International Journal of Scientific & Engineering Research, Volume 4, Issue 5, May 2013
ISSN 2229-5518

Harmonic Analysis of Superconducting Fault Current Limiters (SFCL)

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Abstract— With increasing population and power consumption, new power generation units should connect to the network that they will lead to increase level of network short circuit. Considering the increasing level of short circuit, new circuit breakers should be replaced by higher capacity. But this solution imposes exorbitant costs to the power system operator and practically it is not economical. Another way to deal with increasing level of network short circuit is limiting the fault current. Fault Current Limiter (FCL) is a very effective option for solving this problem, but before installing it in the power system its harmonic effects should be investigated and if necessary, the solutions to reduce harmonic should be studied. The harmonic effects of a new generation of solid-state fault current limiters that can also interrupt the fault current. Then the proposed structure is being compared in terms of harmonic effects with the Superconducting Fault Current Limiter structure (SFCL). It is shown based on IEEE519 standard, that Fault Current Limiting and Interrupting Device (FCLID) structure has less harmonic effects than SFCL structure and doesn't require filtering. For a simple three phase system with DC reactor type SFCL, harmonic analysis has been done. The 3-phase DC reactor type SFCL requires the coupling transformer to be inserted into the power grid. There are two basic transformer configurations (Y or delta connections) of 6-pulse operation, which are most commonly used for the 3-phase DC reactor type SFCL. FCLID model is designed for both single phase and three phase systems and implemented. The Total Harmonic Distortion (THD) value is measured for both the models and the model which gives the less THD value is declared to have better harmonic reduction capacity than SFCL.

Index Terms— fault current limiter, harmonic effects, THD, FFT analysis, SFCL, DC reactor type SFCL, FCLID.

1 Introduction

In recent years due to increase in population and electricity demand, distribution companies gradually have turned on the use of distribution generation sources. Beside the benefits which can be obtained by DG, the integration of DG into existing networks brings up several technical problems [1]. A new fuzzy logic based control strategy [2] is proposed to limit the fault current in distribution systems which include distributed generation units. In the normal mode of operation, the series compensator acts as a line compensator. As soon as the fault is sensed, the new control mode is activated to limit the fault current, and properly interrupt the breaker.

In general case of DC reactor type SFCL, a fault current gradually increases during the fault. It takes above 5 cycles to cut off the fault in the existing power system installed the conventional circuit breakers [3]. Therefore, the fault current increases during the fault even if the SFCL is installed.

The effectiveness of SFCL was studied by the analysis with Electro Magnetic Transient Program (EMTP) and the confirmation test was conducted with the simulator. The increase of the fault current with the introduction of DGs can be limited using SFCL. Accordingly, the DGs can be easily introduced in the power distribution system [4]. Further, the instantaneous voltage sag on the normal lines can be prevented.

The FCL with the spark gap has been proposed to reduce the fault currents during short-circuit faults [5]. Through the breakdown of the spark gap, the FCL can insert large current-limiting impedance in the fault system network. Experiments and Alternate Transients Program (ATP) simulation have shown that the FCL has the capability of reducing the fault currents to lower levels.

A novel saturated core FCL has been designed, built and tested. The concept is based on a closed magnetic circuit for the DC bias field and an open circuit for the AC grid coils. A 4.2 kVA SC-FCL model with copper coils and a 120 kVA SC-FCL [8] superconducting model demonstrated the limiting mode of the FCL exhibiting low losses and low voltage drop on the FCL in nominal current mode.

A novel concept for repetitive current limitation has been proposed [10] which offer the chance of protecting medium voltage networks in a way similar to that of a fuse. By using a series connection of PTC resistors with varistors attached in parallel, it is possible to use polymer thermistors at voltage levels far beyond their intrinsic voltage rating.

Using FCL device, the supply voltage sag is reduced when a short-circuit fault occurs on a cable feeder in the downstream network, hence improving the power quality. The device will eventually isolate the faulted part from the healthy network[11]. It is verified that, with precautions, the operation of the solid-state fault current limiter will not cause problems to either the supply network or the loads.

The ideal high-Tc SFCL system with the DC reactor has negligible influence on the power system under normal operations[13]. However the high-order harmonic currents are generated from the 6-pulse bridge configuration. Passive filter techniques employ tuned LC filters at 5th, 7th, 11th and 13th harmonic frequencies. The harmonic currents can be eliminated using the tuned LC filter and the special bridge configuration. Simulation results are given to validate the harmonic isolation feature at harmonic frequencies and also demonstrate the harmonic filtering process to meet IEEE 519 harmonic standards.

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The development of a solid-state FCLID suitable for low-voltage distribution networks is discussed in [13]. Insulated-gate bipolar transistors and diodes are used to construct the semiconductor switch. Varistors are used as the voltage clamping element. An effective method is adopted to improve the current sharing between parallel varistors in order to provide the required capability of energy absorption. A prototype FCLID for 230-V single-phase, or 400-V three-phase, applications is developed and tested. The results show that the developed prototype is capable of limiting a 3-kA prospective short-circuit current to 120 A for a period of 0.8 s, without exceeding the thermal limits of the chosen switches and varistors.

2 SFCL HARMONIC EFFECTS

SFCLs utilize superconducting materials to limit the current directly or to supply a DC bias current that affects the level of magnetization of a saturable iron core. While many FCL design concepts are being evaluated for commercial use, improvements in superconducting materials over the last 3 years have driven the technology to the forefront. This improvement is due to the ability of HTS materials to operate at temperatures around 70K instead of near 4K, which is required by conventional superconductors. The advantage is that the refrigeration overhead associated with operating at the higher temperature is about 20 times less costly than the initial capital cost.

The working of SFCL mainly depends upon the impedance of the passing current. A larger transformer can be used to meet increased demand on a bus without breaker upgrades. A large, low impedance transformer can be used to maintain voltage regulation at the new power level. Reduced fault-current flows in the high-voltage circuit that feeds the transformer, which minimizes the voltage dip on the upstream high-voltage bus during a fault on the medium-voltage bus.

When operated below critical parameters,

- T_c (temperature)
- I_c (current)
- H_c (magnetic field)

1. Superconductors have virtually zero resistance.
2. When operated above T_c, I_c, H_c normal state resistance is restored.

3. The inherent ability to "switch" from virtually zero resistance to a finite value when I_c is exceeded can be used to limit short-circuit fault currents.

3 DC REACTOR TYPE SFCL

DC reactor type SFCL has zero impedance under the normal condition and large inductive impedance under the fault condition. Its advantage is that it can limit fault current without delay and no damage because it doesn't undergo S/N transition of superconductor .The waveform of the fault current does not have a surge current in the case of application, because DC reactor prevents a sudden increasing of current. Therefore, the fault current gradually increases during the fault. The short circuit current is just limited by the impedance of various system components. Thus, the integration of the SFCL could offer an effective solution to controlling fault current levels in distribution grids.

The 3-phase DC reactor type SFCL requires the coupling transformer to be inserted into the power grid. There are two basic transformer configurations (Y or ¨-connections) of 6-pulse operation, which are most commonly used for the 3-phase DC reactor type SFCL. The SFCL structure with its coupling transformer (Y and delta connected) is shown in Figure.1.

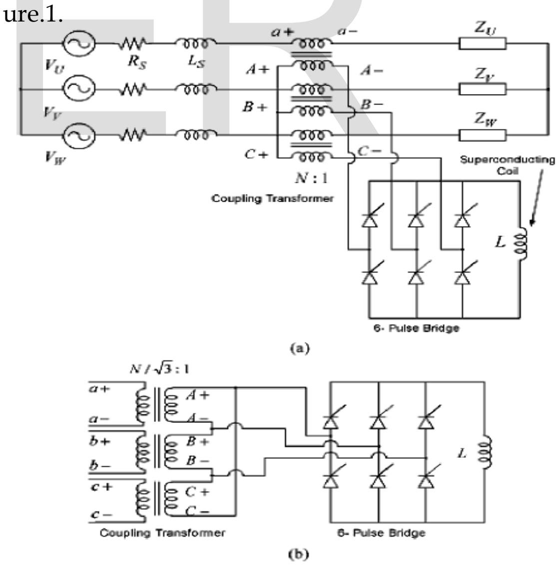

Fig. 1. DC reactor type SFCL arrangement (a)Y-connected 6-pulse bridge (b) delta connected 6-pulse bridge

The system parameters are listed as follow:

- **The phase voltage magnitude of 1 kV.**
- **Source impedance of 0.01.**
- **Load resistance of 10.**

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4 FAULT CURRENT LIMITING AND INTERRUPTING DEVICE (FCLID)

The practical success of a fault-current limiter relies on its design with respect to the intended application. In general, a fault current limiter is desired to have the following performance characteristics,

- Low or zero impedance during normal operation.
- High and controllable impedance during faults.
- Fast transition from normal conducting to current-limiting modes without causing excessive voltage spikes.
- Fast recovery after fault interruption (necessary for applications that require auto reclosure)
- No adverse effects on the selectivity of the overall protection scheme (allow protection coordination)
- High reliability and fail-safe operation
- Low cost with minimum maintenance requirements
- Capability to tolerate and ride through currents associated with normal overload, transformer inrush current, motor starting and energizing a capacitor bank.

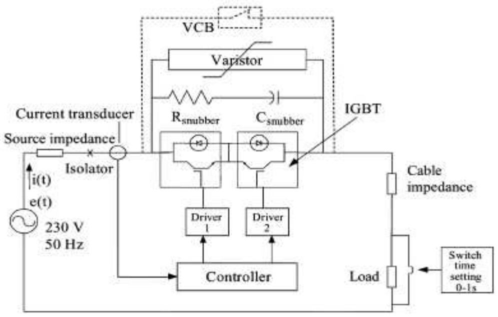

Fig. 2. Schematic diagram of FCLID

During normal operation of the power network, the IGBTs in the synthesized switch are always gated on. Since the IGBTs conduct permanently during this steady-state period, there will be an associated on state power loss which accounts for about 1% of the rated load power. In order to reduce this loss, the FCLID may be bypassed using, for example, a Vacuum Circuit Breaker (VCB).The VCB opens on detecting a short-circuit fault in the downstream power network. The VCB controller may be designed such that it ensures that before opening, the fault level is within the FCLID capability. Otherwise, the VCB remains closed and the fault is dealt with by upstream protective devices.

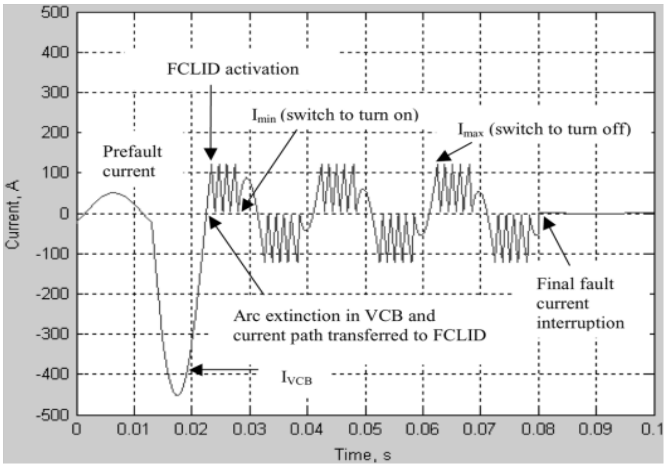

Fig. 3. Current response of FCLID

In addition to the controllability over the profile of the limited short-circuit current, the following features of the developed FCLID can also be expected.

The device inherently integrates the two functions of fault current limiting and interrupting. The power dissipation in the varistor needs to be carefully considered so that the FCLID can operate for the targeted period of time. In some damp and contaminated environments intermittent faults in distribution networks' cables can occur quite frequently. During the operation of the FCLID, the rate of change of current is determined by the total series inductance in the circuit, which depends on the supply system condition and fault location.

Item		Rating
Power system	rated voltage	230 V, rms
	frequency	50 Hz
Current	normal load current	50 A, rms
	short-circuit	3 kA, rms
Solid-state switch	rated voltage	1200 V
	rated pulsating current	300 A
Snubber circuit	resistance	15 Ω
	capacitor	47 nF
Varistor	rated voltage	250 V
	maximum clamping voltage	650 V
	rated energy	880 J

Fig. 4. FCLID specifications & component parameters

4.1 Structure of Solid State FCLID

In an FCLID that applicable for low voltage distribution systems is introduced. It consists of a fast acting, bidirectional switch, a varistor , and a snubber circuit, all connected in parallel . IGBT switches are used to build the bidirectional switch
and the varistor will be used for clamping voltage When a

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ISSN 2229-5518

fault occurred, The IGBT conducts the fault current until it reaches a preset value (I_{max}) at which instant it is turned off. Thus the fault current is diverted to the varistor and snubber circuit. The snubber circuit damps the high dv/dt that appears during the initial phase of the IGBT turn-off process. During this phase, the snubber capacitor is charged and the varistor current starts to build up quickly. The clamping voltage of the varistor is set higher than the peak supply voltage. Therefore, the current in the circuit will start to decrease when this voltage is reached, following R-*L* decay as the source voltage can be considered constant in the relatively short interval within a switching cycle. The semiconductor switch is turned on again to re-establish the current when it reduces to a preset low value (I_{min}). The current will again follow the trajectory of an *R-L* circuit.

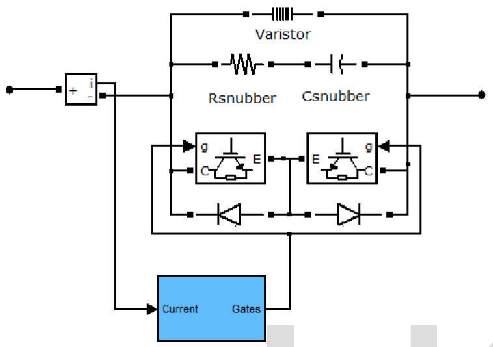

Fig. 5. Structure of simple FCLID

The FCLID can inherently perform two integrated functions: limiting and interrupting the short-circuit current. A switching strategy is proposed to control the limited current when the network condition and fault location vary. This FCLID is able to limit a prospective short-circuit current of 3kA (rms) to 120A(peak). The FCLID can respond quickly after the fault occurrence. Based on the FCLID requirement and characteristics of the available switching devices, IGBTs were chosen for this application. An effective method for improving the current sharing between parallel varistors has been implemented and the required energy rating of the varistors for the FCLID application has been achieved. Prediction of the junction temperature of the IGBT and varistor leads to fully protected and fail-safe operation of the FCLID.

A known difficulty for the high-voltage applications is to connect IGBTs in series to achieve the required voltage rating. While active gate drive could be utilized to improve voltage sharing among series-connected IGBTs, the proposed FCLID implement varistors in its structure which (due to their nonlinear characteristics) can assist in equalizing the voltage sharing.

5 Simulation Results

5.1 Reduction of harmonics and fault current in Single Phase systems

A single phase test system is developed in MATLAB. The THD and the fault current is measured across the system in three cases such as,

- Without using SFCL
- With the presence of SFCL
- Using FCLID

The DC reactor type SFCL is used for the reduction of harmonics only in three phase systems.

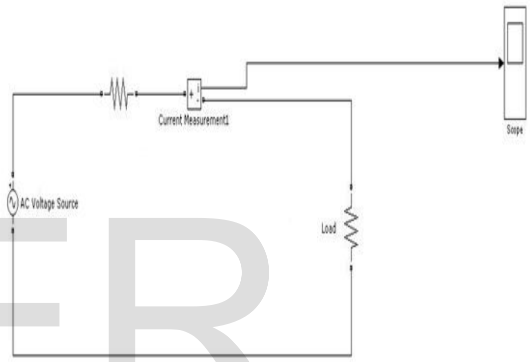

Fig. 6. Simulation model of single phase system without using SFCL

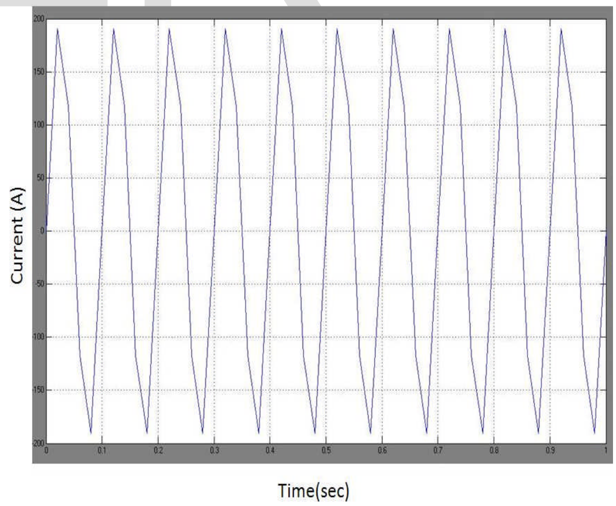

Fig. 7. Current waveform of single phase system without SFCL

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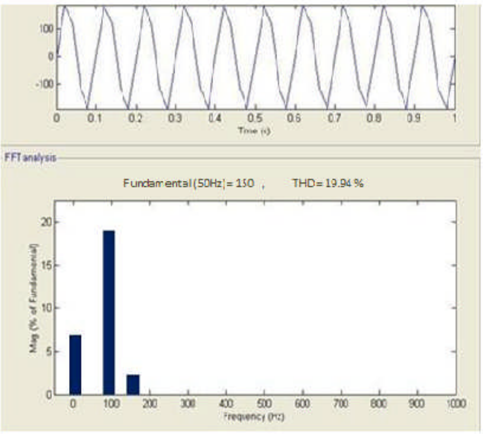

Fig. 8. THD value for single phase system without SFCL

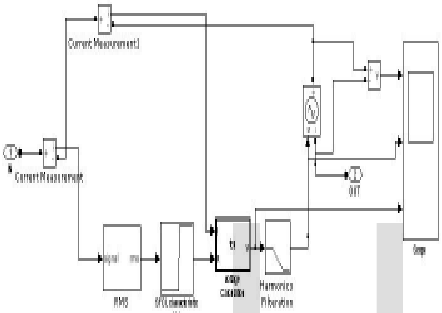

Fig. 9. SFCL model

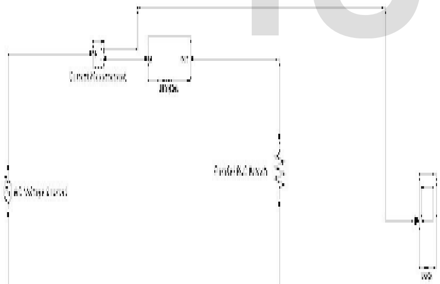

Fig. 10. Single phase system with SFCL subsystem

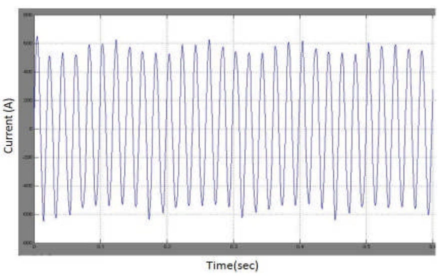

Figure .11. Current waveform for single phase system with SFCL

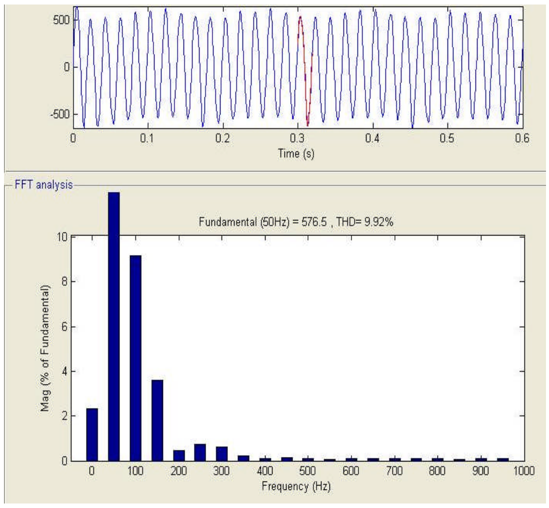

Fig. 12. THD value for single phase system with SFCL

The resistive type SFCL was modeled considering four fundamental parameters of a resistive type SFCL. These parameters and their selected values are:

1) Transition or response time	= 2msec
2) Minimum impedance &	= 0.01Ω
Maximum impedance	= 20Ω
3) Triggering current and	= 550A
4) Recovery time.	= 10msec

The SFCL working voltage is 22.9kV. The maximum impedance value can be varied from 20Ω to 27Ω.

The THD value is reduced from 19.94% to 9.92% with the help of SFCL. By reducing the fault current furthermore the harmonics can also be reduced. By using FCLID the fault current and harmonics can be further reduced.

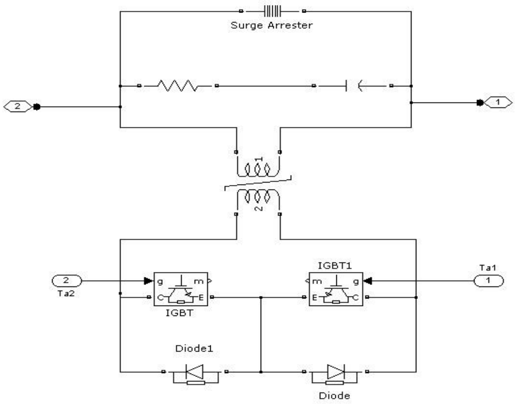

Figure 13: FCLID subsystem

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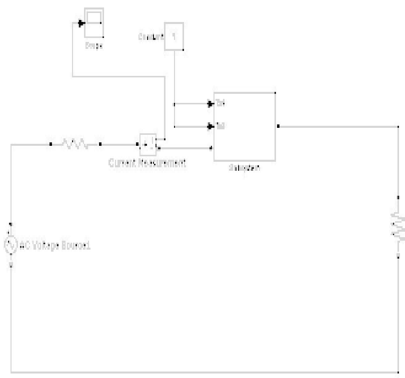

Fig. 14. Single phase system with FCLID

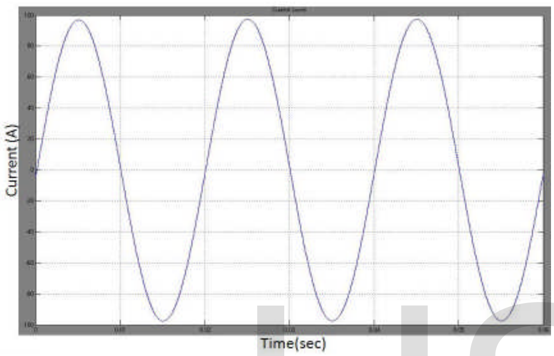

Fig. 15. Current waveform for single phase system with FCLID.

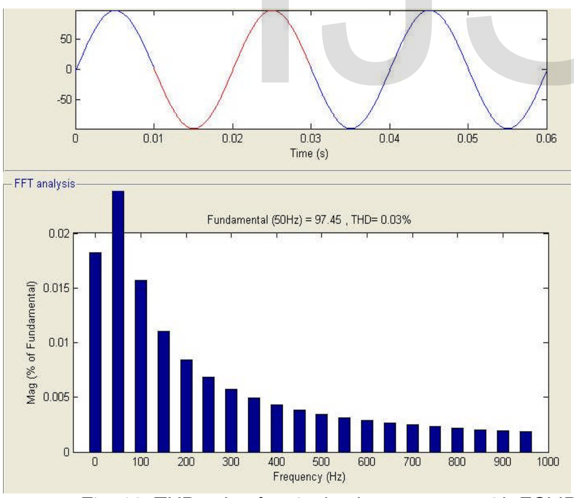

Fig. 16. THD value for single phase system with FCLID

The THD value is reduced to 0.03. From the above analyses it can be declared as FCLID has the more capacity to reduce the fault current and harmonics.

5.2 Reduction of harmonics and fault current in three phase systems.

A single phase test system is developed in MATLAB. The THD and the fault current is measured across the system in three cases such as,

- Without using SFCL
- With the presence of SFCL
    - a. Using DC reactor type SFCL (Y connected 6 pulse bridge)
    - b. Using DC reactor type SFCL (delta connected 6 pulse bridges)
- Using FCLID

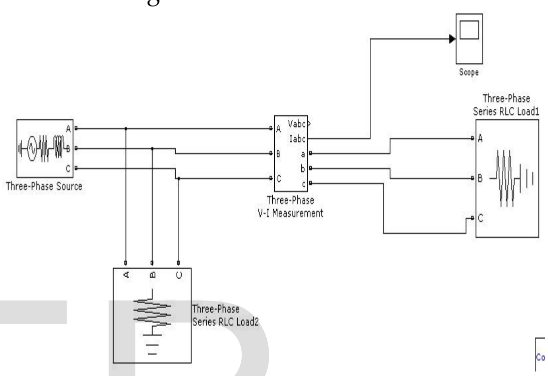

Fig. 17. Three phase test system without SFCL

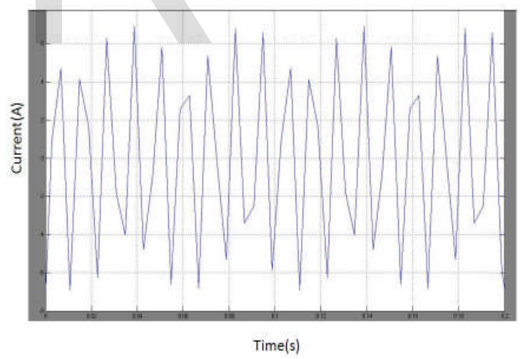

Fig. 18. Current waveform for three phase system without SFCL

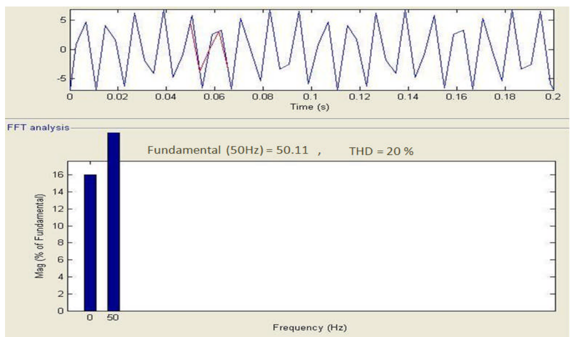

Fig. 19. THD value of three phase system without SFCL

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The THD value of the three phase system is about 20%. This THD percentage indicates that the system is in emergency state i.e., both the fault current and harmonics are higher.

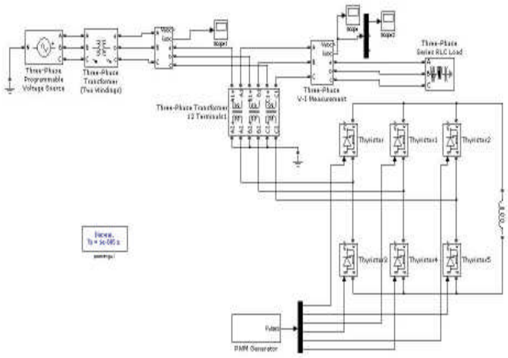

Fig .20. System arrangement if DC reactor type SFCL (Y connected 6 pulse bridge)

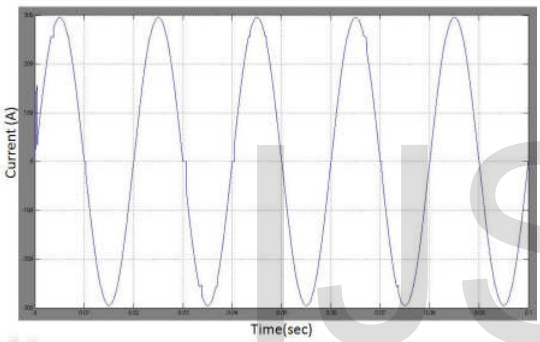

Fig .21. Current waveform for DC reactor type SFCL (Y connected 6 pulse bridge)

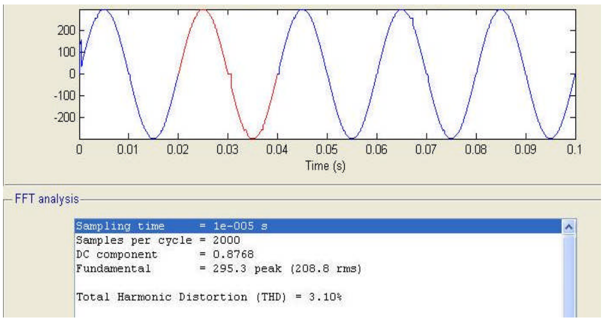

Fig . 22. THD value measured for DC reactor type SFCL (Y connected 6 pulse bridge)

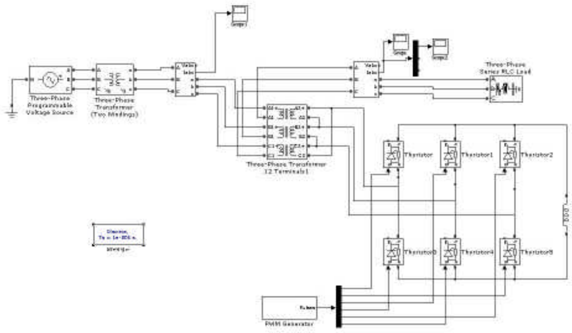

Fig. 23. System arrangement if DC reactor type SFCL (delta connected 6 pulse bridge)

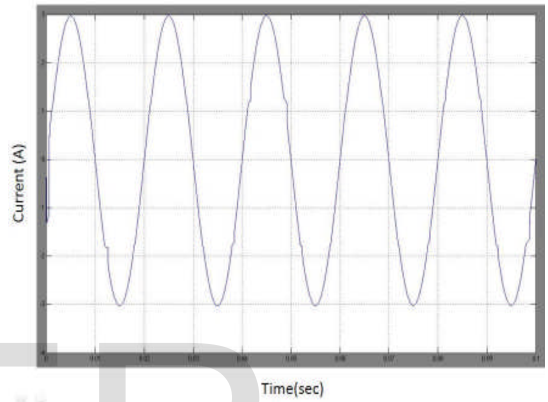

Fig . 24. Current waveform for DC reactor type SFCL (delta connected 6 pulse bridge)

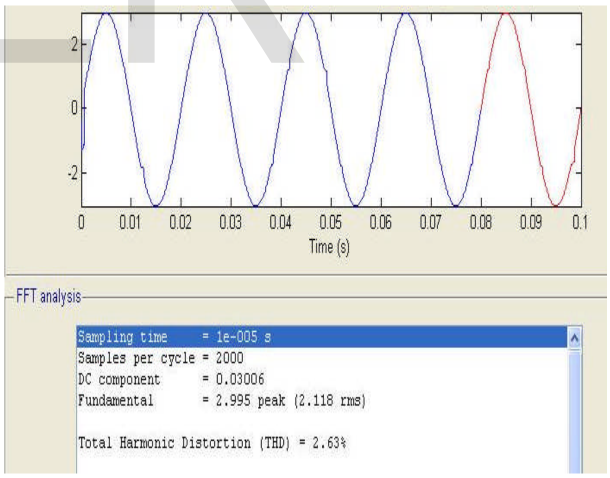

Fig . 25. THD value measured for DC reactor type SFCL (delta connected 6 pulse bridge)

The THD value is further reduced to 2.63%. But the waveform obtained consists of little harmonics which has to be removed. The THD is measured with the help of FFT analysis which gives the exact value of the THD for the specific current waveform obtained.

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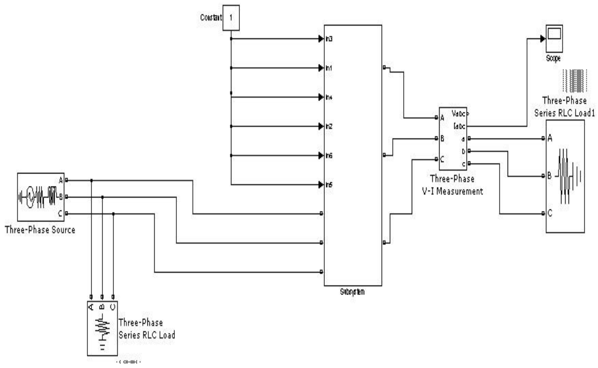

Fig. 26. Three phase system with FCLID

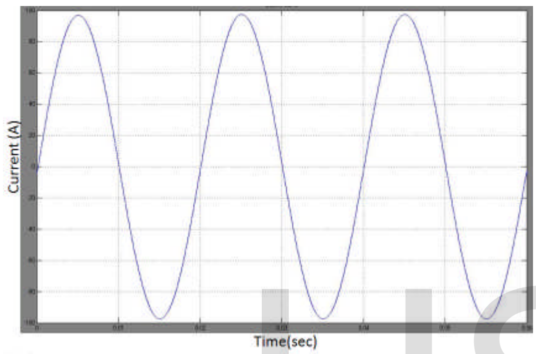

Fig . 27. Current waveform for the three phase system FCLID

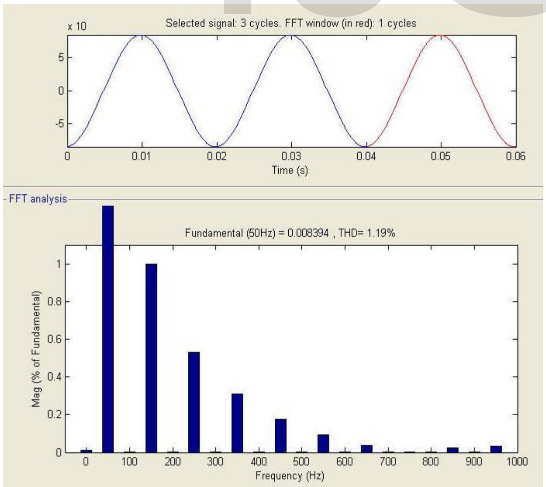

Fig . 28. THD value for three phase system FCLID

The THD value obtained is 1.19%. The THD value is reduced well when compared to DC reactor type SFCL.

5.3 COMMENTS ON RESULTS

From the simulation results obtained using single phase and three phase test systems, the THD value obtained for the three cases such as without SFCL, with SFCL and with FCLID can be compared using the comparison table as shown in Table 1 in order to know by which device the THD and fault current can be reduced simultaneously and also effectively.

From the comparison table shown in Table 7.1 for single phase system without SFCL the THD value is 19.94% and with SFCL THD value is 9.92%. Though the SFCL reduces the harmonics the FCLID device reduces the harmonics up to 0.03%. Thus FCLID is the best device for the reduction of fault current and harmonics in single phase systems.

Similarly for three phase systems without SFCL the THD value is 20% and with DC reactor type SFCL (Y connected 6 pulse bridge) THD value is 3.10% and with DC reactor type SFCL (delta connected 6 pulse bridge) THD value is 2.63% Though the DC reactor type SFCL reduces the harmonics the FCLID device reduces the harmonics up to 1.19%. Thus FCLID is the best device for the reduction of fault current and harmonics also in three phase systems.

TABLE-I
Comparison table of the THD values obtained in single phase and three phase systems

SINGLE PHASE SYSTEM

THD VALUE WITHOUT SFCL	THD VALUE USING SFCL	THD VALUE USING FCLID
19.94%	9.92%	0.03%

THREE PHASE SYSTEM

THD VALUE WITHOUT SFCL	THD VALUE USING DC REACTOR TYPE SFCL (Y-CONNECTED 6 PULSE BRIDGE)	THD VALUE USING DC REACTOR TYPE SFCL (DELTA CONNECTED 6 PULSE BRIDGE)	THD VALUE USING FCLID
20%	3.10%	2.63%	1.19%

6 CONCLUSIONS

The harmonic effects of a new solid stated FCLID and a DC reactor type SFCL are compared. Based on given results it can be said that despite SFCL, introduced FCLID meets IEEE 519 harmonic standards and doesn't need filtering. Based on the analysis and simulation results, the following can be concluded.

- In addition of fault current limiting capability, it can also interrupt it and acts as a backup for circuit breaker.
- In spite of DC reactor type SFCL it doesn't need recti-

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ISSN 2229-5518

fier and coupling transformer.

- Because of low nominal voltage of IGBT, in higher voltage levels a transformer for each switch can be used.
- Because of absence of rectifier, the harmonic currents are very low, thus filtering isn't required.

In the experimental tests conducted, once the FCLID was activated, it remained in the current limiting mode until it was externally stopped and the fault current was permanently interrupted. If the fault is cleared by a downstream protective device, the FCLID can automatically return to the full conduction mode since the current will no longer reach I_{max} and the IGBTs will remain in the ON state. The THD value using FCLID is reduced to 0.03% in single phase systems and 1.19% in three phase systems. Thus FCLID is proved to have better harmonic reduction capacity.

The FCLID can inherently perform two integrated functions: limiting and interrupting the short-circuit current. A switching strategy is proposed to control the limited current when the network condition and fault location vary. This FCLID is able to limit a prospective short-circuit current of 3 kA (rms) to 120A (peak). The FCLID can respond quickly after the fault occurrence. The technology used in this high-speed, multifunction, and multishot system provides useful experience for developing higher-current FCLIDs for 11-kV distribution networks.

REFERENCES

[1] Walid El-Khattam, Tarlochan, S. Sidhu, (2008) 'Restoration of Directional Overcurrent Relay Coordination in Distributed Generation Systems Utilizing Fault Current Limiter', IEEE Transactions on Power Delivery, Vol. 23, No. 2, pp. 576-585.

[2] Baghaee, H.R. Mirsalim, M. Sanjari, M.J. Gharehpetian, G.B. (2008) 'Fault Current Limiting in Distribution Systems with Distributed Generation Units by a New Dual Functional Series Compensator', 2nd IEEE International Conference on Power and Energy (PECon 08), Johor Baharu, Malaysia.

[3] Min Cheol Ahn, Hyoungku Kang, Duck Kweon Bae, Dong Keun Park, Yong Soo Yoon, Sang Jin Lee, and Tae Kuk Ko. (2005) 'The Short-Circuit Characteristics of a DC Reactor Type Superconducting Fault Current Limiter With Fault Detection and Signal Control of the Power Converter', IEEE Transactoins On Applied Superconductivity, Vol. 15, No. 2, pp. 2102-2105.

[4] Takao Sato, Mitsugi Yamaguchi, Tohru Terashima, Satoshi Fukui, Jun Ogawa, Hirotaka Shimizu, Tomoyuki Sato. (2007) 'Study on the Effect of Fault Current Limiter in Power System With Dispersed Generators', IEEE Transactoins On Applied Superconductivity, Vol. 17, No. 2, pp. 2331-2334.

[5] Zhang Xiaoqing, Ming Li. (2008)'Using the Fault Current Limiter With Spark Gap to Reduce Short-Circuit Currents', IEEE Transactions On Power Delivery, Vol. 23, No.1

[6] Vladimir Sokolovsky, Victor Meerovich, István Vajda, Vladimir Beilin.(2004) 'Superconducting FCL: Design and Application', IEEE Transactions on Applied Superconductivity, Vol. 14, No. 3.

[7] Hiroyuki Hatta, Tanzo Nitta, Masakuni Chiba, Shinichi Muroya, and Yasuyuki Shirai, (2003) 'Experimental Study on the Relationship Between the Trigger Current of Transformer-Type Superconducting Fault Current Limiter and the Fault Phase', IEEE Trans. Appl. Supercond., Vol. 14, No. 2, pp. 815–818.

[8] V. Rozenshtein, A. Friedman, Y. Wolfus, F. Kopansky, E. Perel, Y. Yeshurun, Z. Bar-Haim, Z. Ron, E. Harel, and N. Pundak, (2007)'Saturated Cores FCL - A New Approach' IEEE Transactions on Applied Superconductivity, Vol. 17, No. 2.

[9] J. Skindhoj, J. Glatz-Reichenbach, R. Strumpler, (2008) 'Repetitive Current Limiter based on Polymer PTC Resistor', IEEE Transactions on Power Delivery, Vol. 13, No. 2, pp. 489-494.

[10] R. Strumpler, J. Skindhoj, J. Glatz-Reichenbach, J.H.W. Kuhlefelt, F. Perdoncin, (2009) 'Novel medium voltage fault current limiter based on polymer PTC resistors', IEEE Transactions on Power Delivery, Vol. 14, No. 2, pp. 425-430.

[11] M. M. R. Ahmed, Ghanim A. Putrus, Li Ran, Lejun Xiao,(2004) 'Harmonic Analysis and Improvement of a New Solid-State Fault Current Limiter', IEEE Transactions On Industry Applications, Vol. 40, No. 4, pp. 1012-1019.

[12] Krein, P.T. (2010) 'Elements of Power Electronics'. New York: Oxford University Press.

[13] Minseok Joo, (2010) 'Harmonics Control of Inductive Superconducting Fault Current Limiter System with DC Reactor', IEEE Transactions on Applied Superconductivity, Vol. 14, No. 2, pp 831-834.

[13] Ahmed, M.M.R. Ghanim Putrus, Li Ran, and Roger Penlington, (2010) 'Development of a Prototype Solid-State Fault-Current Limiting and Interrupting Device for Low-Voltage Distribution Networks', IEEE Trans on Power Delivery, Vol. 21, No. 4, pp. 1997-2005.