A REVIEW ON SUPERCONDUCTING FAULT CURRENTLIMITERS IN RESTRUCTURED POWER SYSTEMS

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Abstract: *Electric Power Grid is a man-made complex dynamical system. It is highly interconnected and spread over vast areas. In order to meet the rapidly growing power demand,renewable energy resources, distributed generators, electrical vehicles are integrated in the systems further making the power system more complex. These circumstances not only made the power system to operate near to its stability limits and increased the fault limits above the rated values. Such a high short circuit currents above the rating of the existing switch gear suchas circuit breakers, power electronic devices etc., gets demanded. In order to overcome this situations, adoption of superconducting fault current limiter is an economic and reliable solution to limit the high short circuit currents. Hence in this paper, a basic introduction to theprinciple of fault current limiters and their types is presented. Application of superconducting fault current limiters to enhance power system transient stability, power quality, protection systems and fault ride through capabilities is reviewed by analysis presented in the literature. Finally, the few research gaps identified are also reported in the paper.***

Keywords: *Fault current limiter, Protection Switchgear, high short circuit currents*

Introduction

Electricity demand is rising at a very high pace and electricity demand is running ahead of supply. The biggest shift occurring in the distribution network is the advent of distributed energy resources (DES). In order to meet the continuously growing demand for electricity, there has beenan increased integration of DES with the distribution network using electronic power converters. The penetration level of distributed energy resources is projected to increase further in the future. This leads to the increase of fault currents more than the rated capacity of the existing protection switch gear. Under such scenarios, the existing infrastructure will be damaged and need to be protected as it is an expensive affair. So, a device that limits the fault current should be introduced.

A Fault Current Limiter (FCL) is a device that can overcome the above said problems due to increased fault current levels. In power systems, two kinds of fault current limiters are extensivelyused viz. super conducting and non-superconducting FCLs. In recent years several case studies and application of superconducting fault current limiters to different parts of power systems is reported in the literature [1-7]. They are also applied in generation, transmission and distribution system as well as in the presence of renewable energy resources [8-11]. Now-a-days deregulated market mechanism and restructuring of power system resulted in high fault currents. This is also one motive for showing interest towards Fault Current Limiters technologies.

The organization of the paper is as follows: Section I presents the basic principle of Fault Current Limiters (FCLs). Then types of superconducting FCLs are discussed with their advantages in Section II. In Section III, application of superconducting FCLs for identified power system problems. Finally, important research gaps are identified and concluded with possible future scope.

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I. Basic principle of Fault Current Limiter (FCLs)

In order to understand the use of fault current limiter, let us understand different components in short circuit current. It consists of symmetrical component and a decaying DC offset. They combine to form an asymmetrical fault current having a maximum peak in the first cycle, if the fault occurs at zero voltage crossing. This fault current initiated after a fault in the power system can be limited by a device called Fault Current Limiter (FCL). This helps in utilizing a low power protective device as the actual fault current is limited to a lower values.

Ideally, a fault current limiter is one which shows different impedance behaviors at normal and faulty operation of power systems. During the normal operation of power system i.e., before a fault, it acts as a short circuit and as a large impedance in faulty situations. This large limiting impedance can either be realized by superconductors or by power electronics components. It should be able to operate within the first cycle of fault current as discussed and should be able to return to the normal state within a short time after the current is limited. It should also be able to operate reliable for multiple operation with higher longevity. Its presence should not affect the relay coordination. Finally, size and cost the device should be reasonable [12-14].

II. Types of Superconducting Fault Current Limiters (Superconducting FCLs)

Conventionally, the fault current limiters are classified as series type, shunt type and solid state diode types. The implementation principle in series type FCLs is by shorting a capacitor in a tuned LC parallel resonance circuit. In a shunt type of FCL, a bypass switch in parallel to an impedance is opened which is normally closed during healthy operation of power system. On the other hand, current conservation law in a bridge is utilized in the solid state diode type of FCLs [15].

Due to the high nonlinear nature of the superconducting materials, they are very useful to build FCLs. These superconducting FCLs can be classified into the following types based on the structure and principle of operation as [7]

- Inductive type
- Non Inductive type
- Resistive type
- Transformer type
- Magnetic shield type
- Flux lock type

a. **Inductive type**[16]:

As shown in the Fig. 1, Inductive type superconducting FCLs consists of two coaxial windings, wherein the primary winding is made up of copper and secondary winding is made up of a high temperature superconductor. It also has a magnetic core (optional). The whole unit is cooled by bathed in liquid nitrogen. In the pre fault conditions, almost zero impedance is by Inductive type superconducting FCL and a high impedance during contingencies.

b. **Non inductive type**[17]:

The non-inductive type of superconducting FCL presented in [17], has a current limiting coil and trigger coil arranged as shown in the Fig.2. They are magnetically coupled and anti- parallel to each other. This arrangement can further be modified as coaxial arrangement and as a bifilar winding arrangement. Of these two high impedance ratio is offered by the second type of arrangement.

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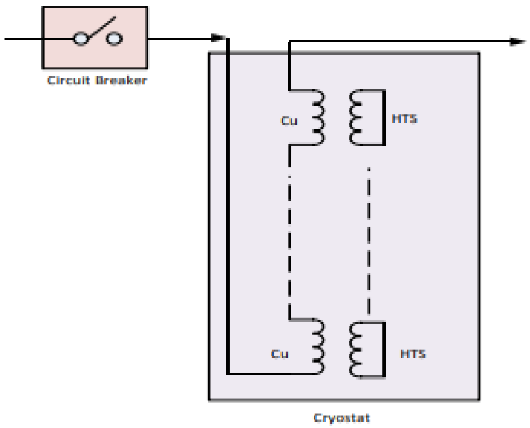

Fig.1: Inductive type

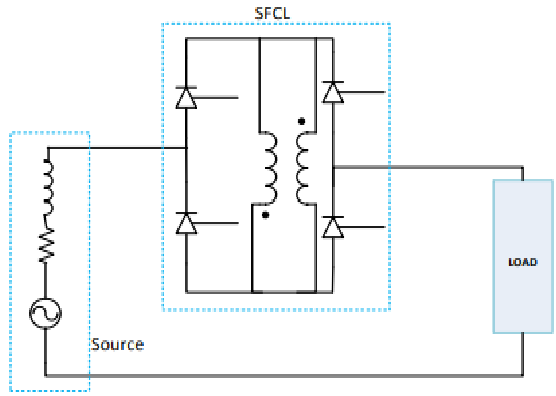

Fig.2:Non inductive type

c. **Resistive type**[18]:

A basic arrangement of n unit in resistive superconducting FCL is shown in Fig.3. It consists of a superconducting (R_{nc}) and stabilizing resistances (R_{ns}) in parallel. Then an inductive coil is connected in series with these parallel resistors. The values of stabilizing and superconducting resistors varies with time depending on the state of power systems according to their characteristics. The value of coil is chosen in such a way that it provides minimal loss duringsteady operations. This type of superconducting FCLs are efficient and quick in suppressing the fault currents to maintain the transient stability of power system.

d. **Transformer type**[19]:

In transformer type of superconducting FCL, the primary winding of the transformer is connected in series with the system load and the secondary winding of the transformer is connected in series with the superconductor as shown in the Fig. 4. From the figure, it can be observed that,during faulty scenarios, an arc is quenched limiting the fault current in the secondary side of the transformer to very less value. This leads to the limiting of fault current on the primary side also. This type of superconducting FCLs has shown better performance in enhancing power system reliability and stability.

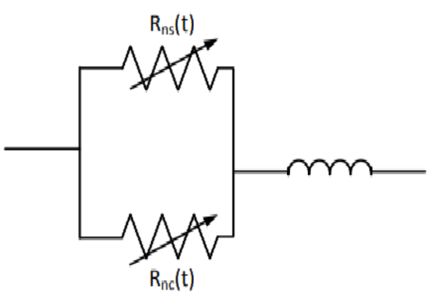

Fig.3: A simple resistive unit in resistive type

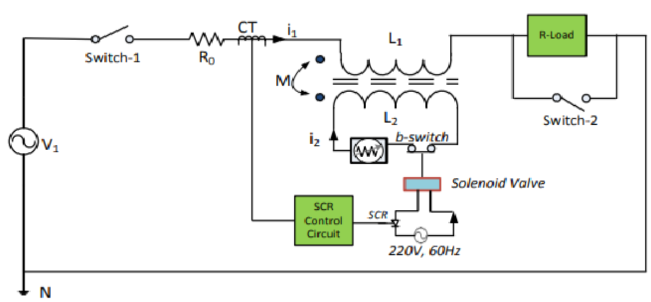

Fig.4: Transformer type

e. **Magnetic shield type**[20]:

As shown in the Fig. 5, Magnetic shield type superconducting FCL has a high temperature superconductor (HTS) tube wound around an iron core below a current carrying primary coil. The currents flowing through the primary coil penetrates in to the iron core through the HTS tube. During a fault, the resistance of HTS tube is reflected into the primary circuit, this infiltrating the magnetic flux leading to the increase of limiter impedance.

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f. **Flux lock type**[21]:

The configuration of the flux lock type superconducting FCL with over current relay (ORC) isshown in Fig.6. This arrangement consists of two parts viz. the current limiting part and a currentinterrupting part. The two parallel connected coils and a high temperature superconductor (HTSC) connected in series to one of the coils forms the current limiting part and The ORC and circuit breaker falls into the current interrupting part. During the steady operation, the magnetic flux cancel each and induce zero voltage across the coil. But during a system contingency, voltage is developed across the coils which limits the fault current. This type of superconducting FCLs has a less power burden for HTSC element. A hybrid type superconducting FCLs is proposed and its operating characteristics are analyzed in [22].

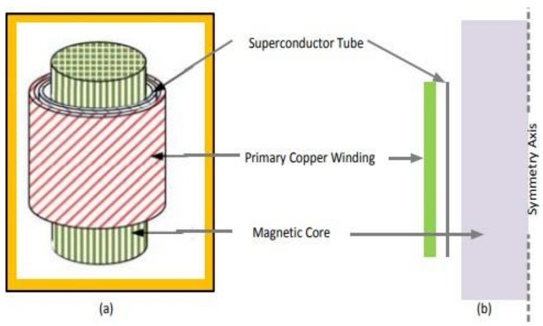

Fig.5: Magnetic shield type

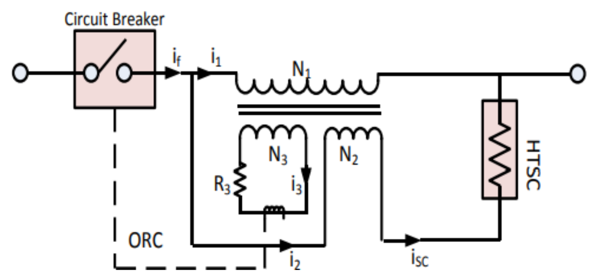

Fig.6: Flux lock type

III. Applications of Superconducting FCLs

Now-a-days, superconducting fault current limiters are extensively used in different parts ofthe power system. In this section, various applications of superconducting fault current limiters are presented. Broadly they are used for the purposes:

a) Transient Stability and Power Quality Enhancement
b) Power System Protection Improvement
c) Fault Current Reduction and Fault Ride Through Capability Enhancement

a. **Transient Stability and Power Quality Enhancement**:

Day-to-day, the power system is expanding in capacity as well as becoming more and more complex due to the interconnection of many renewable energy resources. On the other, increase inpower demand forcing the grid to operate near to the maximum operating points. Such a situation lead to the increased fault level and reduced the security of the system in terms of stability. Such higher short circuit currents results in dip of voltages at different buses below the acceptable limits in view of power quality. So, as discussed a superconducting FCLs are reliable and cost effective solution to improve the power quality and transient stability of the system [24-26].

The studies performed in [23], have summarized the performance of the resistive and inductive type superconducting FCLs in enhancing the power quality and transient stability of power systems. The simulation results shown that a resistive type superconducting FCLs is able to improve the power quality as well as the transient stability of the systems. But enhancement of both power quality and transient stability is not obtained at the same time. As a device to improve the power quality, resistive type superconducting FCLs placed at a feeder location reduced the three phase fault current to 15% and the voltage dip at the faulted bus is reduced by 50%. But, itsperformance for transient stability is very poor. It is investigated that for better transient stability, the value of resistance in the FCL should be as low as possible. The inductive type superconductingFCL located at a particular location is able to enhance both

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the quality as well as the stability of power systems.

b. Power System Protection Improvement

The fault currents levels may exceed the maximum short-circuit ratings of the switchgear. Traditionally, to alleviate the cost of switchgear and bus replacements, the most common ways tolimit high-level fault currents are: uprating of switchgear and other equipment, splitting the powergrid and introducing higher voltage connections (AC or DC), using current-limiting fuses or series reactors or high-impedance transformers, and using complex strategies like sequential network tripping. Nevertheless, these alternatives may create other problems such as loss of power systemsafety and reliability, high cost and increasing power losses [27].

In distribution network, the negative effects of DGs such as false tripping, miss coordination, reach reduction and blinding of protection devices are minimized by the application of superconducting FCLs [28]. Various protection evaluating indices are proposed for each individual effect. A resistive type superconducting FCL is suitable for high fault current and rapid current rising speeds. In a DC distribution system, the effect of resistive type superconducting FCLs is studied on the coordination of protection system is analyzed in [29]. In this paper a transient currentprotection is proposed which takes care of upstream and downstream protection relays. In [30], protection coordination of a flux lock type superconducting FCL with overcurrent relay is proposed.

c. Fault Current Reduction and Fault Ride through Capability Enhancement

In this deregulated power systems, Fault ride through capability is very much necessary. Application of superconducting FCLs for enhancement of fault ride through capability in Wind Farms are reviewed in [31-33]. Double fed induction generators (DFIGs) are highly sensitive to the disturbances in the power systems. As per the new grid code requirements, improvement of fault ride through capability for DFIG is one of the important issue due to partially rated back to back converters in it. This can be overcome by utilization of fault current limiting devices to limitthe fault current levels and also protect back-to-back converter, solid state switches from damage.The interaction of DFIG wind turbine with the grid during a disturbance is illustrated in [33]. In order to have a fault ride through capability for a DFIG, converter control and protection systemsare very much necessary. Whenever high transient currents and voltages are sensed in the generatoror in the converter, protection devices should be triggered otherwise it leads to the damage converter system.

In [31], a modified flux coupled type superconducting FCL is proposed to enhance the fault ride through capability. The application of superconducting FCLs have effectively limited the stator and rotor side fault currents and also improved the voltage sag. This strategy also preventedthe possible disconnection of DFIG from the grid.

Conclusions

The reliability and economic feasibility of superconducting fault current limiters for limiting short circuit currents in the power system is rapidly gaining importance. In this paper, thebasic principle of the fault current limiters is presented. The configuration of various types of superconducting FCLs along with their advantages is also discussed. Application of these devices to enhance grid stability, power quality, protection and fault ride though capability is illustrated with brief literature review. Finally, few research gaps in the application of superconducting FCLsto restructured power are identified as optimal placement of superconducting FCLs in highly renewable energy penetrated system, influence of these devices on the relay coordination, Economic analysis of utilization of these devices in AC/DC systems etc.,.

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References

1. Jo, H.C.; Joo, S.K. Superconducting fault current limiter placement for power system protection using the minimax regret criterion. IEEE Trans. Appl. Supercond. 2015, 25.

2. Blair, S.M.; Elders, I.M.; Booth, C.D.; Burt, G.M.; McCarthy, J.; Singh, N.K. Superconducting fault current limiter application in a power-dense marine electrical system. IET Electr. Syst. Transp. 2011, 1, 93–102.

3. Kim, M.H.; Kim, J.S.; You, I.K.; Lim, S.H.; Kim, J.C. A study on practical impedance of superconducting fault current limiter on bus tie in a power distribution system. J. Int. Counc. Electr. Eng. 2011, 1, 54–59.

4. Lee, J.-G.; Khan, U.A.; Hwang, J.-S.; Seong, J.-K.; Shin, W.-J.; Park, B.-B.; Lee, B.-W. Assessment on the influence of resistive superconducting fault current limiter in VSC- HVDC system. Phys. C Supercond. Appl. 2014, 504, 163–166.

5. Jo, H.C.; Joo, S.K.; Lee, K. Optimal placement of superconducting fault current limiters (SFCLs) for protection of an electric power system with distributed generations (DGs). IEEE Trans. Appl. Supercond. 2013, 23, 3–6.

6. Ye, L.Y.L.; Lin, L.L.L.; Juengst, K.-P. Application studies of superconducting fault current limiters in electric power systems. IEEE Trans. Appl. Supercond. 2002, 12, 900–903.

7. Alam, Md Shafiul, Mohammad Ali Yousef Abido, and Ibrahim El-Amin. "Fault current limiters in power systems: A Comprehensive Review." *Energies* 11.5 (2018): 1025.

8. Mardani, M.; Fathi, S.H. Fault current limiting in a wind power plant equipped with a DFIGusing the interface converter and an optimized located FCL. In Proceedings of the 6th Power Electronics, Drive Systems & Technologies Conference, Tehran, Iran, 3–4 February2015; pp. 328–333.

9. Zhao, Y.; Krause, O.; Saha, T.K.; Li, Y. Stability enhancement in distribution systems with DFIG-based wind turbine by use of SFCL. In Proceedings of the Australasian Universities Power Engineering Conference, Hobart, Australia, 29 September–3 October 2013; pp. 1– 6.

10. Chen, L.; Zheng, F.; Deng, C.; Li, Z.; Guo, F. Fault Ride-Through Capability Improvement of DFIG-Based Wind Turbine by Employing a Voltage-Compensation-Type Active SFCL. Can. J. Electr. Comput. Eng. 2015, 38, 132–142.

11. Gunawardana, S.M.; Perera, S.; Moscrop, J.W. Application of saturated core fault current limiters to interconnected distribution networks. In Proceedings of the Australasian Universities Power Engineering Conference: Challenges for Future Grids, Wollongong, Australia, 27–30 September 2015; pp. 1–6.

12. Fault current limiters, Report on the CIGRE WG A3.10, by CIGRE WG13.10.

13. Schmitt H, "Fault current limiters report on the activities of CIGRE WG A3.16," C. IEEEPower Engineering Society General Meeting, Ouebec, Canada, 2006.

14. 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) in Montreal, Canada, 2005.

15. Vaishnavi, B. V., et al. "Superconducting fault current limiter & its application." *International Journal of Scientific & Engineering Research* 7.5 (2016): 126-134.

16. Kozak, S.; Janowski, T.; Wojtasiewicz, G.; Kozak, J.; Kondratowicz-Kucewicz, B.; Majka, M. The 15 kV class inductive SFCL. IEEE Trans. Appl. Supercond. 2010, 20, 1203–1206.

17. Hoshino, T.; Muta, I.; Nakamura, T.; Salim, K.M.; Yamada, M. Non-inductive variable reactor design and computer simulation of rectifier type superconducting fault current limiter. IEEE Trans. Appl. Supercond. 2005, 15, 2063–2066.

D.O.I : 10.46528/DRSRJ.2021.V11I01.02

18. Sung, B.C.; Park, D.K.; Park, J.W.; Ko, T.K. Study on a series resistive sFCL to improve power system transient stability: Modeling, simulation, and experimental verification. IEEE Trans. Ind. Electron. 2009, 56, 2412–2419.
19. Choi, H.S.; Lee, J.H.; Cho, Y.S.; Park, H.M. Recovery behaviors of the transformer-type SFCL with or without neutral lines. IEEE Trans. Appl. Supercond. 2009, 19, 1793–1796.
20. Heydari, H.; Abrishami, A.A.; Bidgoli, M.M. Comprehensive analysis for magnetic shield superconducting fault current limiters. IEEE Trans. Appl. Supercond. 2013, 23.
21. Kim, J.S.; Lim, S.H.; Kim, J.C. Study on protection coordination of a flux-lock type SFCLwith over-current relay. IEEE Trans. Appl. Supercond. 2010, 20, 1159–1163.
22. Choi, H.S.; Cho, Y.S.; Lim, S.H. Operational characteristics of hybrid-type SFCL by the number of secondary windings with YBCO films. IEEE Trans. Appl. Supercond. 2006, 16,719–722
23. Almeida, M. E., et al. "Enhancement of power system transient stability and power qualityusing superconducting fault current limiters." *2009 international conference on power engineering, energy and electrical drives*. IEEE, 2009.
24. Ye, Lin, LiangZhen Lin, and K-P. Juengst. "Application studies of superconducting fault current limiters in electric power systems." *IEEE Transactions on Applied Superconductivity* 12.1 (2002): 900-903.
25. Salas, C., et al. "Transient analysis in distribution networks using resistive superconductingfault current limiters." *2018 Simposio Brasileiro de Sistemas Eletricos (SBSE)*. IEEE, 2018.
26. Subramani, Mohanraj Bellie, et al. "Applications of solid-state fault current limiters for transient stability enhancement of wind power generation systems." *2015 IEEE 2nd International Future Energy Electronics Conference (IFEEC)*. IEEE, 2015.
27. A. J. Power, "An overviewof transmission fault currents," in *Colloquium on Fault Current Limiters—A Look at Tomorrow*: IEE London, 1995, Digest 1995/026.
28. Hemmati, S.; Sadeh, J. Applying superconductive fault current limiter to minimize the impacts of Distributed Generation on the distribution protection systems. In Proceedings of the 11th International Conference on Environment and Electrical Engineering, Venice,Italy, 18–25 May 2012; pp. 808–813.
29. Xue, S.; Gao, F.; Sun, W.; Li, B. Protection principle for a DC distribution system with a resistive superconductive fault current limiter. Energies 2015, 8, 4839–4852.
30. Kim, J.S.; Lim, S.H.; Kim, J.C. Study on protection coordination of a flux-lock type SFCLwith over-current relay. IEEE Trans. Appl. Supercond. 2010, 20, 1159–1163.
31. Chen, Lei, et al. "Fault ride-through capability enhancement of DFIG-based wind turbine with a flux-coupling-type SFCL employed at different locations." *IEEE Transactions on Applied Superconductivity* 25.3 (2014): 1-5.
32. Naderi, Seyed Behzad, et al. "A review on fault current limiting devices to enhance the fault ride-through capability of the doubly-fed induction generator based windturbine." *Applied Sciences* 8.11 (2018): 2059.
33. Hansen, Anca D., and Gabriele Michalke. "Fault ride-through capability of DFIG wind turbines." *Renewable energy* 32.9 (2007): 1594-1610.

D.O.I : 10.46528/DRSRJ.2021.V11I01.02