International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 1, Jan 2022 pp: 1003-1017 www.ijaem.net ISSN: 2395-5252

A comprehensive Review on Superconducting and Non-Superconducting FCLs for Power Network

Ahmed Raafat Ahmed
Abdallah Mohamed Hamada
Karam Mohamed Abd El Latif
Saady Hassan
Electrical Power and Machines Dept.
Faculty of Engineering at Helwan – Helwan University
Cairo – Egypt
ahmed.raafat@h-eng.helwan.edu.eg

Submission: 18-01-2022 Revised: 28-01-2022 Acceptance: 31-01-2022

Abstract— As a result of integrating a large number of electrical energy sources, especially renewable energy, the fault current will be increasing to unprecedented levels. The use of fault current limiters to face the problem of increasing the expected short-circuit current in the network has become imperative. The new challenge is the increase in types of fault current limiters as a result of the tremendous development in the semiconductor industry. Choosing the appropriate fault current limiter according to the appropriate application is not easy. The huge expansion in the manufacturing of fault current limiter technologies requires studying their suitability with the potential applications, followed by studying the effect of the new FCL on the power grid. This paper presents new classifications for the FCLs from the point of view of different standards and international guides lines. In addition, a comprehensive survey on superconducting and non-superconducting FCLs, as aiming to provide appropriate assistance in the selection of the FCLs.

Key words - Short circuit current; fault current limiter (FCL); distributed generation, types of FCLs, classification of FCLs

I. INTRODUCTION

The demand for electricity is increasing rapidly with a sharp slope, the increase in power demand requires further development and investment in the energy sector. This investment requires a very high cost because that means upgrading all components of the network like; generators, transformers, circuit breakers, and transmission lines and there is no limit to this progress. There are many solutions to manage the increasing power demand. One of the solutions is to use distribution generators and renewable energy like solar, wind, and geothermal. Thus, it is called a distributed generation (DG). Distributed generation is small-scale power generators placed near the load, which can help decrease costs, increase system reliability, save the environment by reducing emissions, and allow multiple choices for energy sources. Although, the (DG) makes an increase in the expected fault current during short conditions, which is a major issue that can be considered an obstacle to DG improvement. The only suitable solution is the fault current limiters because the other solution is system upgrades, which means a very high cost. The greatest advantage of FCL is that they permit use the of old or lower-rated protection devices and avoid costly device replacement or upgrading with the rising of fault current levels. In addition, it protects devices from the first peak during short circuits, and it improves the voltage characteristics during fault conditions [1]–[11].

Several traditional methods are used to manage the short-circuit current in the power network like rearranging the system and splitting buses, reactors, fuses and circuit breakers [12]. Reactors are commonly used but they are not preferred due to their power loss at normal operating conditions. The fuse is a simple device with low prices but it considers a single-use device, which has to be manually replaced by the technical person, which may cause an increase in the duration of the interruption. Circuit breakers (CBs) are different types of protective devices, easily controlled manually or automatically. However, it has a limited lifetime, especially (CBs) with high rated capacity. In addition, they make the first few cycles of the fault current pass through them before taking any action. Scientists are worried about the increase in electricity demand in the future, this issue

International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 1, Jan 2022 pp: 1003-1017 www.ijaem.net ISSN: 2395-5252

has gotten a lot of attention from researchers in recent years. As a result, the fault current limiter (FCL) applications have succeeded in being the most suitable solution for this issue. Recently, different models of FCLs have been applied by various research institutions and companies in other countries around the world [13]–[23]

Selecting the Suitable FCL for a certain application is not an easy task, it depends on many parameters based on the variety of FCLs types, load application, study of FCL effects on the network, in addition, the cost analysis study. Therefore, this research attempts to present a new classification based on several aspects that may concern researchers in this field, like; FCLs applications, the technology of manufacturing, networks and system types, rated power and cost-effective by reviewing the latest research and references that have worked to develop this field.

1. FCLs principle of operation

The FCL is the equipment used to limit excessive current during fault conditions. In addition, functions such as current interruption can be added. Furthermore, different types of limiters are being developed to make its implementation more cost-effective [23]. The role of the FCL is to insert a high impedance during the fault condition and limit the fault current. The operation of FCL and the effect on the fault current are demonstrated in fig. (1).The principle of operation in all FCL technologies is illustrated in Fig. (5). FCL has to keep a system with low impedance during normal operation and high impedance during the fault to limit the fault current in the system [24], [25].

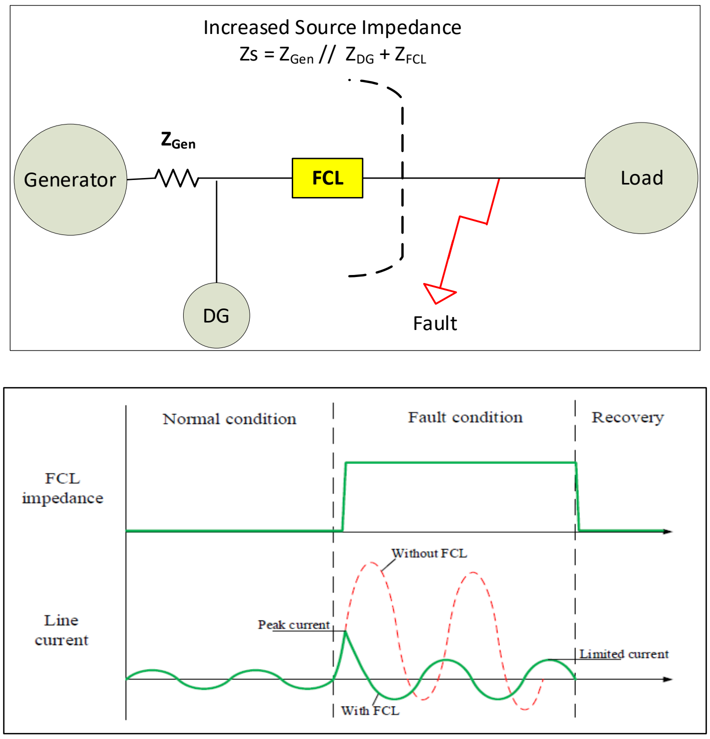

Figure 1 - The principle of operation of a FCL and the effect on the fault current are demonstrated

2. FCLs Classifications

There is no general specification for the fault current limiters. This paper provides a classification for the FCL concepts, IEEE classified the FCLs according to the type of impedance inserted into the circuit in the current limiting mode into two categories [16], Another classification for the FCL technologies was found in CIGREaccording to the behavior during normal operation and fault conditions or according to the network configuration [26]. However, the FCLs can be classified according to the following parameters

- IEEE classifications
- CIGRE classifications.
- Application types.
- Manufacturing material.

2.1. IEEE classifications

According to the IEEE, there are two types of FCLs according to the type of impedance inserted into the circuit in the current limiting mode into two categories; type A and type B, type A as a limiter only and type B provide current interruption capability, each type have two sub-types according to the type of resistance, linear/resistive impedance or non-linear/inductive impedance [16].

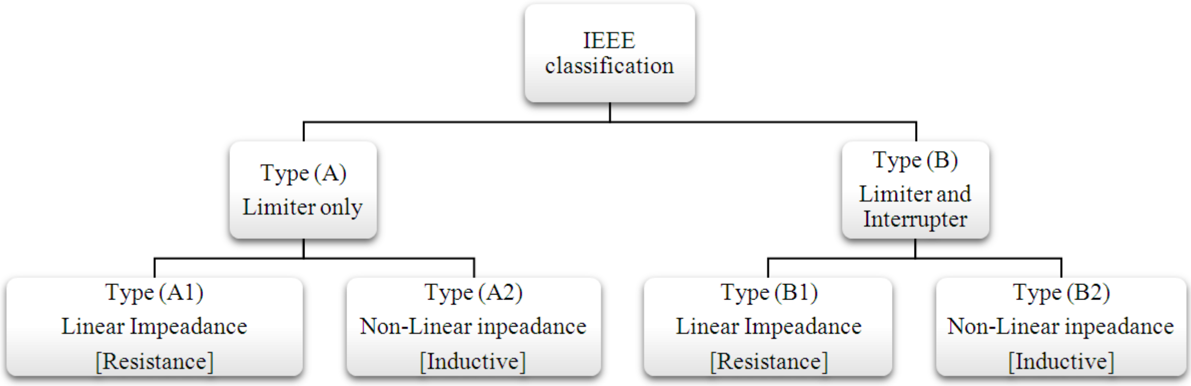

Figure 2 - IEEE classification

2.2. CIGRE classifications

CIGRE, has another point of view in classifying the FCL [26], and they have two types of classifications, we can consider it type (A) and type (B). CIGRE classification type (A) is according to the behavior of FCL during normal operation and fault conditions can be classified into

- Passive : which have permanent impedance during normal and fault condition
- Active : which have a variable impedance can be adapted according to the system condition

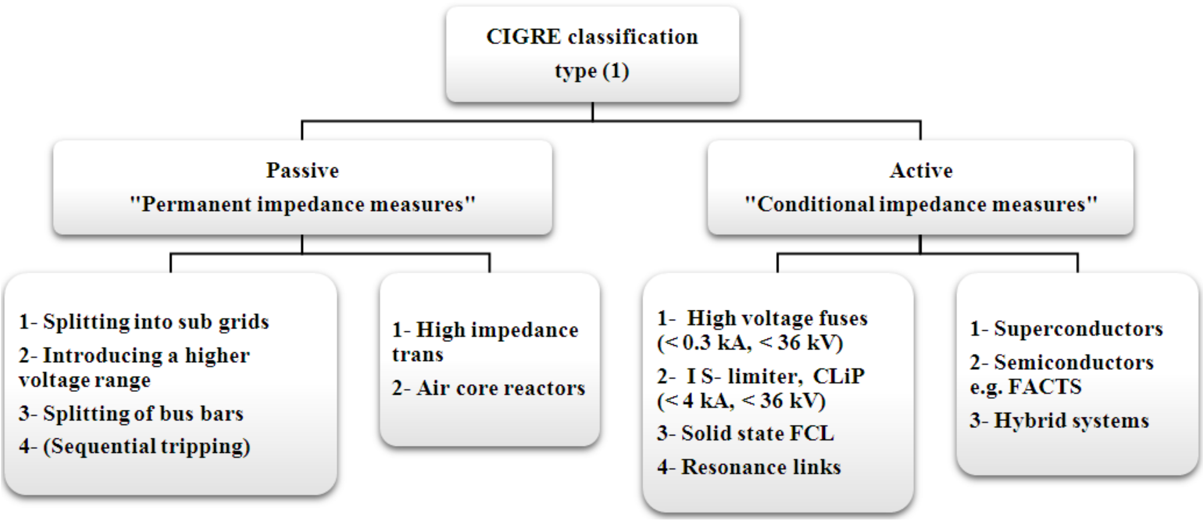

Figure 3 - CIGRE type (A) classifications

CIGRE classification type (B) according to the network configuration can be classified into

- Topological : infrastructure and network arrangement is needed
- Apparatus : a devise will be added in the network according to the required application

International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 1, Jan 2022 pp: 1003-1017 www.ijaem.net ISSN: 2395-5252

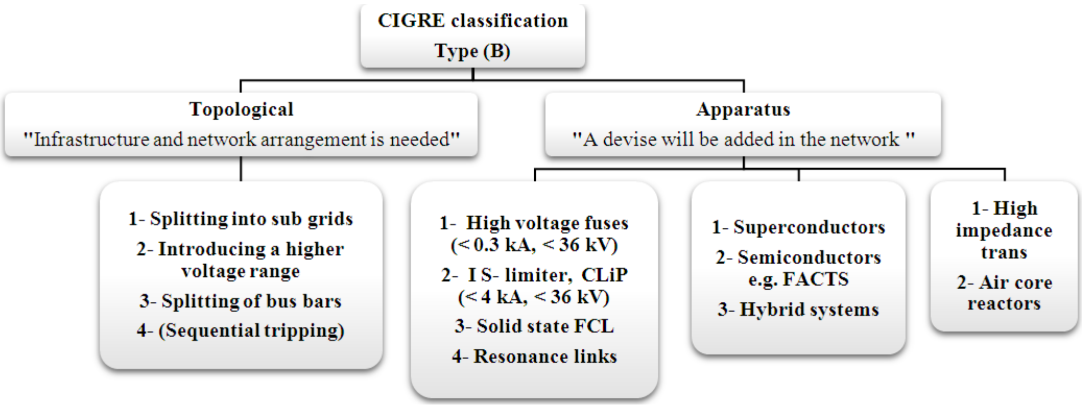

Figure 4 - CIGRE type (B) classification

2.3. Classification according to the application types

The FCL can change its impedance according to the system conditions, so the FCLs have a wide range of applications [27]–[32] . it is countless because it held many hopes for solving the problem of increasing the fault current, Also, it helps with system improvements, such as parallel operation, improvement of voltage

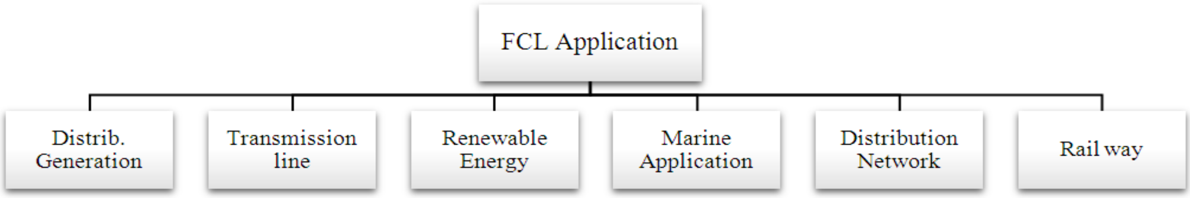

Figure 5 - FCLs application

characteristics, and improvement of system stability. Examples of the FCLs application can be illustrated in Fig. (5)

As a sample from the common application of using the FCL is distributed generation coupling. Adding the DG to the main network needs a high-cost coupling transformer which needs to be protected by FCL, as well as the power plant auxiliary system. It is known that the prospective fault current could be high in the systems located near the main generator. Using FCL's can keep the prospective fault current in capability ranges. Another application is ship propulsion systems. It is normal these days to find a small ship with a 150 MW power generator, which is normal due to the turning from mechanical to electric systems. However, the voltage level on marine power systems is up to 15kV, which makes the current fault level very high, so that FCLs devices are preferred to be used. Another application is the transformer feeder with bus bar coupling. FCL's can be used to couple between two MV bus bars and transformer feeders. The parallel connection between two low-impedance transformers can be made because the FCL can change its impedance according to the system conditions, which leads to lower losses, high quality in voltage characteristics, and higher stability. FCL's also allow installations of large loads without system upgrades [33]–[39] .

2.4. Classification according to manufacturing material

In addition, another classification for the FCL, according to the manufacturing material, was considered superconducting FCL and non-superconducting FCL[40]. Both superconducting and non-superconducting FCL has been widely used for different applications, such as protection, stability, fault current reduction, and interruption. Both types have been extensively applied in transmission and distribution networks and renewable energy systems for different purposes such as stability enhancement, protection improvement, fault current reduction and fault ride-through capability enhancement.

2.4.1. Superconducting FCL

Superconductivity is a set of physical properties observed in certain materials where electrical resistance vanishes and magnetic flux fields are expelled from the material. Any material exhibiting these properties is a superconductor. FCLs which is manufactured from Superconducting material is classified as Superconducting FCLs. as shown in Fig. (6) there is many different type of Superconducting FCLs can be used in network [41] .

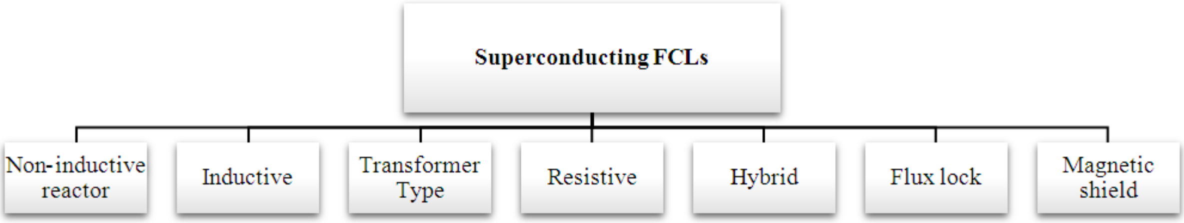

Figure 6 - Superconducting FCLs

A. Non-inductive SFCL

The main principle of the non-inductive Super FCL is tow current coil is connecting into anti-parallel connection with good magnetic coupled between them and a novel non-inductive high temperature superconducting (HTS) unit. Mode. The impedance of the HTS magnet is zero at the normal operation and it will be increase in case of fault. That will help in current limiting and interruption as well. An example for Non inductive SFCL is shown in Fig. (7) [42]–[46].

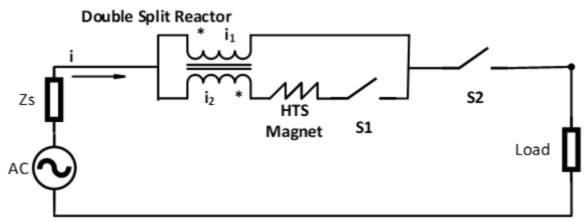

Figure 7 - Non-inductive SFCL.

B. Inductive SFCL

The inductive type is a unique transformer inserted in series on the network. This transformer has a normal primary coil, with a special secondary coil (superconductor ring). The primary winding resistance and leakage inductance determine the impedance of the FCL. Thus, the FCL exhibits a low impedance (approximately the leakage reactance). When the current increases over threshold, the superconductor ring goes into a normal state. In this case, the FCL act like a high impedance (approximately the main field reactance). The circuit of inductive SFCL is shown in Fig. (8) [47]–[49]

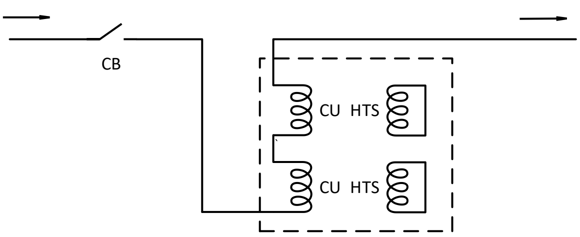

Figure 8 - Inductive SFCL

C. Transformer SFCL

The transformer (SFCL) helps improve the reliability of the power source and increases the system's stability. It consists of two high-temperature superconducting coils. The transformer type SFCL can help to improve supply reliability and power system stability.The load will be connected to the primary side, whereas the secondary side is connected in series with superconductors. The equivalent circuit of the transformer type SFCL is shown in Fig. (9), where E1 is the voltage across the terminals of the SFCL, and I1 and I2 are the current through the primary and the secondary coils, respectively. M is the mutual inductance between the primary coil and the secondary coil, and R2 is the resistance of the secondary coil [50]–[53].

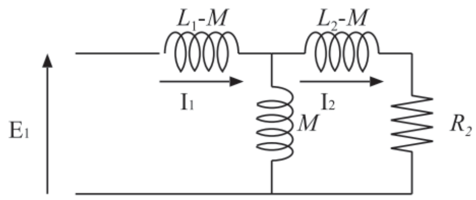

Figure 9 - Transformer type SFCL

D. Resistive SFCL

The resistive superconductor FCLs depend on ohm resistance with the SFCL material. It helps to improve system stability during any transient events by extinguishing the level of fault currents quickly and efficiently. It is just a low-temperature superconducting wire or a known length of high-temperature superconductors. In the case of normal operation, the superconductor is in a superconducting mode without resistance. If the fault current exceeds the critical limits, the superconductor goes into its normal state and it has high resistance connected in series with the network. This resistance will limit the current. Parallel resistance is required to be connected with the superconducting element. A simple structure of resistive SFCL is shown in fig. (10) [54].

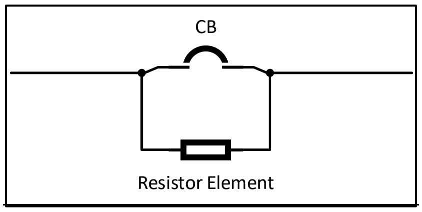

Figure 10 - Resistive type superconductor FCL

E. Flux Lock SFCL

The Flux Lock type SFCL, consists of two coils wound in parallel or series on the iron core. The variation of the winding direction and the inductance ratio between the two coils help adjust the operating current and the limiting impedance, which leads to comprising the size of the SFCL and reducing the power burden superconducting modules. In Fig. (11). The main principle idea is that two magnetic fluxes from two windings cancel each other at a normal time and are not canceled due to the quench occurrence of the HTSC element after a fault occurs. The no cancellation between two magnetic fluxes induces the voltages across two coils and the third winding, which can be contributed as the fault current limiter. After the short-circuit occurs, the load, which needs constant power irrespective of the short-circuit, can be supplied by the third winding [55], [56].

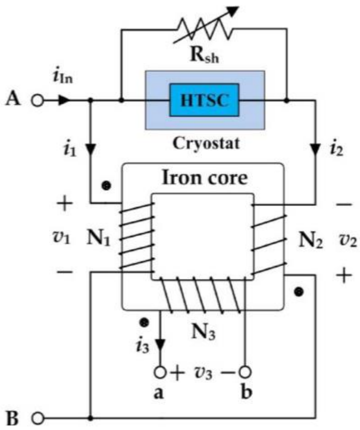

Figure 11 - Flux lock SFCL.

F. Magnetic shield SFCL

It is mainly made from conducting coil, superconducting coil, a cryostat and iron core. All are concentrically arranged. It looks like a transformer have a superconducting coil connecting with the secondary winding at both ends and the primary winding is connected in series with the network. In this type, we need to cool the superconducting material only [57], [58], configuration circuit for this type is shown in Fig. (12)

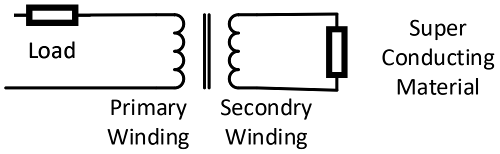

Figure 12 - Inductive-shield type SFCL

G. Hybrid SFCL

The hybrid FCLs use a combination of different technologies to achieve the advantages of each one, like mechanical switches, solid-state materials and others. They need an external element to detect the short-circuit current; short-circuit detection system (SDS) and a commutation circuit, which is considered the main part of limiting and interrupting the current, consisting of a predefined inductor and a capacitor (L_k, C_k). A basic configuration for the HFCL is shown in fig. (13). The load is fed by the main circuit breaker in the normal state and the SDS monitors the load current. Once the SDS detects the fault current and its direction, it sends firing signals to the target thyristors according to the target path for the stored energy in the pre-charged capacitor (C_k) to limit the fault current. Once the current is limited to a target value, the circuit breaker will open to interrupt the fault current [59]–[63].

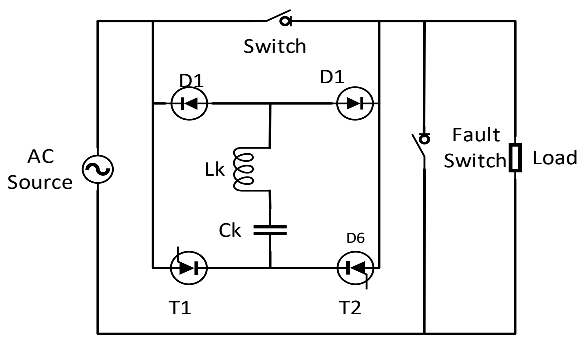

Figure 13 - Single phase configuration for the HFCL

The types of FCL devices continue to increase and research development is trying to achieve the most advantages of each kind using the new technologies. In table (1), the main advantages and disadvantages of each type of superconducting FCLs.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 1, Jan 2022 pp: 1003-1017 www.ijaem.net ISSN: 2395-5252

Table 1 - Comparisons between different types of SFCLs

SFCL Types	Advantage	Disadvantage
Non-Inductive	• Cost is low • Small recovery time • Small AC losses • Switched in H.V is easy	• Volume of cryogenic is high • High leak reactance and Circulating Current
Inductive	• Regarding to coreless construction, the weight and size is very small	• It has losses in standby mode due to the leak reactance • Traditional C.B is needed to avoid HTS winding temperature
Transformer	• A regulation for the fault current can be done. • Small recovery time	• Current limiting time is high • Need high power burden from SFCL
Resistive Type	• Automatic recovery and faster excessive current limiting capability • Lower size • Lower cost • Easy structure	• Superconductor must have along length in case of high voltage application. • It have high losses and long recovery time
Flux lock	• Variable operation current • Low losses in superconducting module	• Big size • Heavy weight • High cost
Magnetic Shield	• Self-detection for short circuit current • Flexible design duo to transformer ratio • Provide electrical isolation between SFCL and power circuit	• Make some distortion for the voltage characteristics in the normal operation • It causes a magnetic field interface which effect on the nearby sensitive devise
Hybrid	• Operating in high current application due to using the conventional C.B • No losses during standby mode	• External circuit for fault current detection is needed

2.4.2. Non-superconducting FCLs

The Non-superconducting fault current limiters are just another type of fault current limiter that can help to extinguish the fault current within a safe range. In addition, they could improve the system stability with minimal cost compared to the superconducting FCLs. As shown in fig. (14) there are many different types of non-superconducting FCLs, [64]–[66] .

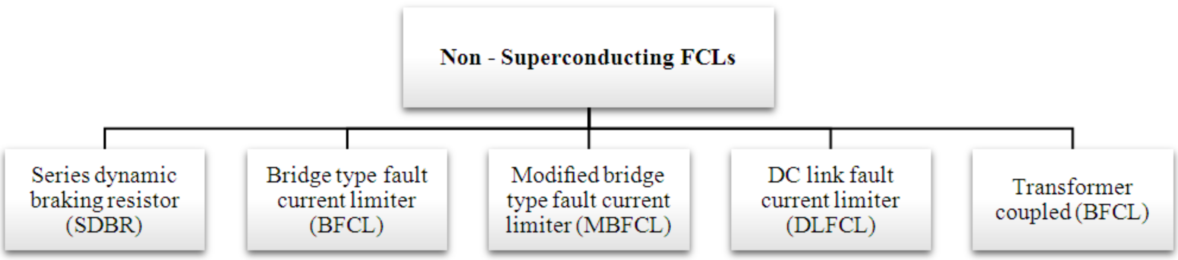

Figure 14 - Non - superconducting FCLs

A. Series dynamic braking-resistor (SDBR)

This type has been widely used in power systems, especially in wind farm applications.The SDBR is made from a resistance element in parallel with a solid-state switch. The switch converts from on-state to off-state based on system conditions, as shown in Fig. (15). In the case of faults, the IGBT of SDBR is turned on and turned off in a dynamic model. The IGBT gate got a switching pulse was generated in the control circuit. The SDBR is connected in series with the line to limit current during disturbances [67]–[69].

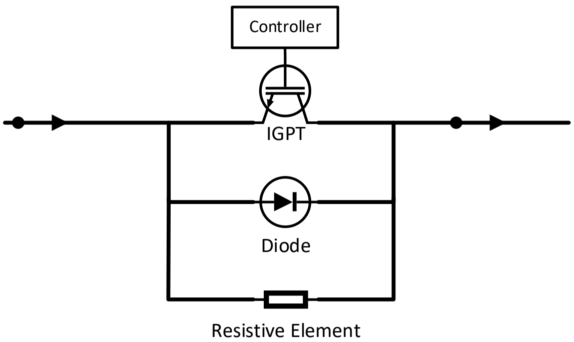

Figure 15 - SDBR Configuration

B. **Bridge type (BFCL)**

BFCL consisted of two main parts, shunt and bridge, as shown in Fig. (16). the principal work is to place induction and resistance at the start of the fault. It has a low cost of application because it does not need superconductive material for its operation [70]–[72].

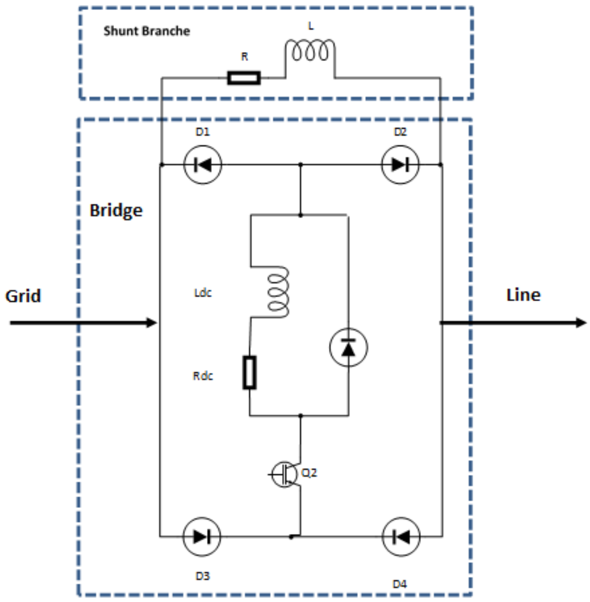

Figure 16 - Bridge type fault current limiter

C. **Modified bridge FCL (MBFCL)**

Any change in the shunt impedance can affect the behavior of the BFCL. That is why it is called modified BFCL. This type was improved for the enhancement of fixed-speed and variable-speed wind farms. An example for this type is shown in fig. (17) [73], [74]

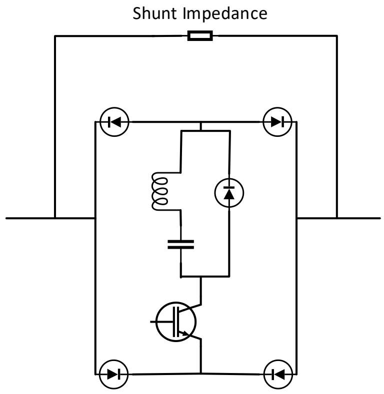

Figure 17 - Modified bridge type fault current limiter

D. **DC Link type (DLFCL)**

According to most common technologies for limiting current, a FLC has to be inserted in series with each phase on the AC side of the voltage source inverter (VSI). This approach is the well-known application of FCLs in the power system. But DLFCL just one single set is installed, which is placed on the DC side of the VSI, and it is employed to limit the VSI's fault current in all three phases during all types of a grid fault.Also, from the power circuit topology point of view, the DLFCL uses the diode rectifier bridge and the fully controllable solid-state switch as a high-speed switch. So, the application of the DLFCL on the DC side of the VSI, in comparison with the previously introduced structures for AC side application, results in a considerable reduction in the current limiting costs of the FCLs. A simple configuration for the DLFCL is shown in Fig. (18) [75], [76].

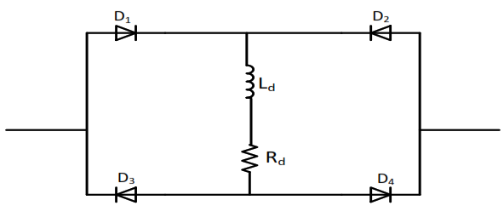

Figure 18 - DC link FCL.

E. **Transformer coupled bridge (BFCL)**

It is also known as the transformer isolated rectifier bridge FCL. This type is proposed for high voltage applications because it can provide an electric

International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 1, Jan 2022 pp: 1003-1017 www.ijaem.net ISSN: 2395-5252

isolation between the Ac and DC sides. In addition, a bypass resistor element can be placed to absorb the current distortion during normal mode condition and to reduce voltage spikes, as shown in Fig. (19) [77], [78].

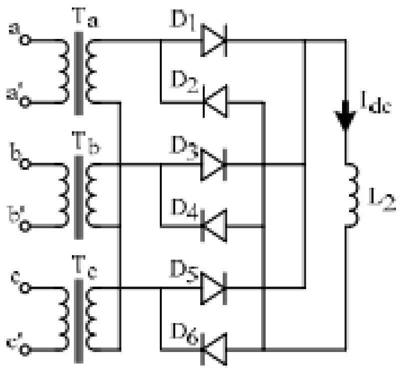

Figure 19 - Transformer coupled (BFCL)

2.5. Parameters and Placement Selection of Fault Current Limiters

Selecting the optimal elements and the best location for the FCL is considered the most important part of the FCL design. There are many different types and many different applications. Choosing the most suitable type for a certain application is the main point in the FCL design. It will save money and make significant improvements to the system stability during a fault condition. Selecting the best location with the optimal elements for the FCL is subjected to many different parameters, like a type of application, rated voltage, rated current, and the current fault level expected on the network. Techniques for selecting the best parameters and location have been reported [79]–[88].

2.6. Field Tests of FCLs

The field test is necessary to confirm that the FCLs is meet the manufacturing specifications. The test applied on the FCL is classified according to IEEE Std. C37.302-2015 to Production (routine) tests and field inspection, There is many practically installation and field tests have been done in different country with results and recommendations for further study. testing and this test is demonstrated in Table (2) [16], [90]–[95]

.

Table 2 - Production (routine) tests and field inspection

Production (routine) tests	Field inspection, testing
❖ Power frequency voltage withstand test ❖ Partial discharge ❖ Control circuit voltage and wiring checks ❖ Visual inspection ❖ FCL technology-specific tests	❖ Inspection and installation verification list o Inspect components for physical and structural damage, unusual physical conditions, defects, and signs of corrosion, o Inspect equipment and components to be assembled for correct shipped parts, o Inspect equipment for cleanliness and being free of dents, scratches or missing parts, o Inspect wiring for insulation damage, broken leads, tightness of connections, and proper crimping, o Verify equipment nameplates and identification labels against drawings, and o Verify removal of shipping braces. o Verify equipment grounding for adjustment and alignment, ❖ General test before commissioning which including: o Trip circuits, o Cryogenic or cooling systems, o Disconnect or other switches, o Dielectric integrity of the main circuit, and o Continuity check of the main circuit.

2.7. Current Challenges and Future Works

The new technology in manufacturing FCLs opens new horizons for researchers in developing new types that will consider all the requirements provided in the FCLs to play the target roles with high efficiency. Still, researchers will face new challenges in selecting the most suitable FCLs for suitable applications with minimal cost. Regarding this view, it is recommended that research be conducted to cover the following points for FCL application in power systems.

- Financial study for different types of FCLs
- The parameters for selecting the optimal design and optimal location according to the application type, considering the network uncertainties.
- Comprehensive studies for superconducting and non-superconducting FCLs
- Development of the non-superconducting FCLs and conducting their field tests for real network applications.
- Development in ways of fault current detection which help the FCLs to act fast and accurately.

2.8. Conclusion.

FCLs proved that they can protect the network from the perspective fault current, without any huge investment in new equipment. Since there is a wide range of FCLs types that need to be classified, making a selection of the suitable type for the required application is an easy task. This paper presents different types of classification according to IEEE, CEGRE, and other parameters. In addition to, a comprehensive survey on superconducting and non-superconducting FCLs was present which present the most available and suitable type for different applications

REFERENCES

[1] A. R. Fereidouni, B. Vahidi, T. Hoseini Mehr, and M. Garmroodi Doiran, "Enhancement of power system transient stability and power quality using a novel solid-state fault current limiter," J. Electr. Eng. Technol., vol. 6, no. 4, pp. 474–483, 2011, doi: 10.5370/JEET.2011.6.4.474.

[2] J.-Y. Zou, D. En-Yuan, and J.-X. Chen, "Study of the Fast-Closing Switch Used for Fault Current Limiters in Power System," J. Shanghai Univ. (English Ed., vol. 6, no. 1, pp. 92–96, 2002.

[3] C. S. Chang and P. C. Loh, "Investigation Of Voltage Quality Improvement with Co-Ordinated Applications of Fault Current Limiter," in 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings, 2000, pp. 2562–2567, doi: 10.1109/PESW.2000.847218.

[4] A. J. Power, "An over view Of Transmission Fault Current Limiters," in IEE Colloquium on Fault Current Limiters - A Look at Tomorrow, 1995, pp. 1/1-1/5.

[5] J. C. Krause, "Short-circuit current limiters : literature survey 1973-1979," Eindhoven, 1980. doi: 80-E-109.

[6] B. Il Kang, "Application of thyristor-controlled series reactor for fault current limitation and power system stability enhancement," University of Colorado, 1994.

[7] A. Otete, "A Novel Fault Current Limiter," FLORIDA STATE UNIVERSITY, 2004.

[8] A. Thirumalai, "Design of Data Acquisition System and Fault Current Limiter for an Ultra Fast Protection System," ARIZONA STATE UNIVERSITY, 2011.

[9] G. S. Malhi, "Studies of fault current limiters for power systems protection," MASSEY UNIVERSITY, 2007.

[10] K. B. RASMIN, "Planning And Impact of Distributed Generation in SESB Existing System," UniversitiTun Hussein Onn Malaysia, 2014.

[11] S. Chen, "A non-superconducting fault current limiter (NSFCL)," Northeastern University, 2014.

[12] Survey of Fault Current Limiter (FCL) Technologies, Tech.Updat. EPRI, Palo Alto CA : 2008. 1016389, 2005.

[13] K. Smedley and A. Abramovitz, "Development of Fault Current Controller Technology Prototyping, Laboratory Testing and Field Demonstration - Final Project Report," California, 2013.

[14] A. Safaei, M. Zolfaghari, M. Gilvanejad, and G. B. Gharehpetian, "A survey on fault current limiters : Development and technical aspects," Electr. Power Energy Syst., vol. 118, no. May 2019, p. 105729, 2020, doi: 10.1016/j.ijepes.2019.105729.

[15] S. Ravyts, G. Van Den Broeck, L. Hallemans, M. D. Vecchia, and J. Driesen, "Fuse-Based Short-Circuit Protection of Converter Controlled Low-Voltage DC Grids," IEEE Trans. Power Electron., vol. 35, no. 11, pp. 11694–11706, Nov. 2020, doi: 10.1109/TPEL.2020.2988087.

[16] IEEE Guide for Fault Current Limiter (FCL) Testing of FCLs Rated above 1000 V AC IEEE Power and Energy Society. IEEE, 2015.

[17] P. G. Slade, R. E. Voshall, J. L. Wu, -J J Bonk, E. J. Stacey, and W. F. Stubler, "The Utility Requirements for A Distribution Fault Current Limiter," IEEE Trans. Power Deliv., vol. 7, no. 2, pp. 507–514, 1992.

[18] S. Ghaemi and M. Abapour, "Effect of Fault Current Limiter (FCL) On Reliability And Protection Coordination of Distribution System," in 24th Iranian Conference on Electrical Engineering (ICEE), 2016, pp. 726–

731.
[19] M. Noe and B. R. Oswald, “Technical and Economical Benefits of Superconducting Fault Current Limiters in Power Systems,” IEEE Trans. Appl. Supercond., vol. 9, no. 2, pp. 1347–1350, 1999.
[20] C. Xiaodan et al., “Effects of Fault Current Limiter on the Safety and Stability of Power Grid and 1ts Application: A Research Review,” in IEEE PES Asia-Pacific Power and Energy Conference, 2016, pp. 2494–2498.
[21] J. Kozak, M. Majka, and S. Kozak, “Experimental Results of a 15 kV, 140 A Superconducting Fault Current Limiter,” IEEE Trans. Appl. Supercond., vol. 27, no. 4, Jun. 2017, doi: 10.1109/TASC.2017.2651120.
[22] M. Steurer, K. Fröhlich, W. Holaus, and K. Kaltenegger, “A novel hybrid current-limiting circuit breaker for medium voltage: Principle and test results,” IEEE Trans. Power Deliv., vol. 18, no. 2, pp. 460–467, Apr. 2003, doi: 10.1109/TPWRD.2003.809614.
[23] M. Verma, V. A. Centeno, Y. Liu, J. De, and L. Ree, “A comprehensive overview, behavioral model and simulation of a Fault Current Limiter,” State University, 2009.
[24] M. Steurer and K. Fröhlich, “Current limiters-state of the art,” in Fourth Workshop & Conferance on EHV Technology, CSIC Auditorium, Indian Institute of Science, 1998, p. 16p.
[25] C. R. Clarke, A. Kamiab, and A. Abramovitz, “Current Limiter Performance Under an Actual Multiple Fault Event,” in IEEE Power and Energy Society General Meeting, 2012, vol. 1, pp. 1–7, doi: 10.1109/PESGM.2012.6343971.
[26] Conseil international des grands réseaux électriques. Comité d’études A3. and Impr. Conformes), Guideline on the impacts of fault current limiting devices on protection systems. CIGRÉ, 2008.
[27] G. Tang and M. R. Iravani, “Application of a Fault Current Limiter To Minimize Distributed Generation Impact on Coordinated Relay Protection,” 2005, doi: IPST05 - 158.
[28] S. Dhara, A. Kumar Shrivastav, P. K. Sadhu, A. Ganguly, and A. K. Shrivastav, “A Fault Current Limiter Circuit to Improve Transient Stability in Power System,” Int. J. Power Electron. Drive Syst., vol. 7, no. 3, pp. 767–778, 2016, doi: 10.11591/ijpeds.v7i3.10904.
[29] S. B. Naderi, P. Davari, D. Zhou, M. Negnevitsky, and F. Blaabjerg, “A review on fault current limiting devices to enhance the fault ride-through capability of the doubly-fed induction generator basedwind turbine,” Appl. Sci., vol. 8, no. 11, Oct. 2018, doi: 10.3390/app8112059.
[30] H. Hatta, S. Muroya, T. Nitta, Y. Shirai, and M. Taguchi, “Experimental Study on Limiting Operation of Superconducting Fault Current Limiter in Double Circuit Transmission Line Model System,” IEEE Trans. Appl. Supercond., vol. 12, no. 1, pp. 812–815, 2002.
[31] S. M. Blair, N. K. Singh, I. M. Elders, C. D. Booth, G. M. Burt, and J. Mccarthy, “Investigation Of Superconducting Fault Current Limiter Application In A Power-Dense Marine Electrical Network,” in 5th IET International Conference on Power Electronics, Machines and Drives, 2010, pp. 1–6, doi: 10.1049/cp.2010.0024.
[32] H. H. Mohammad Mordadi-Bidgoli, “Comprehensive FEM Analysis for Saturable Core Fault Current Limiters in Distribution Network Mohammad,” in The 22nd Iranian Conference on Electrical Engineering (ICEE), 2014, pp. 665–670, doi: 10.1109/IranianCEE.2014.6999623.
[33] A. Y. Hatata, A. S. Ebeid, and M. M. El-Saadawi, “Application of resistive super conductor fault current limiter for protection of grid-connected DGs,” Alexandria Eng. J., vol. 57, no. 4, pp. 4229–4241, Dec. 2018, doi: 10.1016/j.aej.2018.11.009.
[34] S. M. Blair, C. D. Booth, I. M. Elders, N. K. Singh, G. M. Burt, and J. McCarthy, “Superconducting fault current limiter application in a power-dense marine electrical system,” in IET Electrical Systems in Transportation, Sep. 2011, vol. 1, no. 3, pp. 93–102, doi: 10.1049/iet-est.2010.0053.
[35] K. Satpathi, A. Ukil, and J. Pou, “Short-Circuit Fault Management in DC Electric Ship Propulsion System: Protection Requirements, Review of Existing Technologies and Future Research Trends,” IEEE Transactions on Transportation Electrification, vol. 4, no. 1. Institute of Electrical and Electronics Engineers Inc., pp. 272–291, Dec. 28, 2017, doi: 10.1109/TTE.2017.2788199.
[36] L. Kovalsky, X. Yuan, K. Tekletsadik, A. Keri, J. Bock, and F. Breuer, “Applications of superconducting Fault Current Limiters in electric power transmission systems,” in IEEE Transactions on Applied Superconductivity, Jun. 2005, vol. 15, no. 2 PART II, pp. 2130–2133, doi: 10.1109/TASC.2005.849471.
[37] C. Neumann, “Superconducting Fault Current Limiter (SFCL) in the Medium and High Voltage Grid,” 2016, pp. 1–6, doi:

10.1109/PES.2006.1709336.
[38] R. Asghar, "Fault Current Limiters Types, Operations and its limitations Vector control of 3 phase Induction Machine View project A study of LVRT enhancing capability of DFIG wind turbine through Fault current Limiters View project," Int. J. Sci. Eng. Res. Vol., vol. 9, no. 2, pp. 1020–1026, 2018, [Online]. Available: http://www.ijser.org.
[39] H. Javadi, "Fault current limiter using a series impedance combined with bus sectionalizing circuit breaker," Int. J. Electr. Power Energy Syst., vol. 33, no. 3, pp. 731–736, Mar. 2011, doi: 10.1016/j.ijepes.2010.11.023.
[40] S. Yadav, G. K. Choudhary, and R. Kumar Mandal, "Review on Fault Current Limiters," Int. J. Eng. Res. Technol., vol. 3, no. 4, pp. 1595–1603, 2014, [Online]. Available: www.ijert.org.
[41] K. B. S. Deeksha Sharma, "Basic Concepts of Superconducting Fault Current Limiter," in 1st IEEE International Conference on Power Electronics. Intelligent Control and Energy Systems (ICPEICES), 2016, pp. 1–5.
[42] T. Hoshino, I. Muta, T. Nakamura, K. M. Salim, and M. Yamada, "Non-inductive variable reactor design and computer simulation of rectifier type superconducting fault current limiter," in IEEE Transactions on Applied Superconductivity, Jun. 2005, vol. 15, no. 2 PART II, pp. 2063–2066, doi: 10.1109/TASC.2005.849452.
[43] Y.-S. & T.-K. ong-Keun, Park & Min-Cheol, Ahn & Seong-Eun, Yang & Chan-Joo, Lee & Seok, Bok-Yeol & Yoon, "Fault Current Limiting Characteristic of Non-inductively Wound HTS Magnets in Sub-cooled LN_2 Cooling System," J. Korea Inst. Appl. Supercond. Cryopenics, vol. 8, no. 2, pp. 29–32, 2006, [Online]. Available: https://www.researchgate.net/publication/263996875.
[44] D. K. Park et al., "Development of 220 V/300 a class non-inductive winding type fault current limiter using 2G HTS wire," in IEEE Transactions on Applied Superconductivity, Jun. 2007, vol. 17, no. 2, pp. 1863–1866, doi: 10.1109/TASC.2007.897756.
[45] L. Martini et al., "Development, testing and installation of a superconducting fault current limiter for medium voltage distribution networks," in Physics Procedia, 2012, vol. 36, pp. 914–920, doi: 10.1016/j.phpro.2012.06.229.
[46] J. Zhu et al., "Design and evaluation of a novel non-inductive unit for a high temperature superconducting fault current limiter (SFCL) with bias magnetic field," IEEE Trans. Appl. Supercond., vol. 29, no. 5, Aug. 2019, doi: 10.1109/TASC.2019.2898518.
[47] D. Cvori, "Novel Topology of Saturated-core Fault Current Limiter," University of Novi Sad, Serbia, 2010.
[48] C. Zhang, Y. Tang, Y. Xu, L. Ren, Z. Wang, and S. Liang, "Analysis of magnetic circuit and leakage magnetic field of a saturated iron-core superconducting fault current limiter," in IEEE Transactions on Applied Superconductivity, 2017, pp. 1–5, doi: 10.1109/TASC.2017.2672819.
[49] Y. Shirai et al., "Current limiting characteristics of inductive type SCFCL with ZnO device and resistor in parallel," in IEEE Transactions on Applied Superconductivity, Jun. 2006, vol. 16, no. 2, pp. 654–657, doi: 10.1109/TASC.2006.870524.
[50] T. H. Han and S. H. Lim, "Comparative Study on Current Limiting Characteristics of Transformer-Type SFCL with Common Connection Point between Two Secondary Windings," IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018, doi: 10.1109/TASC.2017.2786264.
[51] B. I. Jung, H. W. Choi, and H. S. Choi, "Reduction of the power burden of a transformer-type SFCL using a vacuum interrupter," IEEE Trans. Appl. Supercond., vol. 25, no. 3, Jun. 2015, doi: 10.1109/TASC.2014.2387120.
[52] M. Nishioka, Hideyoshi & Baba, Jumpei & Suzuki, Kozo & Ainslie, "A Basic Study of a Transformer Type Superconducting Fault Current Limiter using a YBCO Thin Film as a Resistive Element," in The International Conference on Electrical Engineering, 2008, pp. 1–5, [Online]. Available: https://www.researchgate.net/publication/235736038.
[53] A. Azizpour, S. Moghimi, and S. Dadfar, "Improvement Transient Stability of Fixed Speed Wind Energy Conversion System by Using Transformer-Type Superconducting Fault Current Limiter," In- ternational Res. J. Eng. Technol., vol. 4, no. 11, pp. 1090–1098, 2017, [Online]. Available: https://hal.archives-ouvertes.fr/hal-02093481.
[54] S. H. Lim et al., "Fault current limiting characteristics of resistive type SFCL using a transformer," in IEEE Transactions on Applied Superconductivity, Jun. 2005, vol. 15, no. 2 PART II, pp. 2055–2058, doi: 10.1109/TASC.2005.849450.

[55] J. S. Kim, S. H. Lim, and J. C. Kim, "Study on protection coordination of a flux-lock type SFCL with over-current relay," in IEEE Transactions on Applied Superconductivity, Jun. 2010, vol. 20, no. 3, pp. 1159–1163, doi: 10.1109/TASC.2010.2045749.
[56] S. H. Lim, "Operational Characteristics of a Flux-Lock-Type SFCL With an Uninterruptible Power Supplying Function," IEEE Trans. Appl. Supercond., vol. 24, no. 3, Jun. 2014, doi: 10.1109/TASC.2013.2295194.
[57] K. Kaiho, H. Yamaguchi, K. Arai, M. Umeda, M. Yamaguchi, and T. Kataoka, "A current limiter with superconducting coil for magnetic ®eld shielding," Phys. C Supercond., vol. 354, no. 1–4, pp. 115–119, 2001, doi: 10.1016/S0921-4534(01)00061-2.
[58] A. Hekmati, M. Vakilian, and M. Fardmanesh, "Proposed flux-based optimization method for determination of minimum superconductor material in shield-type superconducting fault current limiters," Sci. Iran., vol. 19, no. 6, pp. 1843–1849, 2012, doi: 10.1016/j.scient.2012.09.001.
[59] J. Czucha, T. Lipski, and J. Kyborski, "Hybrid Current Limiting Interrupting Device For 3-Phase 400 V Ac Applications," in Trends in Distribution Switchgear, 1998, pp. 161–166.
[60] J. Zyborski, T. Lipski, J. Czucha, and S. Hasan, "Hybrid Arcless Low-Voltage AC/DC Current Limiting Interrupting Device," IEEE Trans. POWER Deliv., vol. 15, no. 4, pp. 1182–1187, 2000.
[61] S. Hasan, E. S. M. El-Refaie, A. H. Kasem Alaboudy, and A. M. Hamada, "An AC hybrid current limiting and interrupting device for low voltage systems," Alexandria Engineering Journal, vol. 57, no. 3. Elsevier B.V., pp. 1535–1548, Sep. 01, 2018, doi: 10.1016/j.aej.2017.03.049.
[62] A. M. S. Atmadji and J. G. J. Sloot, "Hybrid Switching: A Review of Current Literature Compact and Small," Int. Conf. Energy Manag. Power Deliv., vol. 2, pp. 683–688, 1998.
[63] J. S. Kim, S. H. Lim, and J. C. Kim, "Comparative analysis on current limiting characteristics of hybrid superconducting fault current limiters (SFCLs) with first half cycle limiting and non-limiting operations," J. Electr. Eng. Technol., vol. 7, no. 5, pp. 659–663, 2012, doi: 10.5370/JEET.2012.7.5.659.
[64] M. J. Mehrdad Tarafdar Hagh,Seyed Behzad Naderi, "Application of Non-superconducting Fault Current Limiter to Improve Transient Stability," in IEEE International Conference on Power and Energy (PECon2010), 2010, pp. 642–650.
[65] M. T. Hagh, B. Naderi, and M. Jafari, "Using Non-superconducting Fault Current Limiter as Inrush Current Limiter," in 7th international Conferenace on Electrical and Electronics Engineering (ELECO), 2011, pp. 269–273, [Online]. Available: https://www.researchgate.net/publication/255569211.
[66] M. T. Hagh and M. Abapour, "Non-superconducting fault current limiters," Eur. Trans. Electr. Power, vol. 19, no. 5, pp. 669–682, Jul. 2009, doi: 10.1002/etep.247.
[67] M. A. U. M. Shafiul Alam, M. A. Abido, Md Ismail Hossain, Md. Shamimul Haque Choudhury, "Series Dynamic Braking Resistor Based Protection Scheme for Inverter Based Distributed Generation System," 2018.
[68] A. Causebrook, D. J. Atkinson, and A. G. Jack, "Fault ride-through of large wind farms using series dynamic braking resistors (March 2007)," IEEE Trans. Power Syst., vol. 22, no. 3, pp. 966–975, Aug. 2007, doi: 10.1109/TPWRS.2007.901658.
[69] M. R. Islam et al., "Fault ride through capability improvement of dfig based wind farm using nonlinear controller based bridge-type flux coupling non-superconducting fault current limiter," Energies, vol. 13, no. 7, p. 24p, 2020, doi: 10.3390/en13071696.
[70] M. R. Kalaipriya, "Analysis of the Fault Current Limiting Requirement and Design of The Bridge-Type FCL in the Multi-Terminal DC Grid," 2019, [Online]. Available: www.ijert.org.
[71] M. S. Alam and M. A. Y. Abido, "Fault ride-through capability enhancement of voltage source converter-high voltage direct current systems with bridge type fault current limiters," Energies, vol. 10, no. 11, Nov. 2017, doi: 10.3390/en10111898.
[72] H. Nourmohamadi, M. Nazari-Heris, M. Sabahi, and M. Abapour, "A Novel Structure for Bridge-Type Fault Current Limiter: Capacitor-Based Nonsuperconducting FCL," IEEE Trans. Power Electron., vol. 33, no. 4, pp. 3044–3051, Apr. 2018, doi: 10.1109/TPEL.2017.2710018.
[73] G. Rashid and M. H. Ali, "A modified bridge-type fault current limiter for fault ride-through capacity enhancement of fixed speed wind generator," IEEE Trans. Energy Convers., vol. 29, no. 2, pp. 527–534, 2014, doi: 10.1109/TEC.2014.2304414.
[74] M. Firouzi, "A modified capacitive bridge-

type fault current limiter (CBFCL) for LVRT performance enhancement of wind power plants," Int. Trans. Electr. Energy Syst., vol. 28, no. 3, Mar. 2018, doi: 10.1002/etep.2505.

[75] A. Jalilian, M. T. Hagh, M. Abapour, and K. M. Muttaqi, "DC-link fault current limiter-based fault ride-through scheme for inverter-based distributed generation," IET Renew. Power Gener., vol. 9, no. 6, pp. 690–699, Aug. 2015, doi: 10.1049/iet-rpg.2014.0289.

[76] M. T. Hagh, A. Jalilian, S. B. Naderi, M. Negnevitsky, and K. M. Muttaqi, "Improving Fault Ride-Through of Three Phase Voltage Source Inverter During Symmetrical Fault Using DC Link Fault Current Limiter," 2015, doi: 10.1109/AUPEC.2015.7324862.

[77] A. Abramovitz and K. Ma Smedley, "Survey of solid-state fault current limiters," IEEE Trans. Power Electron., vol. 27, no. 6, pp. 2770–2782, 2012, doi: 10.1109/TPEL.2011.2174804.

[78] M. Firouzi, M. Pishvaie, G. B. Gharehpetian, and F. Razavi, "System studies of DC reactor type fault current limiter in distribution grid," Renew. Energy Power Qual. J., vol. 1, no. 7, pp. 60–63, Apr. 2009, doi: 10.24084/repqj07.243.

[79] H. C. Jo and S. K. Joo, "Superconducting Fault Current Limiter Placement for Power System Protection Using the Minimax Regret Criterion," IEEE Trans. Appl. Supercond., vol. 25, no. 3, Jun. 2015, doi: 10.1109/TASC.2015.2411052.

[80] H. C. Jo, S. K. Joo, and K. Lee, "Optimal placement of superconducting fault current limiters (SFCLs) for protection of an electric power system with distributed generations (DGs)," IEEE Trans. Appl. Supercond., vol. 23, no. 3, 2013, doi: 10.1109/TASC.2012.2232958.

[81] A. Mahmoudian, M. R. Islam, A. Z. Kouzani, and M. A. Parvez Mahmud, "Optimal Allocation of Fault Current Limiter in Distribution Network with NSGA-II Algorithm," 2020, doi: 10.1109/ASEMD49065.2020.9276231.

[82] X. Ling and Y. Li, "Reinforcement learning for optimal allocation of superconducting fault current limiters," in IEEE Power and Energy Society General Meeting, 2020, vol. 2020-Augus, doi: 10.1109/PESGM41954.2020.9281474.

[83] A. Elmitwally, E. Gouda, and S. Eladawy, "Optimal allocation of fault current limiters for sustaining overcurrent relays coordination in a power system with distributed generation," Alexandria Eng. J., vol. 54, no. 4, pp. 1077–1089, Dec. 2015, doi: 10.1016/j.aej.2015.06.009.

[84] X. Zhang, H. S. Ruiz, J. Geng, and T. A. Coombs, "Optimal location and minimum number of superconducting fault current limiters for the protection of power grids," Int. J. Electr. Power Energy Syst., vol. 87, pp. 136–143, 2017, doi: 10.1016/j.ijepes.2016.11.014.

[85] P. Yu, B. Venkatesh, A. Yazdani, and B. N. Singh, "Optimal Location and Sizing of Fault Current Limiters in Mesh Networks Using Iterative Mixed Integer Nonlinear Programming," IEEE Trans. Power Syst., vol. 31, no. 6, pp. 4776–4783, Nov. 2016, doi: 10.1109/TPWRS.2015.2507067.

[86] S. Zare, A. Khazali, S. M. Hashemi, and F. Katebi, "Fault Current Limiter Optimal Placement by Harmony Search Algorithm Saeid," in 22nd International Conference on Electricity Distribution, 2013.

[87] Mandar Jangale and K. D. Thakur, "Optimum Positioning of Superconducting Fault Current Limiter for Wind Farm Fault Current in Smart Grid," in International Conference on Electronics, Communication and Aerospace Technology, 2017, pp. 312–316.

[88] X. Zhang et al., "Power flow analysis and optimal locations of resistive type superconducting fault current limiters," Springerplus, vol. 5, no. 1, Dec. 2016, doi: 10.1186/s40064-016-3649-4.

[89] A. Kavousi-Fard, B. Wang, O. Avatefipour, M. Dabbaghjamanesh, R. Sahba, and A. Sahba, "Superconducting Fault Current Limiter Allocation in Reconfigurable Smart Grids," in 3rd International Conference on Smart Grid and Smart Cities (ICSGSC), 2019, pp. 76–80.

[90] Y. Xin et al., "Factory and field tests of a 220 kV/300 MVA statured iron-core superconducting fault current limiter," IEEE Trans. Appl. Supercond., vol. 23, no. 3, 2013, doi: 10.1109/TASC.2012.2234205.

[91] and F. Y. Y. XinMember, IEEE, J. Z. Wang, H. Hong, W. Z. Gong, J. Y. Zhang, X. Y. Niu, A. L. Ren, D. J. Si, M. R. Zi, Z. Q. Xiong, Field Tests on a 35kV/90MVA Superconducting Fault Current Limiter. International Conference on Power System Technology, 2010.

[92] O. B. Hyun, "Brief review of the field test and application of a superconducting fault current limiter," Prog. Supercond. Cryog., vol. 19, no. 4, pp. 1–11, Sep. 2017, doi: 10.9714/psac.2017.19.4.001.

[93] H. R. Kim et al., "Installation and testing of

SFCLs," IEEE Trans. Appl. Supercond., vol. 22, no. 3, 2012, doi: 10.1109/TASC.2011.2181812.
[94] L. Martini et al., "Live grid field-testing final results of the first italian superconducting fault current limiter and severe 3-phase fault experience," IEEE Trans. Appl. Supercond., vol. 25, no. 3, Jun. 2015, doi: 10.1109/TASC.2014.2371917.
[95] L. Martini et al., "Live-grid installation and field testing of the first italian superconducting fault current limiter," IEEE Trans. Appl. Supercond., vol. 23, no. 3, 2013, doi: 10.1109/TASC.2012.2234499.

Ahmed Raafat Ahmed
He received his B.S degree in Electrical Machine and Power System Engineering from Helwan Uni. Egypt in 2008 and received his Postgraduate Diploma in Engineering, in Electrical Installation Engineering, from Helwan University, Egypt 2011. His research interests are FCLs, Transformers, and partial discharge. Currently, he is Manager of the testing and commissioning department in one of the companies specializing in this field.
E-mail: Ahmed.raafat@h-eng.helwan.edu.eg

Abdallah Mohamed Hamada
He was born in El-Bahira, Egypt, on April 7, 1983. He holds a Ph.D. in electrical engineering and is currently an Assistant Professor at the Faculty of Technological, Alexandria, Egypt. His research focuses on power system protection, distribution networks, renewable energy systems, and Hybrid circuit breakers for AC&DC applications.
E-mail: abdallahmhe@yahoo.com .

Karam Mohamed Abd El Latif
Associate Professor in the Dept. of Electrical Engineering at Helwan Uni., Helwan, Egypt. His research interests include power system protection, power quality and power electronics. E-mail: karam106@yahoo.com

Saady Hasan received his B.S., and M.S. degrees in Electrical Machine and Power System Engineering from Helwan University, Egypt in 1983 and 1990 and received the Ph.D. degree in Electrical Engineering from Technical University of Gdansk, Poland in 1996. His research interests are circuit breakers and power system protection. Currently, he is a professor at Helwan University.
E-mail: ahsaady500@gmail.com