Protection of the VSC-HVDC Systems by employing Saturated Iron-Core Superconductive Fault Current Limiter

Irene George

B Tech student, Electrical and Electronics Engineering, APJ Abdul Kalam Technological University, Kerala, India

***Abstract*- The high-voltage direct-current transmission based on voltage source converter (VSC-HVDC) system point towards the development of the distributed generation, which gain more importance nowadays. But one of the challenge faced is that VSCs are vulnerable to dc short-circuit faults. The reason behind it is the huge discharge current of the dc-link capacitor. Therefore saturated iron-core superconductive fault limiter is used to limit this current which will offer superior technical performance in comparison with conventional methods. Due to this advantage and practical demand SISFCL has been applied on transmission lines. The working principle behind the SISFCL are discussed . The relationship between the inductance and dc gird current of the SI-SFCL is deduced. Thus Current limiter (SISFCL) is introduced to limit the fault current to a relatively low level is discussed.**

Index Terms- Fault analysis, dc line to line fault, VSC HVDC, superconductive fault current limiter.

I. INTRODUCTION

Increase in electric power generation capacity has led to increase in the fault current level. Many conventional protective devices are installed for protection of excessive fault current in power systems, such as circuit breakers, tripped by over-current protection relay.
To overcome the high fault current, different types of fault current limiting devices have been used. Current-limiting fuses, series reactors, and high-impedance transformers were used. They have the response time delay that allows initial of two and three fault current cycles to pass through before getting activated. These may cause problems, such as loss of power system stability, high cost and increase in power losses, which may leads to decreased operational flexibility and reliability. Superconducting Fault Current Limiter (SFCLs) is innovative one which has the capability to suppress fault current level within the first cycle of fault current. SFCL have zero impedance under the normal condition and large impedance under fault condition. There are several kinds of SFCLs being used for current limitation such as saturated iron core SFCL, inductive SFCL and resistive SFCL. Each SFCL has its own merits and demerits. Saturated iron core SFCL, uses low temperature superconductors in inductive-SFCL and resistive-SFCL are generally designed by HTSs. A high temperature superconducting fault current limiter (SFCL) can be used to reduce the short-circuit current during fault. SFCLs can ensure increase in the safety, availability of electrical systems in power stations.
They have an important role in expanding the power grid. High voltage direct-current transmission based on voltage source converters (VSC-HVDC) is attracting research interest in the development of the smart grid.
By comparing with HVDC system based on traditional line commuted converters, the voltage source converter has advantages like flexible control of active and reactive power, high power quality even without harmonic filters and easy connection to a weak AC system. Therefore, the VSC-HVDC system will be developed further and more widely used in electrical industry in the future. However major problems to be faced in this field are high vulnerability to fault conditions and a lack of reliable DC switchgear products. If a short-circuit fault occurs on the DC cable, the current will surge tenfold within one or two milliseconds mainly due to the discharge of the DC-link capacitor, and as a result

AC grid will feed large fault currents into the DC side through the freewheeling diodes. Hence the converter electronics can be easily damaged .During the transient stages of the fault . This is one of the main factor that hindering the wider application of the VSC-HVDC transmission . The saturated iron-core superconductive fault current limiter (SISFCL) is introduced to limit the fault current to a great extent.

II. CHARACTRISTICS AND WORKING PRINCIPLE OF SISFCL

A. various types of superconducting fault current limiters

Superconducting fault current limiters are of two types:

1. The resistive type SFCL which is connected in series with the network.

2. The inductive SFCL which consists of transformer with a superconducting shielding tube in the secondary.

The resistive type is a superconducting element connected in series with the network. It is the simplest type of SFCL. It can be a low temperature superconducting wire or a certain length of high temperature superconductors. When the current is normal, the superconductor is in the superconducting state without resistance. If the current increases over the critical current, the superconductor goes into its normal state and it has a high resistance connected in series with the network. This resistance will limit the current. A parallel resistance should be connected with the superconducting element in order to avoid hot spots during quench, for adjusting the limiting current and to avoid over-voltages due to the fast current limitations. The resistive SFCLs are smaller and lighter than the inductive SFCL.

The inductive type having a special transformer connected in series with the network. This transformer has a conventional primary coil, and a rather special secondary coil, a superconductor ring. When the current is normal, the superconductor ring gives a deexcitation . In normal operation the primary winding resistance and leakage inductance will determine the impedance of the SFCL . Thus during normal operating condition the FCL exhibits a low impedance (approximately the leakage reactance). When the current increases over the critical current, the superconductor will offer high impedance.

B. saturated iron core superconducting fault current limiter

A typical SISFCL mainly consists of three parts iron cores, ac coils and dc superconducting coils, as shown in Fig. 1. In the normal operation condition, the dc current in superconducting coil drives both iron cores into deep saturation. As the saturation region having low permeability, the inductance of SISFCL is very small in normal operation condition. When a fault occurs, the high ac current drives the working points of two iron cores to be out of saturation alternately each half cycle. Since the permeability of the cores increases in the non saturated region, a high impedance value is obtained to limit the fault current.

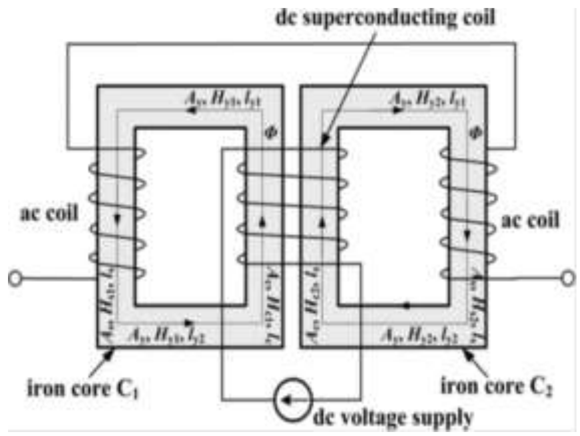

Fig.1.Basic structure of saturated iron core superconducting fault current limiter.

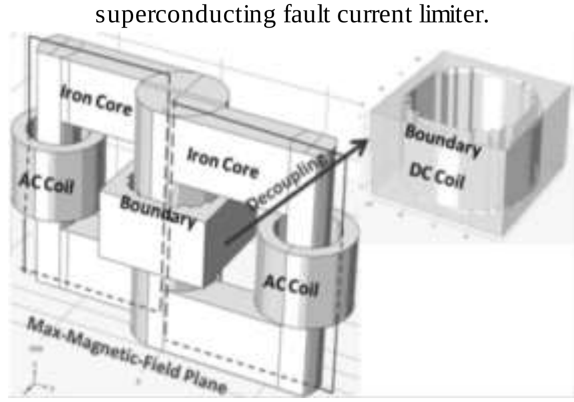

Fig.2.The Iron structure of the SISFCL

The major challenges to the development of the SISFCL have been reducing the device volume and weight, and reducing the transformer coupling between the ac coils and the dc superconducting bias coils . The SISFCL addressed in this paper uses loose coupling structure, which is shown in Fig. 2. The high-voltage section (ac coils) and low-voltage section (dc superconducting coil) are separated to make the structure more compact. The two separated iron cores include central cylinders, yokes and side cylinders, which have different cross-sectional areas Ac, Ay and As. Central cylinders are surrounded by the dc superconducting coil, and side cylinders are surrounded by the ac coils which are connected into the power system to limit fault current. To allocate the main part of the magnetization potential onto side cylinders, the cross-section areas of side cylinders are designed smallest in practical application. The electromagnetic transient process of the three independent single-phase SISFCL are the same.

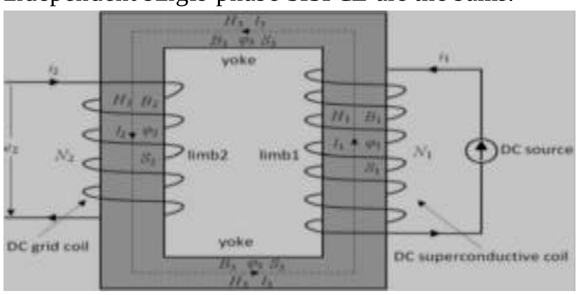

Fig.3.simplified diagram of SISFCL designed for VSC HVDC systems

The structure of a simplified SI-SFCL is shown in Fig. 1, which consists of 3 parts: one magnetic iron core in a rectangle shape, one coil of the DC grid, and one DC superconductive coil with a magnetization circuit.

According to Faraday law of electromagnetic induction, the voltage induced in the DC grid coil e_2 is

$$e_2 = -N_2\frac{d\phi 2}{dt} \quad (1)$$

where $\phi 2$ is the magnetic flux of limb 2, and $N2$ is the number of turns around limb 2. With the flux leakage neglected, $\phi 1$, $\phi 2$ and $\phi 3$ are equal.

The magnetic flux is

$$\phi 2 = B2S2 , \quad (2)$$

where $B2$ is the magnetic flux density, and $S2$ is the cross sectional area of limb 2. The relationship between $B2$ and magnetic field intensity $H2$ is

$$B2 = \mu H2 , \quad (3)$$

where μ is the permeability of the iron core. Combining equations (1)–(3) we obtain

$$e2 = -N2S2\frac{d(\mu H2)}{dt} \quad (4)$$

According to Ampere circuital theorem, the relationship between $H2$ and the currents of both coils is

$$H2 = \frac{N1i1 - N2i2}{l} \quad (5)$$

where l is the overall length of the core, which is the sum of l , $l2$ and $2l3$. Given that the current of the DC superconductive coil is fixed, equ.(4) can be expressed as

$$e2 = L2\frac{di2}{dt} \quad (6)$$

where $L2$ is the equivalent inductance of the SI-SFCL,

$$L2 = \frac{N2^2 2\ S2}{l}\left(\mu - \frac{N1i1 - N2i2}{N2}\frac{d\mu}{di2}\right) \quad (7)$$

Under normal power system conditions, the SISFCL works

in its normal non-limiting state, which operates in for most of the time. In this state, rated current will flow through the DC coils, and a large DC magnetic field bias is generated in the iron cores by the large current in the superconducting DC coil. The iron cores are kept in deep saturation with low permeability. As the inductance is proportional to permeability, the reactance of the SISFCL is small, and it has a minimal effect on the rest of the power system.

When short circuit faults occur, a large fault current will flow through its DC coils, and the SISFCL will enter its current-limiting state. For the active type SISFCL, the DC current will be cut off immediately, and for the passive type SISFCL, the same DC bias will be maintained, regardless of the short-circuit fault. For both these two types, due to the large fault current, the iron cores will no longer always be in deep saturation. When the iron cores work in the linear region of the B-H curve, the permeability increases by thousand times, so the average reactance of the SISFCL is large. This reactance enables the SISFCL to limit the fault current.

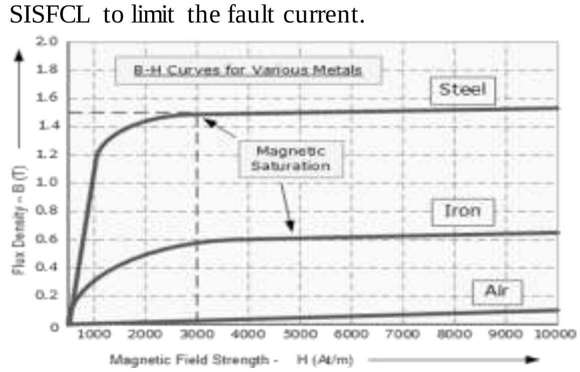

Fig.4. B-H curves for various metals

The working principle of the SISFCL can be explained as follows. During normal operation of the VSC-HVDC system, the DC source of the SI-SCFL provides the exciting current for the superconductive coil. The magnetic flux of the core stays in deeply saturated state. Then fiux density remains almost constant for different values of field intensity.

The B-H curve for iron core is shown in fig.4. As the normal current of DC grid coil is not large enough to draw the core out of the saturated state, the inductance of the SI-SCFL is so small that it has little influence on power transmission. After a fault occurs in the VSC-HVDC system, the greatly increased fault current of the DC system coil draws the core from deep-saturation state into non-saturated state in the current limiting region. The inductive reactance becomes so large that the fault current is curbed in this region.

III. ANALYSIS OF SI-SFCLS IN THE VSC-HVDC SYSTEMS

A. vsc hvdc systems

HVDC stands for high voltage direct current. It is designed to deliver large amount of electricity over long distances with negligible losses. Losses occurring in transmission level can be reduced to great extent by HVDC transmission. Conventional line commuted converters make use of thyristors. It has only turn on control. But semiconductor device such as IGBT, both turn on and turn off can be controlled. Mainly used in self commutated converters.

Voltage source converters in which the dc voltage always has one polarity, and the power reversal takes place by the reversal of dc current polarity. High Voltage Direct Current technology has proved to be an efficient, cost effective and reliable way of transmitting electrical power over long distances as compared to the classic and traditional AC transmission. Except for the advantages of traditional HVDC, VSCHVDC also has the characteristic of fast independent control of active and reactive power, unaltered voltage polarity when flow is turned, power quality improving ability and ability to compensate dynamic reactive power.

B. dc line to line fault

The common faul that can be occurring in DC transmission line are line to ground fault and line-to-line fault. Because faults of cables are usually caused by external mechanical stress, therefore the faults are generally permanent, for which a lengthy repair is needed. The converters should be blocked immediately while a cable fault is detected. But for overhead line, the faults are always caused by lightning and pollution. Faults along the line are likely to be temporary, which demands a fault restoration after the fault clearance.

The line-to-line fault means insulation failure between the dc conductors. It demand converter to be blocked. But we should note that, the ac system is still short- circuited through the VSC freewheeling diodes. This means the ac system will continue to feed current into the fault even if the converter is blocked, to avoid this besides blocking the converters. The DC line is also needed to be isolated from the ac system.

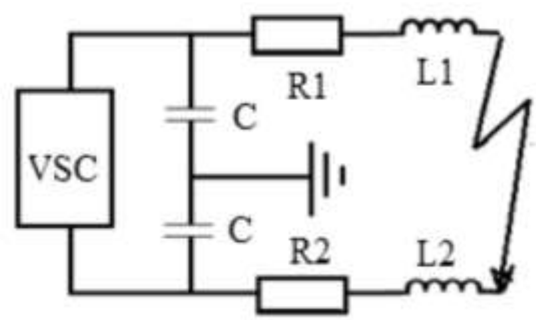

Fig.5.Circuit showing dc line to line fault

When a fault occurs the IGBTs will be blocked to avoid exposing to over-current caused by the fault. A DC line-to-line fault can be expressed by an equivalent circuit shown in Fig 5. R1, R2, L1, L2 are the equivalent resistances and inductances of the positive and negative lines from the VSC to the fault location respectively and C is the capacitance of the dc-link capacitor in parallel with the VSC.

When a DC line-to-line fault occurs, a loop circuit without source is formed which is shown in fig.6 and the DC-link capacitor starts discharging rapidly; consequently the DC voltage collapse occurs. The natural fault current response is characterized by a high peak and fast rate of change. This stage ends as the capacitor voltage drops to zero. When the dc-link capacitor begin to discharge through the transmission line, the voltage in line will decrease rapidly, but the

DC current will increase. It will lead to a huge over-current in the ac side.

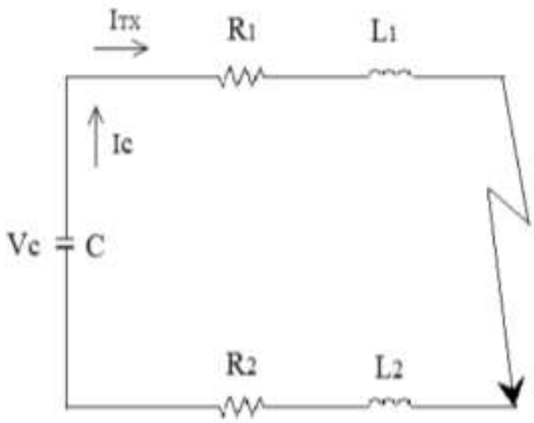

Fig.6.capacitor discharge stage

When the dc fault commutates to the converter side diode freewheeling stage will be initiated which is shown in fig.7. This is the most hazardous period since the circulating fault current is able to destroy the anti-parallel diodes. When the dc-link voltage drops to zero, the freewheel diodes and cable inductance will form a loop circuit. Initially, the IGBT is blocked for self-protection, and there is a initial over-current though the diodes, which may make huge damage to the diodes. Then the both diode and DC current will decrease rapidly.

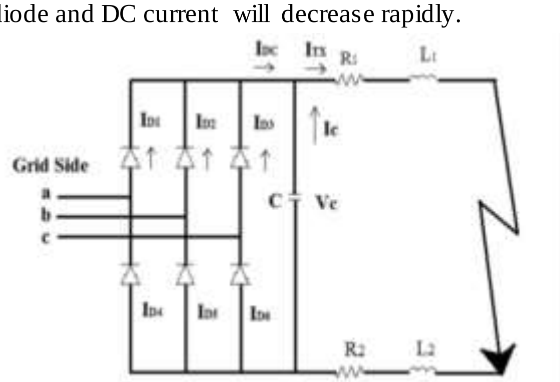

Fig.7.freewheeling diode stage

I C .Recovery method

The equivalent circuit of a VSCHVDC system which employs SISFCL is shown in Fig.8. Each junction where the DC rail meets the cable is installed with one SI-SFCL. The moment an inter-pole short-circuit fault occurs on the DC cable, the IGBTs of the bridge will be blocked under self protection and then the control system will stop working. Therefore, the control system exerts no influence on the system after the fault . Before the voltage of the DC rail udc drops below the magnitude of the inter-phase voltage of the AC side, all the free-wheel diodes are blocked due to the reverse voltage and the DC system is insulated from the AC side. This is the key stage for the SI-SFCL to limit the discharge current of the capacitor and slow the voltage drop on the DC rail.

The quation (7) shows the relation between inductance and permeability. When core is in saturation permeability is low. So from the above relation the inductance will be low, which means the impedance is low. When fault occurs core is drawn into unsaturated state where permeability will be more, there by inductance will be high .There by offering very high impedance.

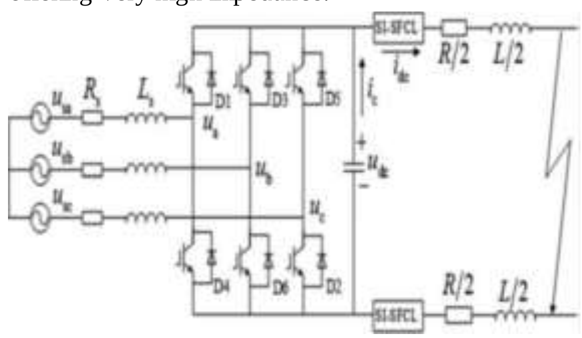

Fig.8.equivalent circuit of vsc hvdc system employed with SISFCL

IV.CONCLUSION

VSC-HVDC technology is continually developing and more applied in renewable power utilizing projects, so it has a broad prospect. DC transmission line faults have a detrimental effect on VSC-HVDC system operation and may make damage to the system components.

This paper analyses line to line fault occurrence in VSC HVDC systems and the role of SI SFCL to overcome this one.

To limit DC-fault currents, the SI-SFCL is introduced into VSC-HVDC systems. Based on the working principle studied, it is known that the inductance of an SI-SFCL is almost 0 in the saturated region yet rises sharply to a large value in the narrow non-saturated region. Therefore it offers very small impedance to the power system which has no effect on normal transmission. When the short circuit fault occurs, the current surges, and fault monitoring system will instantly cut off the DC exciting-current within a few milliseconds by means of power electronic switch, such as insulated gate bipolar transistor (IGBT) or integrated gate commutated thyristor (IGCT), in the DC control circuit. Then both of the two cores go out of deep saturation status so that fault current in the two AC winding will produce large inductive EMF which can limit fault current. The advantage of this concept is that it does not require the superconductor to become normal to operate. The relationship between the inductance and the current of the DC grid coil is also presented in the form of equation. The effectiveness of the SI-SFCL is proved by comparing fault currents and voltages of the VSC HVDC system.

REFERENCES

[1] J.Rafferty, D. J. Morrow, and L.Xu, "Analysis of VSC-based HVDC system under DC faults," in Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc., Vienna, Austria, Nov. 2013, vol. 45, pp. 459–464.

[2] W.Ahmed and P. Manohar, "DC line protection for VSC-HVDC system," in Proc. 2012 IEEE Int. Conf. Power Electric Drives Energy Syst., Bengluru, India, Dec. 2012, pp. 1–6.

[3] Danhua Liu, Tongzhen Wei, QunhaiHuo, Lixin Wu, "DC Side Line-to-line Fault Analysis of VSC- HVDC and DC- fault-clearing Methods", IEEE 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp.2395-2399, Nov 2015.

[4] Jin Yang, John Fletcher, O'Reilly, "Short-Circuit and Ground Fault Analyses and Location in VSC-Based DC Network Cables", IEEE Transactions on Industrial Electronics, Vol. 59, Issue 10, pp. 3827 – 3837, Oct. 2012.

[5] Y. Xin,W. Gong, X. Niu, and Z.Cao, "Development of saturated iron core HTS fault current limiters," IEEE Trans. Appl. Supercond., vol. 17, no. 2, pp. 1760–1763, Jun. 2007.

[6] D. Larruskain, I. Zamora, and O.Abarrategui, "Fault current limiters for VSC-HVDC systems," in Proc. 10th IET Int. Conf. AC DC Power Transmiss., Birmingham,U.K., Dec. 2012, pp.1-6

[7] Manish Kumar, Manjeet and Pooja Khatri, "Study of Faults On HVDC Transmission Lines", Golden Research Thoughts, Vol. 3, Issue. 8, pp. 1-11, Feb 2014.

[8] F. Mourinho, D. Motter, J. Vieira, R. Monaro, and L. Blond, "Modeling and analysis of superconducting fault current limiters applied in VSCHVDC systems," in IEEE Power Energy Soc. Gen. Meet., Denver, CO, USA, Jul. 2015,

[9] Y. Chen, X. Liu, J. Sheng, and L.Cai, "Design and application of a superconducting fault current limiter in DC systems," IEEE Trans. Appl. Superconductivity., vol. 24, no. 3, Jun. 2014, Art. no. 5601305

[10] X. Liu, J. Sheng, Z. Hong, Z. Jin, and J. Gu, "Research on applicationof superconducting fault current limiter in VSC-MTDC power system," Dianwang Jishu, vol. 39, no. 4, pp. 983–988, Apr. 2015.