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Fault Current Limiters Types, Operations and its limitations

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ABSTRACT: Fault currents can degrade circuit breakers and other expensive system components. By installing FCLs, many utilities can protect the system from detrimental condition with low cost. Solid state and superconductor based FCL technology are developed and getting greater attention from the market. With the cost reduction in high power switching devices and introduction of HTS wires the FCLs can be utilize for numerous applications at commercial and transmission level. This paper highlights the downsides of FCLs that will be problematic for fault current protection. The downsides can be further improved to amputate the possibility of failure and enhance reliability of systems.

Keywords: Grid Fault, Fault current limiter, Superconductor FCL, Solid State FCL.

1. INTRODUCTION

Fault current is the accidental or abnormal connection between phases or phase to earth. In electrical fault the impedance of system becomes very low at effected point as a result of 5 to 15 times of rated current flow through the system. When this large fault current passes through the components, create excessive heat which can be damage or burn the equipment. Mismatch loads, overload of power system equipment, short circuits, or failure of devices are the major reasons for transient current. Many protection devices were introduced to control the excess fault current. The most common used are fuses, circuit breaker, and reactors. These devices have numerous constraint and not feasible to regulate the fault current. The fuse interrupts the entire portion which is cover by it until it is manually replace [1].

Air-Core Reactors (ACR) has a voltage drop which requires voltage regulation to level the output voltage. Further it has high stray magnetic field which produce eddy current losses in nearby equipments and produce heat and it is very difficult to enclose [2] [3]. The circuit breaker used for HV system have high-priced such as for 66kV substation the cost of CB is from $18,000 to $20,000 excluding installation and maintenance expenses while the life span is inadequate [4]. There has been an increased in research surveys for the alternate solution of enhancing the stability of electrical power systems. One solution is the used of fault current limiter (FCL). Fault current limiter recognizes and limits the short circuit level during substation fault without disconnecting wind turbine. The FCL is the series protection device which shows low impedance during normal operation. When the fault occurs on the system, the impedance increases to a predetermined value and so prevents over-current strain which can cause damaging, degradation, electromechanical forces and additional heating of electrical equipment.

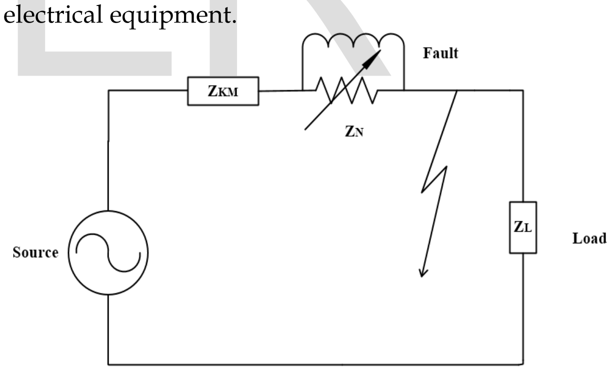

Figure 1: Equivalent circuit of FCL

2. IDEAL FAULT CURRENT LIMITER

FCL are suitable for various application in power system such protection of electrical generator, transmission and distribution system and bus bars. Ideally FCL should be capable of confining the first peak of fault current and withstand stresses imposed on distribution and transmission system due current and voltage. In normal operation mode, it exhibits low impedance, low voltage drops and low power loss while in fault condition it should have large impedance. It should provide instantaneous and accurate judgment between a temporary overcurrent

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situation and a true fault event. The recovery time should be minimum under full load current, or even under overcurrent conditions. The installation and maintenance cost should be low and should have long service life [5].

The transition period from normal state to faulted state should fast enough to provide protection from the continuous fault. However, a very immediate increase of the impedance leads to unsafe overvoltage in the circuit. The time of impedance change from 2ms to 4 ms is sufficient for the restriction of the first fault current peak and prevent over voltages [6].

3. Operational Principle

For symmetrical three-phase fault, when the capacity of the circuit breaker is less than the transient (Is) and steady state fault current (Iss), then the FCL should limit the excesses current. This leads to the constraint on FCL impedance Z_n:

$$Z_n > \frac{U_{ph}}{I_{cc}} - Z_{KM} \quad (1)$$

where U_{ph} is phase voltage, Z_{km} impedance of the circuit under fault condition. The maximum value of impendence Z_k that initiates the operation of the FCL and limit excessive current only,

$$Z_{k} < \frac{U_{ph}}{2I_{nm}} - Z_n \quad (2)$$

The initiation current of the FCL (I_a) to its impedance Z_n can be related from the following equation:

$$I_a > 2k_{tc}I_{nm}\frac{U_{ph}}{U_{ph}-2Z_nI_{nm}} \quad (3)$$

Where K_{tc} is the transient current coefficient. For non-symmetrical faults, the conditions are replaced by more complex expressions and depend on the type of fault.

4. Types of Fault Current Limiter

Many FCLs types are introduced to limit overcurrent as well as to improve LVRT capabilities of wind turbine but these have some constraints and drawbacks that reduce the capability of LVRT which will be examined in next section. FCL are classified into major two groups which uses different technique for limiting excess current such as superconducting FCL [5] and Solid FCL.

4.1 Superconductor Fault Current Limiter

Superconductor materials can conduct electricity and carry electrons from one atom to another with no resistance. The current limiting performance initiate with the variation in temperature, current and magnetic field [7]. In Figure 2, superconducting state exists when T < Tc, H < Hc and J < Jc. When superconductor materials cooled down below its critical temperature, resistance immediately drops to zero. At this stage superconductors have the ability to perfectly conduct electrical current. A basic property of SFCL is the electric field strength E, which depends on current density J, the temperature T and the magnetic flux density B. If there is no applied field [8],

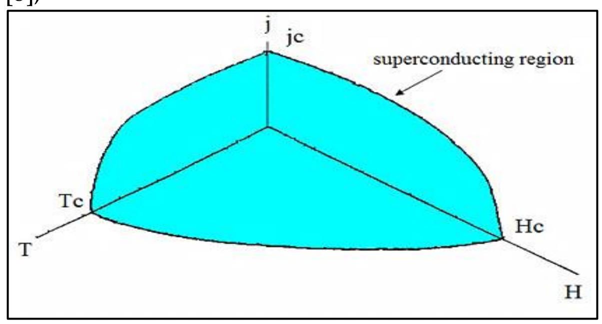

Figure 2: Boundary limit for superconductor [7]

$$E = E(J,T) \quad (4)$$

Superconductor conductor usually obeys power law for flux flow.

$$E(J,T) = Ec.\left(\frac{J}{Jc}\right)^{n(T)} \quad (5)$$

Both critical electric field (Ec) and current density (Jc) are the functions of temperature. During faulted condition, the temperature of superconductor rises with passage of time.

$$C\frac{\partial T}{\partial t} = E(J,T) \cdot J(t) \quad (6)$$

Due to non-linear behavior of superconducting materials they are very suitable for FCLs operation [9]. The superconductor FCL are broadly classified into two groups: quench type SFCLs and non-quench-type SFCLs. In the non-quench-type SFCL, the transition between two states is not required [10].

4.1.1 Quench type Superconductor FCL

In quench-type SFCL, transition occurs from superconducting state to normal stage and the resistances of the superconductor exponentially increase and restrict the current passing through the material. These phenomena are called quenching. Under quenching state of SFCL, the over current radiate excessive thermal energy which rapidly increases the temperature of the SFCL element. A cooling arrangement is used to prevent overheating and reduce to the thermal effect on the element [11]. Quench-type SFCL further classified into:

- **RESISTIVE TYPE SFCL**

In resistive type SFCLs shown in Figure 3, the superconducting materials are connected in series with the line to be protected. Resistive type superconductor FCL works on a zero-resistance principle. During normal operation, the value of current and temperature are less than the critical values of Ic & Tc and show small impedance to the flow of current. During faulted condition, due to large current density the temperature of superconducting material rises. Hence transition occurs from superconducting to normal state as a result the resistance increased proportional to the current. Thus, the excessive current is limited [12].

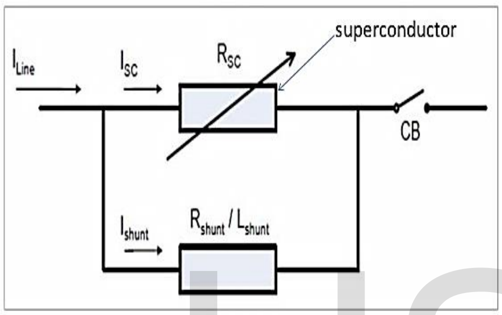

Figure 3: Resistive type SFCL [16]

The resistivity of the superconductor materials is a binary function of temperature and current density [13].

$$\rho = \begin{cases} 0 & (J < Jc, T < Tc) \\ \rho c(\frac{J}{Jc})^{n-1} & (J > Jc, T < Tc) \\ \rho_{HTS}(T) & T > Tc \end{cases} \qquad (7)$$

Where

$$\rho_{c} = E_c / J_c \qquad (8)$$

$$Jc = J_{c0}(Tc - T)/(Tc - T_{op}) \qquad (9)$$

Where, ρc is the critical resistivity, Jc_0 is the critical current density, n is the exponential index and Top is operational Temperature. The resistive type has an advantage over other type of SFCL for its smaller size and simple construction. Due to uneven heating of the superconductor during quenching process make it inappropriate as a current limiter because excessive heat damages the HTS material. This type has high total energy losses and the recovery period after fault clearance could be up to several minutes which are inadequate for wind farms to support grid voltage.

- **INDUCTIVE TYPE SFCL**

The inductive shielded iron core type SFCL consists of a transformer device with cooper primary winding which is magnetically coupled to the superconducting secondary shorted winding. The secondary side superconducting materials (Li) are situated in cryostat which is a refrigerant. Through mutual coupling of AC coils an electrical connection is made linking the line and the superconducting materials. The magnetic field produced due to primary link the secondary superconducting material. On the occurrence of fault, current on secondary increases which quench the HTS element and as a result a voltage increase occur across L_1 that counteract to fault current [14].

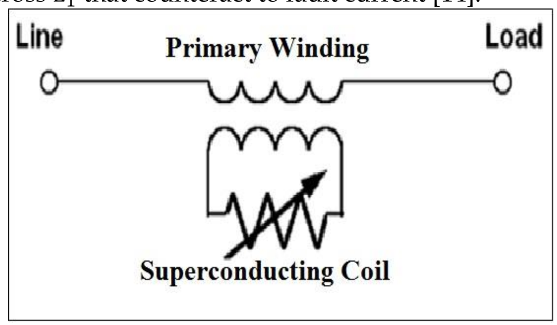

Figure 4: Inductive type SFCL [12]

Under normal operation the flux density can be calculated as [15],

$$B_0 = \mu_0 \frac{N}{l_1} I \qquad (10)$$

During fault condition, the flux density (B) penetrates into the core by a factor of μ_r, and hence the inductance considerably increases.

$$B_c = \mu_r (B_0 - \mu_0 J_c (r_{20} - r_{2i})) \qquad (11)$$

Where $(r_{20} - r_{2i})$ is the thickness of the superconducting material.

The main drawbacks of the shielded iron core type inductive SFCL are its weight which is due to its heavy iron core, and the voltage drop throughout normal operation triggered by leakage reactance. This leakage reactance exists between the spaces of two windings and also distorts the magnetic field in the air gap.

- **MAGNETIC SHIELDING TYPE SFCL**

The Magnetic Shielding SFCL is constructed of an outside copper coil which is in series to the power system. In the middle shielding cylinder of superconductor is connected around the iron core. During normal operation, magnetic flux produced by the cooper coil is shielded and the input impedance is very small because it does not pass through the iron core.

During faulted condition, due to the excessive current passing through the coil the magnetic flux increase proportionally. The shielding effect of the superconductor disappear and the input impedance considerably very high. The magnetic flux passes through the iron core which builds a large inductance into the current path. The current-limiting action will occur due to the change of this input impedance. This type of SFCL has the drawback that the equipment used is heavier and has large size. The sufficient recovery time after fault clearance is another problem with magnetic shielding type SFCL which is not keeping grid codes requirement [17].

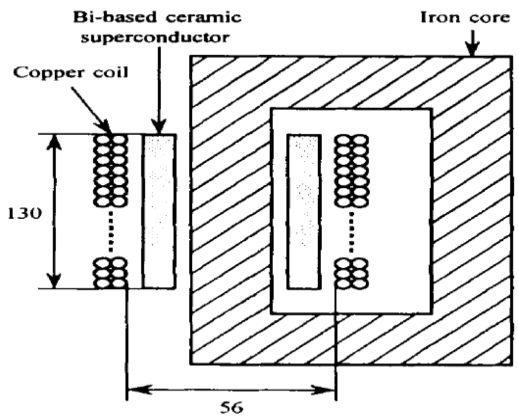

Figure 5: Magnetic Shielding type SFCL [17]

4.1.2 Non-quench type SFCL

In non-quench type SFCLs, the transition between superconducting and normal state is not required. This type are further classified into bridge type SFCL, saturated core type SFCL, and active type SFCL. These types maintained the properties of superconductor during short circuit and reduce fault current level by control mechanism.

- **Bridge type SFCL**

The bridge-type in Figure 6 consists of Diode Bridge, superconducting coil and voltage supply [18]. Superconducting coil (SC) has been displayed by Ld which is connected on the secondary side of coupling transformer. AC current is converted to DC current through bridge rectifier when then bypass the limiting coil (Ld). Under normal operation the DC current and AC current are relatively small which forward biased all the diode and bypasses the inductance and have small impedance. During fault, AC current outstrips from DC bias current as a result two diodes switch to blocking mode and introduce limiting coil in the path of current and limit the excess current.

During normal operation, the system current i_{sys} can be calculated as [19]:

$$i_{sys} = \frac{U_m}{R_1+R_2} sin(\omega t + \varphi) \qquad (12)$$

Where is R_1 the line impedance of system R_2 is the load impedance. When fault occurs at $t_0$on the system, SFCL starts to limit the fault current at t_1. The delay time is t_d and the fault phase angle is $\theta = \omega t_0 + \varphi$. The fault inrush current can be calculated as:

$$i_s = \frac{U_m}{R_{\ 1}} sin(\omega(t_0 + t_d) + \varphi) \qquad (13)$$

While the system current when the limiting inductor is inserted can be expressed as:

$$i_s = I_s\, sin(\omega t + \varphi_- arctg \frac{\omega l}{R_1}) + C_1 e^{-\frac{R_1}{L}t} \qquad (14)$$

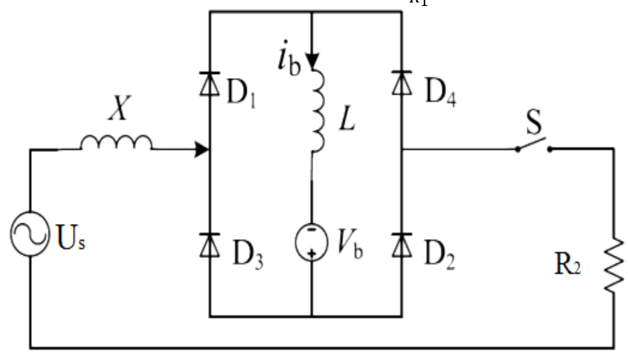

Figure 6: Bridge type SFCL [19]

The drawback of bridge type SFCL is its high total losses and complex structure. During fault condition, the response of this type of SFCL is slow and the requirements of device on the heat dissipation for the resistance bridge circuit are complex. This type of SFCL is not fail safe because it can't limit the fault current if one of the semiconductor devices fail and lead to short circuit. A circuit breaker is operated to decrease the time for fault current through superconducting coil which can lead excessive rise in temperature.

- **Saturable core type SFCL**

Saturable-core SFCLs shown in Figure 7 exploit the magnetic properties of iron that alter the reactance of the line to which it is coupled. AC windings are made of conventional conductors while the superconductor coil is energizing from the DC power supply [21]. In nominal conditions, superconducting coil saturates the iron core which has relative permeability of one. So, it emerges as an air-core reactor to the current path. During grid faults, the peak value of positive and negative half cycles of current forced out the saturation of core and develops very high impedance. The impedance under normal condition is [20],

$$X_{ins} \approx \omega \frac{\mu_0 N^2 A\beta}{l} \qquad (15)$$

When short circuit occur, the fault impedance is estimated by the expression as,

$$X_{fault} \approx \frac{N\omega A_{core}B_{sat}}{\sqrt{2}I_{fault}} \quad (16)$$

The drawback of saturable core SFCL is that it produces harmonics in the current and voltage waveforms due to uneven behaviors of cores. During normal operation, a considerable loss occurs in the bias circuit and iron cores. This increase the temperature of DC coil and restricts the bias current level. Moreover, it has complex current supply for superconducting winding and it should be carefully installed to avoid any current in DC bias coil which can lead to damaging of DC bias supply [20].

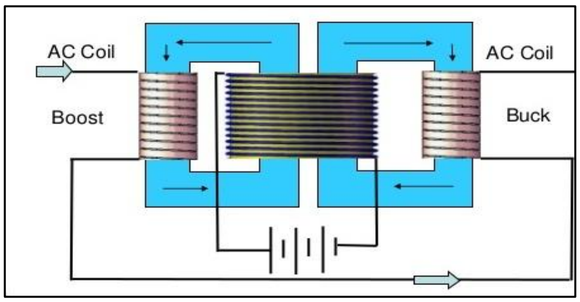

Figure 7: Saturable core type SFCL [21]

- **ACTIVE TYPE SFCL**

This type of SFCL comprise of an air-core superconductor transformer and a PWM converter. The air core has an advantage over iron core that it consumes low losses. During normal operation, the converter works as a rectifier and transfer energy from the AC to the DC side to charge the superconducting magnet. During short circuit, the limiting impedance in series with the AC main circuit is controlled by varying the magnitude and phase angle of secondary currentI_2. This cause the primary winding voltage to increase and which can respond to the slope of the voltage by short circuit and hence the level of current will be restrained [22].

$$Z_{sfcl} = \frac{U_s(j\omega L_{S1}) - j\omega M_S I_2 Z_1}{U_S + j\omega M_S I_2} \quad (17)$$

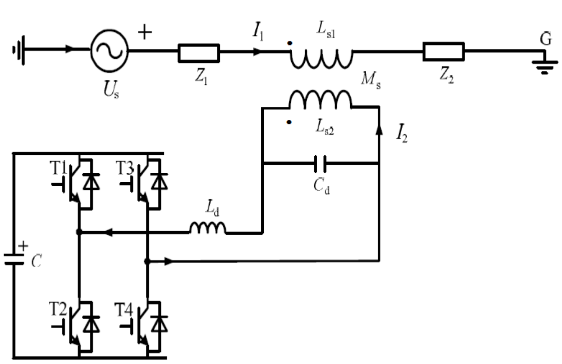

Figure 2.8: Active type SFCL [22]

This type of superconducting FCL has considerable magnetizing current which create losses in superconducting transformer, superconducting magnet, and power transistors. It also required series circuit breaker for current interruption capability as active type superconducting fault current limiter don't have the ability for interruption.

4.2 SOLID STATE FAULT CURRENT LIMITER

SSFCL comprise of semiconductor devices such as GTO, IGBT, IGCT, and SCR which are capable of interrupting short circuit current before reaching its peak value. The SSFCL consist of solid state switch, limiting impedance, voltage source element, an overcurrent indicator and a control device. Solid state switches have no contact and no electric arc so it has little noise and longer life time. The limiting performance of SSFCL is based on on/off switching condition of semiconductor devices. During normal operation, it offers very low impedance to the current path. When a fault happens, the current is diverted into the high impedance path where current limiting reactor reduces the peak current [23].

Solid-State FCLs are further classified into the following types:

- **IMPEDANCE TYPE SSFCL**

Impedance type is the mostly used type of solid state FCL which comprises of power semiconductor devices in parallel with a resistor or inductor. During normal operation, S_1 carry current for positive cycle which is activated at the zero crossing while the S_2 remain off. For negative half cycle, S_2 start conduction while S_1 turn off. Under normal conditions, the impedance is low which is equal to the on-state resistance of the semiconductor device [24].

$$Z_{FCL} = R_{on} \quad (18)$$

In fault condition, the switching devices S_1 and S_2 are turn off immediately and the current is transfer to the shunt impedance branch $Zshunt$, which restrict the fault current to a value much lower than its potential level. During turn-off period overvoltage rises across the semiconductor devices and to protect against excessive transient voltages, a varistor is used for its protection. The impedance required to achieve current limiting capability is large in size. This type is not feasible for weak power system due to the fact that the magnitude of current fluctuates with location and type of fault while there is no other way to limit the magnitude of excess current because of fixed size of impedance.

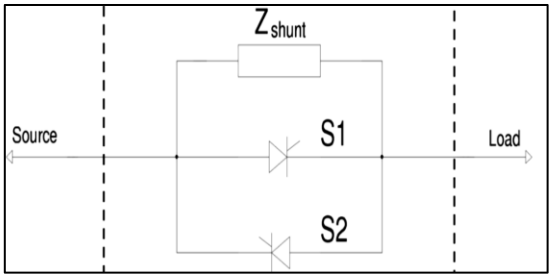

Figure 9: Impedance type SSFCL [24]

- **Bridge type SSFCL**

Bridge-type FCLs are realized by means of a current-fed diodes switch. A diode or thyristor controlled bridge is used to insert the DC reactor on the secondary side of transformer. The rating of diode and limiting reactance is twice the max value of load current.

$$U_S \sin \omega t = i_l Z_s + 2V_{DF} + i_1 r + L_1 \frac{di_1}{dt} \qquad (19)$$

During normal conditions, semiconductor switch s_d is closed to bypass the discharging resistor. Hence, secondary side of transformer is shorted and the impedance is very low [25]. When the fault occurs, the ac current level approximates to the dc current value on the secondary side of transformer. At this point, the semiconductor switch s_d turn on and off to include the discharging resistor in the circuit. The limiting inductor limits the fault current.

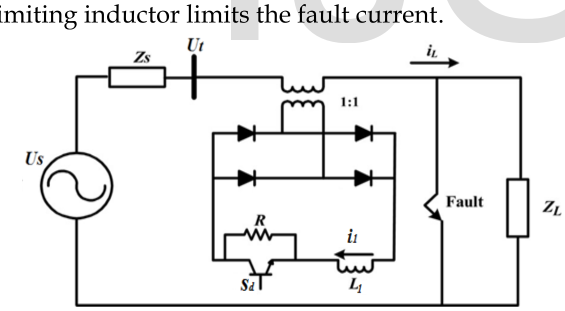

Figure 10: Bridge type SSFCL [26]

This type of FCLs have limitation due to voltage drop in power diodes and the loss of the DC reactor consequence in waveform distortion of line current, particularly during starting or load increasing [26]. In bridge type SSFCL the reactor is installed on the DC side of the rectifier, which is subjected to high DC voltage during fault condition. During fault, the current increase very rapidly which cause inductor saturation. When the inductor saturation happened, FCL will loss the current limiting ability and cannot maintain the fault condition for a specified time. This type of FCL only helps in fault ride through of short durations.

Resonant type SSFCL

Resonant type FCL uses switch for its operation and include resonant circuit to limit the excess current. When switch S_d is turn on during normal operation, the SCR bridge rectifier bypasses the resonant circuit. The DC reactor L_{dc} charged to maximum value and become short circuited, which have almost negligible voltage drop. The equation for line current is,

$$U_s \sin(\omega t) = R i_L + L \frac{di_L}{dt} \qquad (20)$$

During a fault, the dc current is greater than the maximum acceptable current I_0 and the control circuit turns off the semiconductor switch. At that instant, the DC reactor is discharge through freewheeling diode. Now the path for the current is through the parallel resonance circuit. The impedance of resonant circuit mismatch and hence the circuit is out of resonance. By the large impedance, the fault current is restrained [27].

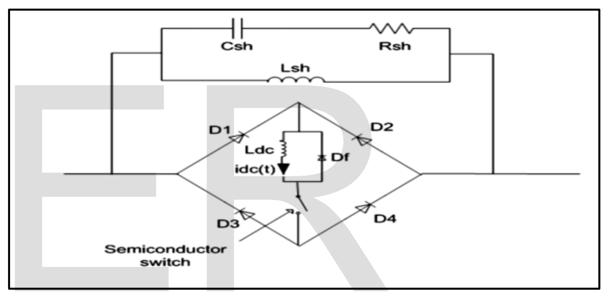

Figure 11: Resonant type Solid State FCL

During fault, the parallel LC branch starts to resonate. The line current start oscillation with greater magnitude due to resonance. These oscillations can cause stress on the system and in severe case damage the equipment. This type has also high loss at standby and cause voltage dip or over voltages during fault transients due to which the wind turbine operation is affected and reduces reactive power support during faults. It also required large infrastructure to hold the capacitors and tuning of devices is essential to provide low impedance [28].

Conclusion

Integration of renewable energy with the main grid is the requirement for numerous countries. This approaches increases the chance of short-circuit capacity in electrical systems. To limit the peak value of fault current is one of the greatest challenging situations in modern power systems. The fault current limiter recognizes and limits the short circuit level during substation fault without disconnecting integrated systems. FCL presented several applications in power systems as reduce current stresses, enhance system stability, improve voltage sags and avoid blackout. Many studies have proposed different types of FCL but due to certain constraint its feasibility have confront in various features. In this paper different types of FCL and its limitations are emphasized. . Low total cost of implementation and reliable design are the two most important characteristics that all customers want see in FCLs so that their investments are aligned. The aim is to enhance the downsides of available FCLs and make it available for commercial and industrial prospective.

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REFERENCES

[1] Ravish Kumar, Ruchika Choudhary, and Vikas Kumar, “HIGH VOLTAGE FUSE BLOWN INDICATOR WITH VOICE BASED ANNOUNCEMENT SYSTEM”, International Journal of Information Research and Review Vol. 03, Issue, 05, pp. 2358-2361, May, 2016

[2] Oswald Mendrock, and Trench, “Short-circuit current limitation by series reactors”, energize - pp.45-49, October 2009.

[3] Heresh Seyedi, and Barzan Tabei, “Appropriate Placement of Fault Current Limiting Reactors in Different HV Substation Arrangements”, Scientific Research, Circuits and Systems, 3, pp.252-262, May 2012.

[4] RUBEND. GARZON, “High Voltage Circuit Breakers Design and Applications “Second Edition, Revised and Expanded, MARCEL DEKKER INC, New York, 2002.

[5] Hongyang Huang, Zheng Xu, and Xi Lin, “Improving Performance of Multi-Infeed HVDC Systems Using Grid Dynamic Segmentation Technique Based on Fault Current Limiters”, IEEE Trans. On Power System, vol. 27, no. 3, pp. 1664-1672, August 2012.

[6] Vladimir Sokolovsky, Victor Meerovich, and István Vajda, “Superconducting FCL: Design and Application,” IEEE Trans. On Applied Superconductivity, vol. 14, no. 3, September 2004.

[7] M. Cyril Prakhash, M. Bhoopathi, C. Rajasuresh, and P. Vivekanandhan, “A Review on Application of Superconducting Fault Current Limiters in Power Systems”, International Journal on Applications in Electrical and Electronics Engineering, Volume 1: Issue 6: pp. 9-12, June 2015.

[8] W. Paul, M. Chen, M. Lakner, J. Rhyner, D. Braun, and W. Lanz, “Fault current limiter based on high temperature superconductors”, Elsevier, Physica C354, pp.27–34 2005.

[9] Woo-Jae Park, Byung Chul Sung, and Jung Wook Park, “The Effect of SFCL on Electric Power Grid with Wind-Turbine Generation System", IEEE Trans. On Applied Superconductivity, vol.20, no.3, pp.1177-1181, June 2010.

[10] M. Firouzi, and G. B. Gharehpetian, “Improving Fault Ride-Through Capability of Fixed-Speed Wind Turbine by Using Bridge-Type Fault Current Limiter”, IEEE Trans. On Energy Conversion, Paper no. TEC-00405-2012, pp.1-9, January 2013.

[11] C. H. Kim, K. M. Lee, and K. W. Ryu, “A Numerical Study on Temperature Increase in the Resistive SFCL Element Due to the Quench Condition”, IEEE Trans. On Applied Superconductivity, vol. 16, no. 2, pp. 636-641, June 2006.

[12] Electric Power Research Institute: Superconducting Fault Current Limiters: Technology Watch 2009, 1017793, Technical Update, December 2009.

[13] Joseph Duron, Francesco Grilli, Bertrand Dutoit, and Svetlomir Stavrev, “Modelling the E–J relation of high-Tc superconductors in an arbitrary current range”, Science Direct, Physica C: 401, pp. 231-235, 2005.

[14] J. Kozak, M. Majka, S. Kozak, and T. Janowski, “Comparison of Inductive and Resistive SFCL”, IEEE Trans. On Applied Superconductivity, vol. 23, no. 3, June 2013.

[15] Arsalan Hekmati, Mehdi Vakilian, and Mehdi Fardmanesh, “Flux-Based Modeling of Inductive Shield-Type High-Temperature Superconducting Fault Current Limiter for Power Networks”, IEEE Trans. On Applied Superconductivity, vol.21, no.4, pp.3458-3464, August 2011.

[16] S. Eckroad, “Superconducting Fault Current Limiters”, Electric Power Research Institute, December 2009.

[17] Kazuhiro Kajikawa, Katsuyuki kaiho, Noriharu Tamada, and Toshitada Onishi, “Magnetic-Shield Type Superconducting Fault Current Limiter with High T, Superconductors”, Electrical Engineering in Japan, vol.115, no.6, pp.1026-1031, October 1995.

[18] M. Firouzi, G.B. Gharehpetian, and B. Mozafari, “Bridge-type superconducting fault current limiter effect on distance relay characteristics”,

Science Direct, Electrical Power and Energy Systems 68, pp. 115–122, Dec 2015.

[19] Hu You, and Jianxun Jin, "Characteristic Analysis of a Fully Controlled Bridge Type Superconducting Fault Current Limiter", IEEE Trans. On Applied Superconductivity, vol. 26, no. 7, October 2016.

[20] Jeff Moscrop, and Scott Hopkins, "Development and Performance Analysis of a Saturated Core High Temperature Superconducting Fault Current Limiter", 19th Australasian Universities Power Engineering Conference, pp. 1-6, 2009.

[21] Franco Moriconi, Francisco De La Rosa, Frank Darmann, Albert Nelson, and Larry Masur, "Development and Deployment of Saturated-Core Fault Current Limiters in Distribution and Transmission Substations", IEEE Trans. On Applied Superconductivity, vol. 21, no. 3, pp. 1288-1293, June 2011.

[22] Lei Chen, Changhong Deng, Fang Guo, Yuejin Tang, Jing Shi, and Li Ren, "Reducing the Fault Current and Overvoltage in a Distribution System with Distributed Generation Units Through an Active Type SFCL", IEEE Trans., pp. 1-5, July 2013.

[23] Sushma Yadav, Dr. G K Choudhary, and Dr. G K Choudhary, "Review on Fault Current Limiters", International Journal of Engineering Research & Technology (IJERT), vol. 3, issue 4, pp. 1595-1603, April 2014.

[24] Erik Darnell Johnson, "A Silicon Carbide Based Solid-State Fault Current Limiter for Modern Power Distribution Systems", Thesis for the degree of Doctor of Philosophy in Electrical Engineering, University of Arkansas, December 2012.

[25] Chen Gang, Jiang Daozhuo, Wu Zhaolin, and Lu Zhengyu, "Simulation Study of Bridge Type Solid State Fault Current Limiter for High-Voltage Power Network", IEEE, pp. 2521-2526, 2003.

[26] K. Smedley, and A. Abravomitz, "Development of fault current controller technology", Energy Research and Development Division, June, 2011.

[27] Seyed B. Naderi, Mehdi Jafari, and M. Tarafdar Hagh "Parallel-Bridge Resonance-Type Fault Current Limiter", IEEE Trans. On Industrial Electronics, vol.60, no.7, July 2013.

[28] G. Tang, and M. R. Iravani, "Application of a Fault Current Limiter to Minimize Distributed Generation Impact on Coordinated Relay Protection", International Conference on Power Systems Transients (IPST'05), Canada, pp.1-6, June 2005.