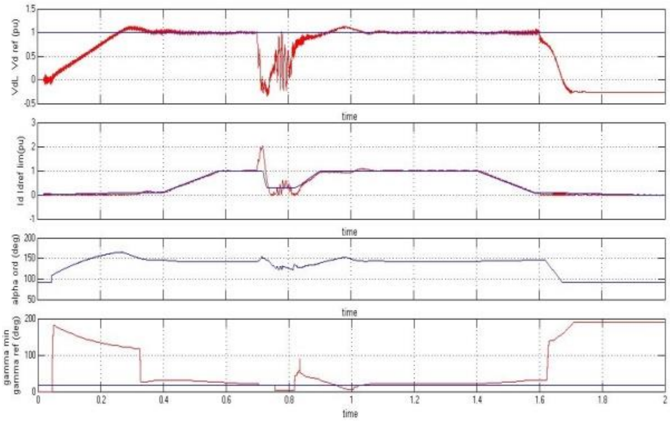


Fig.11: Inverter scope data after L-G fault

B. Three Phase Fault

Similar to the L-G fault, three phase fault also causes commutation failure in the inverter valves. To analyze the effect of three phase fault and the operation of CFPREV in mitigating Commutation failure a three phase fault is applied on the AC system. The fault is applied at t= 0.7s to t =0.8s. The resulting fault current is as in the fig. 12.

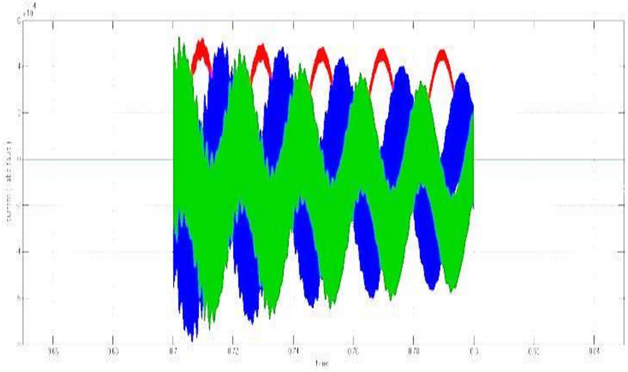


Fig. 12: Three phase fault current

After the fault application at t=0.7s the current increases to 2 pu. The VDCOL detects this increase and the reference current value is reduced to 0.3pu. After the fault clearance at t=0.8s the reference current is again ramped up to the normal value. Rectifier control also shows similar control operation. The Alpha ord increase from the normal value of 18˚ to a value above 100˚.

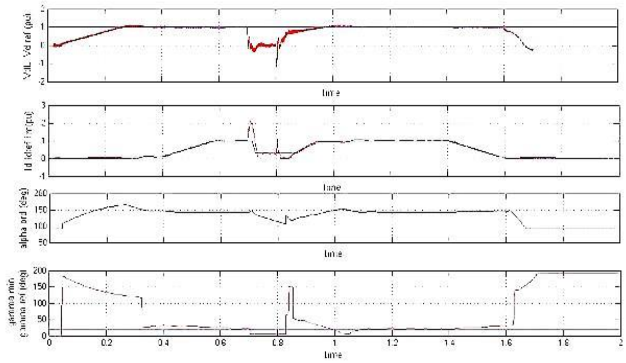


Fig. 13: Inverter scope data after three phase fault

The voltage reduces to a value below zero. Thus rectifier acts as inverter during the fault and the energy stored in the line is returned back to the AC network leading to the fast extinction of the fault.

C. Harmonics Reduction Using Tuned Filters

HVDC system injects harmonics of order 12n±1 in to the AC grid. So to reduce these injected harmonics tuned filters are incorporated in to the system. The LCC based HVDC system under study connects AC system1 rated at 500kV, 60Hz and AC system2 rated at 345kV, 50Hz. Hence the harmonics injected to the 500kV and 345kV AC grids are of different frequencies due to different fundamental frequencies. Hence two sets of filters have to be designed for the two AC systems, one with fundamental frequency 60Hz and the other with 50Hz.

Single tuned filter for the AC systems can be designed using the equations (2) and (3). The filters are designed for reduction of 11th and 13th harmonics. For higher order harmonics reduction a high pass filter is used.

These filters also have to provide the reactive power. The HVDC system under analysis is transferring an active power of 1000MW. So assuming the reactive power compensation required by the system to be about 600Mvar, which is to be provided by the filters and capacitor bank. Hence reactive power to be supplied by each single tuned filter is selected to be 150Mvar. After calculations the values of the inductance and capacitance for the filter are obtained as:

For 500kV, 60Hz AC system
$C_{11}=1.578\times10^{-6}$ F $\quad L_{11}=0.0368$ H
$C_{13}=1.582\times10^{-6}$ F $\quad L_{13}=0.02631$ H

For 345kV, 50Hz AC system
$C_{11}=3.978\times10^{-6}$ F $\quad L_{11}=0.021$ H
$C_{13}=3.987\times10^{-6}$ F $\quad L_{13}=0.01503$ H

With these values and also using the equations (4)-(13) the double tuned filter can be designed for both AC systems. The inductance and capacitance values thus obtained are as:

For 500kV, 60Hz AC system
$L_1=0.01534$ H $\quad C_1=3.16\times10^{-6}$ F
$L_2=4.2929\times10^{-4}$ H $\quad C_2=1.1613\times10^{-4}$ F

For 345kV, 50Hz AC system
$L_1=8.76\times10^{-3}$ H $\quad C_1=7.965\times10^{-6}$ F
$L_2=2.4394\times10^{-4}$ H $\quad C_2=2.941\times10^{-4}$ F

Using these values following results were obtained.

TABLE 1
COMPARISON OF THD REDUCTION USING TUNED FILTERS

AC SYSTEM 1: 500kV, 60Hz			
Parameters	Without filter	With single tuned filter	With double tuned filter
V_{abc}	5.22%	0.09%	0.17%
I_{abc}	9.11%	9.04%	8.91%
AC SYSTEM 2: 345kV, 50Hz			
V_{abc}	3.81%	0.21%	0.4%
I_{abc}	10%	9.84%	9.79%

Thus it is found that the double tuned filter has the similar harmonics reduction capability as two single tuned filters. Hence to provide the required harmonics filtering single tuned filters can be replaced by double tuned filter because of its economic benefits (low cost compared to two single tuned filters).

VI. CONCLUSION

The commutation failure caused due to the AC system faults was analyzed. The mitigation of commutation failure by the protective scheme also studied. Designing of double tuned filter for the harmonics reduction in the HVDC system is done and the comparative study of THD reduction using both single tuned and double tuned filters completed.

REFERENCES

[1] Lidong Zhang and Lars Dofnas “A Novel Method to Mitigate Commutation Failures in HVDC Systems,” *ABB Utilities Power System Technology, Proceedings PowerCon* 2002, Volume: 1 , 13-17 Oct. 2002, Page(s): 51-56 vol.1

[2] HE Yi-hong and SU Heng, “A New Method of Designing Double Tuned Filter,” *2nd International Conference on Computer Science and Electronics Engineering (ICCSEE 2013)*

[3] Venkatesh P, Dr. M. N. Dinesh, “Harmonic Analysis Of 6-Pulse and 12-Pulse Converter Models” *International* OPEN ACCESS *Journal Of Modern Engineering Research (IJMER)*

[4] Prabha Kundur, *Power system Stability and Contro.* EPRI Power Engineering Series, McGraw-Hill, 1994.