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Selection of Resistive and Inductive Superconductor Fault Current Limiters Location Considering System Transient Stability

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Superconductor fault current limiter (SFCL) is an effective device to suppress high fault currents. This paper presents a comparative study of resistive and inductive fault current limiters from transient stability point of view. Appropriate location and type of the limiters in a HV substation is selected by a qualitative approach based on the equal area criterion. Study system is simulated by DIgSILENT software to verify the qualitative analysis.

Keywords:Resistive And Inductive Superconductor Fault Current Limiters, Transient Stability, Equal Area Criterion, Critical Clearing Time

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I Introduction

One of the new challenges for power system engineers is increased fault current level in high voltage substations. In some substations short circuit currents are comparable or even exceed the capacity and ratings of installed circuit breakers and their lateral equipment. This is partly due to the installation of new generation units and increased penetration of distributed generators (DGs) in power networks which in turn increase the amount of power captured by a short circuit [1]. In addition, with the increasing stress on modern power systems, many utilities more and more face the threat of transient stability problems [2]. To reduce fault current level in existing high voltage substations, various solutions such as transformers with higher impedance and split busbars have been proposed. On the other hand, application of superconductor fault current limiters (SFCLs) is one of the practical countermeasures of the fault current problem and are expected to offer a better solution [3]. SFCL presents low (near zero) impedance under the normal conditions and so does not degrade the steady state stability. Under a fault condition, the SFCL quenches and this phenomenon causes a fast raise of the limiter impedance up to a value, ZSFCL, needed for limiting the fault current. Impedance of SFCL can change the transient stability of power systems. After fault removing, SFCL automatically returns (recovers) into the initial state [4]. Several prototypes of SFCL have been successfully tested in distribution networks [5-6]. At present, there are some studies directed to design and construct of SFCL for application in the high voltage substations [7-8]. The next step is to apply the SFCL in power networks for practical use. There are three major subjects in this area: Optimal location to install, optimum resistance (or inductance) value of SFCL and protection coordination with other existing protective devices [9-11]. Moreover, there have been works on analyzing transient stability of a power system including installed SFCLs. The preliminary studies show that application of SFCLs can improve the transient stability of the power networks by reducing the fault current level in a fast and efficient manner [12-13]. SFCLs are divided in two main classes: Resistive and Inductive. The resistive superconductor fault current limiter (RSFCL) is an efficient device which is based on the principle of high temperature superconductors (HTS). The RSFCL has an element which is in a superconductive state in the event of a normal current occurrence, and which is in a normal conductive state and having a predetermined resistance when a fault occurs. RSFCL has advantages such as simpler structure, smaller size, and possibly lower capital cost than the other types [14]. The inductive superconductor fault current limiter (ISFCL) is normally based on the magnetic shielding. The inductance of the coil is changed by the shielding effect of the superconduction cylinder. ISFCL can be the most common type due to simple construction of the superconduction winding in the form of Bi2223 bulk superconductor [15]. Several studies have been done to compare resistive and inductive SFCLs from construction [16], fault current limiting [17] and requirements, specifications and performances [18] points of view. However, there is no specific and deep investigation reports about comparing the influence of resistive and inductive SFCLs on transient stability of a power system. In this paper, the influence of superconductor fault current limiters on the transient stability of a high voltage substation connected to an infinite bus is analyzed for different types (Resistive and Inductive) of SFCL and different installed locations in substations (Transformer feeder and Line feeder). A qualitative approach based on the equal area criterion is used to compare the types and installed locations of SFCL. These results were confirm in the experiments on the

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electrodynamic model of a 230 kV substation in Iran's electric utility.

II INFLUENCE OF VARIOUS TYPES OF SFCL ON THE POWER SYSTEM TRANSIENT STABILITY ENHANCEMENT

In this section a qualitative analysis is carried out based on the equal area criterion to compare the influence of resistive and inductive SFCLs on the transient stability of a substation. Different installation locations of the SFCLs and their influence on the transient stability is also considered and determined by the comparison of ratio of the accelerating and damping areas.
In accordance with the equal area criterion the transient stability is kept if the acceleration area is equal or less than the damping area. Consider the simple substation topology shown in Fig.1. The substation configuration is single busbar and it has one generator-transformer block feeder and two line feeders which connected the substation to the infinite bus.

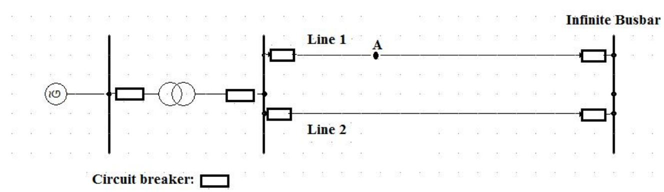

Figure 1

Analysis of transient stability is performed for three phase short circuit as the worst case fault. Three phase fault occurs in one of the lines near the substation (point A). It is assumed that the fault is temporary and is removed during reclosing operation. The transmitted power from the generator to the system in the normal regime is thus the same as after reclosing operation and is given by the following well-known expressions:

$$P = \frac{|V_b|\ |E|}{X'_d} \sin\delta$$

$$X'_d = X_u + 0.5 \times X_l \quad (1)$$

$$X_u = X_d + X_t$$

Note that in the normal regime, the values of resistances are small when compared with inductances and all resistances are thus negligible.

A Inductive SFCL

In this section, the influence of different installation locations of ISFCL on the power system transient stability is analyzed and appropriate place in the substation will be obtained. It is assumed that all resistances can be neglected.

A.1 ISFCL in a Line Feeder

First case considers ISFCL is installed in a line feeder. For a three phase fault at point A, the power-angle curve relationships and equivalent circuit of the network in two cases: (a) during fault and (b) after breaker opening are shown in the Fig. 2 , Eq. 2 and Fig. 3 , Eq. 3 , respectively.

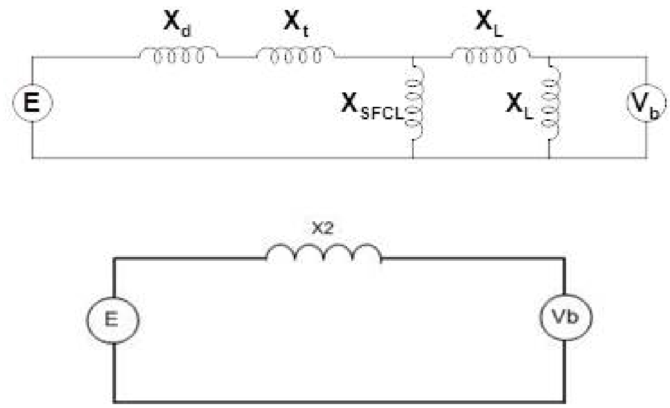

Figure 2: ISFCL in a Line Feeder - During fault

$$P = \frac{|V_b|\ |E|}{X_2} \sin\delta$$

$$X_u = X'_d + X_t \quad (2)$$

$$X_2 = X_u + X_L + \frac{X_u \times X_L}{X_{SFCL}}$$

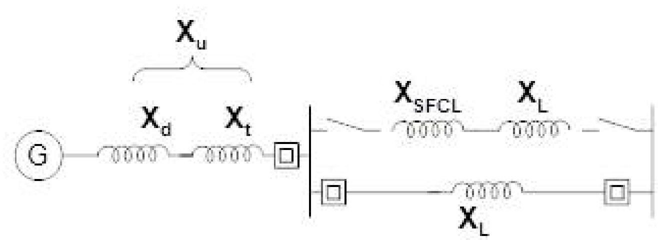

Figure 3: ISFCL in a Line Feeder - After breaker opening

$$P = \frac{|V_b|\ |E|}{X_S} \sin\delta$$

$$X_S = X_u + X_L \quad (3)$$

Delta-star transformation has been used to obtain the expressions. The power-angle curves and the acceleration and damping areas for this case are shown in Fig 4. During fault, the generator rotor accelerates, the angle δ increases from δ_0 to δ_1. The angle δ_0 corresponds to opening the circuit breakers.

A.2 ISFCL in a Transformer Feeder

The second possible case of the ISFCL installation location is in the unit transformer-generator block feeder. In the case of a three-phase fault at point A, the transmitted power during the fault falls to zero. The equivalent circuit of the power system

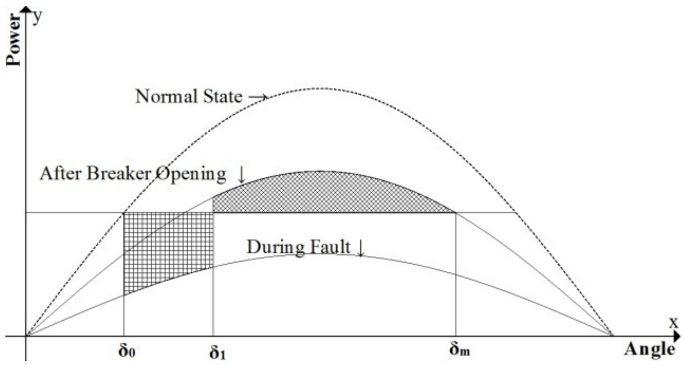

Figure 4: Power diagram for analysis of transient stability of the ISFCL installed in a line feeder

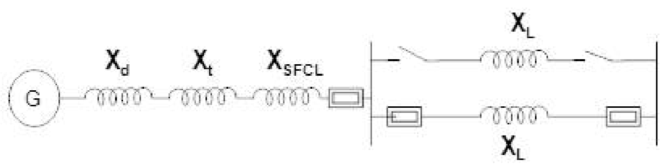

Figure 5: Equivalent Circuit of power system after breakers opening-ISFCL is in transformer feeder

and the power-angle curve relationship after breaker opening are shown in Fig. 5 and equation 4, respectively.

$$P = \frac{|V_b|\ |E|}{X_S} \sin \delta$$

$$X_u = X'_d + X_t \tag{4}$$

$$X_S = X_u + X_{SFCL}$$

Fig. 6 shows the power diagram for this case. It is assumed that the ISFCL can return into the initial state (low impedance) immediately after the interruption of the fault current, without any delay.

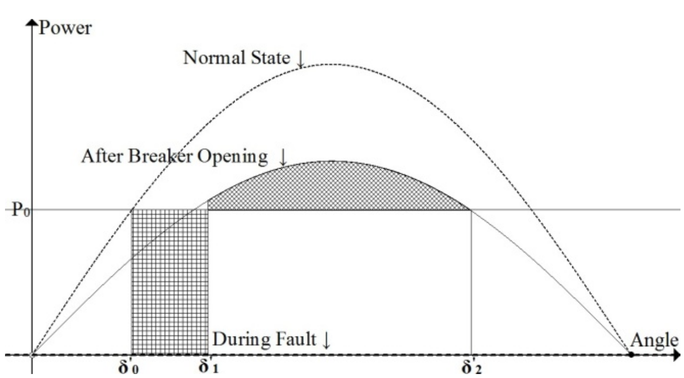

Figure 6: Power diagrams for analysis of transient stability of the ISFCL installed in the unit transformer feeder

Comparison of Figs 4 and 6 shows that, if the ISFCL comes back into the initial state immediately after fault interruption, the squares of damping area is the same but installation of ISFCL in the line feeder decreases the acceleration area compared to the installation of the limiter in the transformer feeder. Therefore, installation of the ISFCL in the line feeder enhances the transient stability of the power network and is a better choice as the transient stability point of view.

Note that if the ISFCL does not come back into the initial low impedance state during a no current pause, the damping area decreases in comparison with the case of immediately recover and the transient stability is consequently degraded. Therefore, to enhance the transient stability, it is better the ISFCL recovers to the initial state as soon as possible.

B Resistive SFCL

In the following, appropriate installation place of RSFCL is obtained by comparing the power-angle curves for two different locations: line feeder and transformer feeder. In the case of RSFCL all resistances of the power network are taken into account. Also, it is assumed that under a fault event the resistance of RSFCL fast increases (jumps) up to a high value and keeping unchanged during the fault and sometime after [19]. In fact, the RSFCL requires time t_r to return into the initial state after interruption of a fault current.

B.1 RSFCL in a Line Feeder

Now, consider RSFCL has been installed in a line feeder. For the three-phase fault on one of the parallel lines and near the substation, power-angle curve relationship and equivalent circuit of the network during the fault and after breakers opening are similar to the case of the ISFCL, except that ZSFCL=RSFCL. The power angle expression during the fault can be derived as follow:

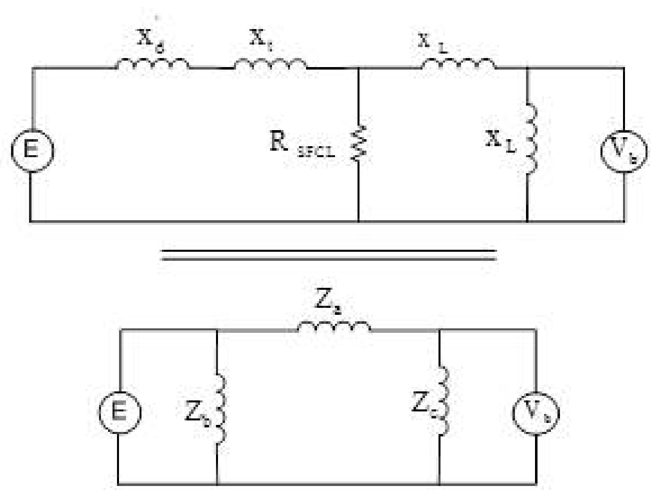

Figure 7: Equivalent Circuit of power system - RSFCL is in line feeder

$$P = \frac{E^2}{|Z_b|} \cos \angle Z_b + \frac{E^2}{|Z_a|} \cos \angle Z_a - \frac{EV_b}{|Z_a|} \cos\left(\delta + \angle Z_a\right)$$

$$Z_b = R_{SFCL}\left(1 + \frac{X_u}{X_L}\right) + jX_u \tag{5}$$

$$Z_a = -\frac{X_u X_L}{R_{SFCL}} + j\left(X_u + X_L\right)$$

The power-angle curves and the accelerating and damping areas for this case are shown in Fig. 8. Note that the transmitted power during a three phase fault is not zero and the resistance value of RSFCL causes the power diagram slightly shifts.

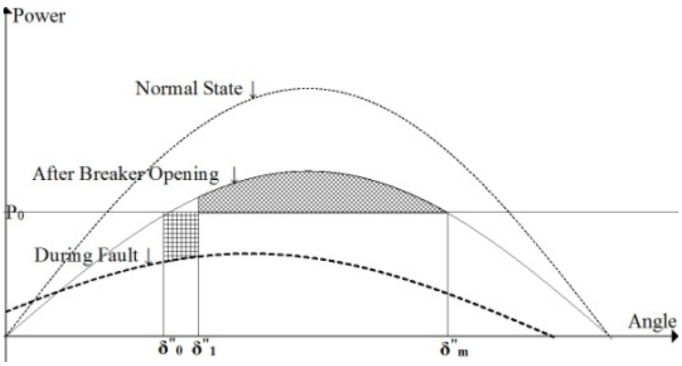

Figure 8: Power angle curve- RSFCL has been installed in a line feeder

B.2 RSFCL in a Transformer Feeder

During the fault, voltage of substation busbar is approximately equal zero but in contrary to the case of ISFCL, the transmitted power exists and is lost in the resistance of the RSFCL. Moreover, this power dose not change with the load angle (Fig. 9 and Eq. 6). After breakers openings, it is assumed that the RSFCL comes back into the initial state with some time delay and RSFCL remains in conductive state (Fig. 10 and Eq. 7).

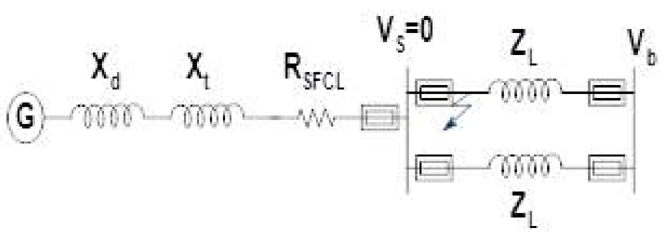

Figure 9: RSFCL in a Transformer Feeder - During the fault

$$Z = \left(R_a + R_{SFCL}\right) + j\left(X_d + X_t\right)$$

$$Z_L = R_L + jX_L \tag{6}$$

$$P = E_a^2 \frac{\left(R_a + R_{SFCL}\right)}{\left(R_a + R_{SFCL}\right)^2 + \left(X_d + X_t\right)^2}$$

$$P = \frac{|V_b|\,|E|\left(R_e\cos\delta + X_e\sin\delta\right) + |V_b|^2 R_e}{R_e^2 + X_e^2}$$

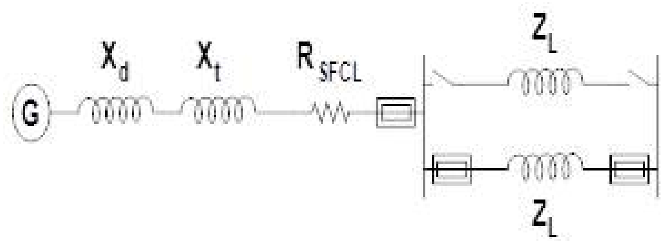

Figure 10: RSFCL in a Transformer Feeder - After breaking opening

$$R_e = R_a + R_{SFCL} + R_L \tag{7}$$

$$X_e = X_u + X_L$$

Power-angle curve for this case are shown in Fig. 10. Comparing Fig. 7 and 10 shows that, installation of RSFCL in the transformer feeder increases the damping area. But the square of the acceleration area depends on the system operating point and this area can decrease or increase in comparison to the case when RSFCL is installed in the line feeder.

Generally speaking, there is not a general rule for appropriate place assignment of RSFCL in a substation. In some operating points, installation of RSFCL on the transformer feeder may improve the transient stability and in some others can degrade it. Note that if the RSFCL immediately comes back into the initial low impedance state during a no current pause, the damping area decreases and the transient stability is degraded

III TIME DOMAIN SIMULATIONS

SHAZAND, BAKHTAR a 230KV substation in Iran's electric utility was selected as a case to study the proposed only one SFCL is used but the incoming feeder contribution is not individually limited. In case of a fault occurrence at a busbar it can reduce some portion of the feeding sources approach. Substation configuration is shown in Fig. 11. The nominal parameters of the system are given in Appendix. As shown in the Figure the selected substation is of the double busbar types and the substation topology contains two main buses with closed coupler circuit breaker.

At present, short circuit magnitude of the substation (by a three-phase fault at the substation busbar) is 34.5 kA and the rated interrupting capacity of the circuit breakers is 40 kA. The contributions of the line and generator feeders in total applied short circuit magnitudes are also shown in Fig. 11. Expansion of Iran's power grid until 2018 has been considered by 10 percent annual increase in energy demand. According to the calculated fault current magnitude by the end of 2018, the magnitudes would be higher than the circuit breakers interrupting capacity In order to restore the reliability of substation, it should be either redesigned once more to deploy suitable equipments or fault current limiters must be employed to suppress fault current magnitudes to an acceptable level.

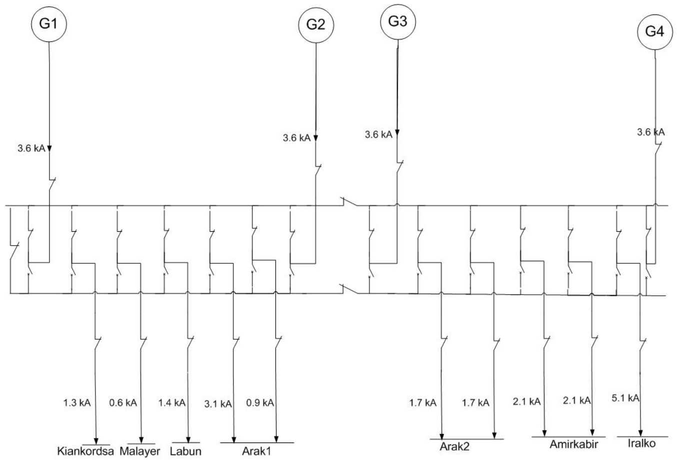

Figure 11: The contributions of the line and generator feeders in total applied short circuit magnitudes in SHAZAND substation

A Candidate Locations of SFCLs

The possible places of the SFCLs at the substation can be listed as follows:

A.1 Series deployment with the critical line feeders

In this case, the fault currents of the critical line feeders, which have higher contribution in the busbar short circuit magnitudes would decrease to an acceptable level. Line feeders connected to the substation busbars, contributes to rise the total short circuit magnitude. However, contribution of some feeders is greater than the others. Once the contribution of each line feeder to the fault level has been evaluated, it would be possible to specify the critical line feeders. In fact, the critical feeders are those with great portion of to busbar short circuit magnitude increment. Fig. 11 depicts these lines: ARAK 1, AMIRKABIR (Double circuits) and IRALKO.

A.2 Series deployment with the generator-unit transformer feeders

In this case, the fault currents of all generators are individually limited by installation of one SFCL in each generator-transformer feeder. In case of a fault occurrence at a busbar, the SFCLs can reduce the generator fault currents.

B Selection of SFCL Resistance/Reactance

State transition from superconductive state to normal state occurs just as the fault appears in the location where the limiter is placed. Appropriate SFCL impedance obtains from the desired fault current magnitude for the selected substation (31.5KA).
Table I shows the obtained resistances and reactances for different installation locations and various types of SFCLs in SHAZAND substation. It should be considered that in the second case, ARAK 1, AMIRKABIR (Double circuits) and IRALKO are the four line feeders where the SFCLs are installed. In the first case, there is one SFCL in each generator-unit transformer feeder (totally 4 SFCLs).

Table 1: Resistance and reactance of the SFCLs for various types and installation places

Installation place	SFCL Type	Resistance/ Reactance(Ω)	Short circuit level (kA)
Generator Feeders	Resistive	28	31.004
	Inductive	13	31.02
4 Line feeders	Resistive	25	31.042
	Inductive	20	31.112

C Transient Stability Evaluation

In this section, the most appropriate location of SFCLs from fault level limitation point of view is introduced. Although listed cases offered in Table I limit the short circuit level of the substation to the desired values, but the simulation results show that the damping performance of the system is a function of the location and the resistance/reactance values of the SFCLs. furthermore those values have a significant effects on transient stability of the system. The remaining open question is the selection of optimal location and type of the SFCL to improve more effectively the system transient stability. In fact, a second point should be taken into account: The damping improvement of generator speeds or generally speaking the transient stability improvement of the system caused by SFCL type selection and its different possible locations.
In this paper the criterion used for analyzing the transient stability is critical clearing time (CCT). The longest fault time, after which stability of the generators can be maintained, is called CCT. It is a major factor which shows the transient stability limit of power systems. The short circuit has to be removed in a shorter time interval than the critical clearing time. Currently, two main tools for CCT calculation are the direct method and the time-domain simulation method. The direct method can be used to calculate the CCT in the minimum possible time. With the time-domain simulation method, it is possible to calculate CCT with the maximum accuracy [14].
In this paper, CCT is calculated with time-domain simulation method. For transient stability studies, the system should be studied with various pre-contingency conditions that stress the system. Two pre-contingency conditions according to full load in summer 2013 and low load in autumn 2013 are considered. To determine the worst-case scenario of transient stability, it is considered that three phase fault location is at the beginning of the one of the radiating lines from the substation (IRALKO line). For SHAZAND substation, numerical simulations were performed and CCT values for various types of SFCL and installation places were calculated. The results have been shown in Table 2 and 3.

Waveforms of the angular separation of the rotors of the generators G1(group II) and G4(group I) (Rotor angle of generator G4 was taken as reference), are depicted in Figs. 12 and 13 for resistive and inductive SFCL respectively. Different loca-

Table 2: CCT for various SFCL types and their installation places- peak load in summer, 2013

Installation place	SFCL Type	CCT/ (msec)	Active SFCLs)
Generator Feeders	Resistive	531	all unit trans.
	Inductive	297	all unit trans.
4 Line feeders	Resistive	391	IRALKO line
	Inductive	336	IRALKO line

tion impacts of SFCLs are shown as well. Three phase fault location is at the beginning of the IRALKO line. Fault clearing time is assumed to be 350 msec and 300 msec in Fig. 12 and 13, respectively.

Table 3: CCT for various types of SFCL and installation places- Low load in autumn 2013

Installation place	SFCL Type	CCT/ (msec)	Active SFCLs)
Generator Feeders	Resistive	770	all unit trans.
	Inductive	460	all unit trans.
4 Line feeders	Resistive	570	IRALKO line
	Inductive	570	IRALKO line

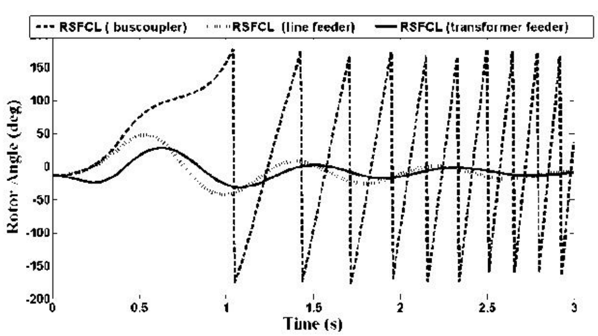

Figure 12: Rotor angle variations for different locations of RSFCLs - Fault Clearing Time: 350 ms

IV CONCLUSION

A qualitative analysis based on equal area criterion and time domain simulation was performed to compare the resistive and inductive fault current limiters from transient stability enhancement point of view. Installation location of limiters in a single substation arrangement was analyzed. The followings are the major outcomes of the study:
- RSFCL is a better choice than ISFCL for enhancing power

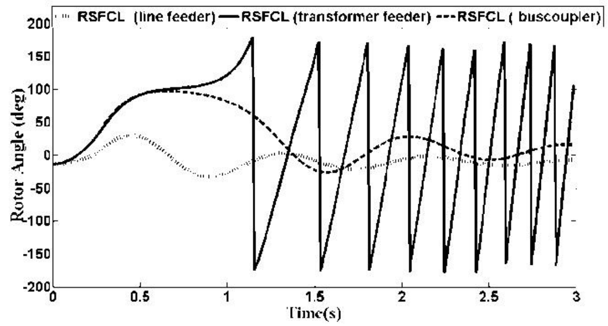

Figure 13: Rotor angle variations for different locations of ISFCLs - Fault Clearing Time: 300 ms

system transient stability.
- ISFCL is better to be installed in line feeders.
- With RSFCL, a general rule cannot be stated to allocate an appropriate place of limiter.

V APPENDIX

Table 4: Generator parameters

Parameters	unit	Value
S_n	MVA	300
U_n	kV	20
$\cos\phi$		0.85
X_d	pu	2.17
X_q	pu	2.17
X'_d	pu	0.321
X'_q	pu	0.3
X''_d	pu	0.1986
X'_q	pu	0.1986
T'_{do}	s	1.16
T'_{qo}	s	0
T''_{do}	s	0.035
T''_{qo}	s	0.035

Table 5: Transformer parameters

Parameters	unit	Value
S_n	MVA	312
U_n	kV	400/19
U_k	(%)	12.5

Table 6: Lines parameters

Parameters	unit	Value
R	Ω/km	13.539
X	Ω/km	154.912
$Length$	km	0.965

REFERENCES

[1] U. A. khan, J. K. Seong, S. H. Lee, S. H. Lim and B. W. Lee, *"Feasibility Study of superconducting Current Limiter Application in a Co-generation*

Plant,", IEEE Transactions on Applied Superconductivity, Vol.21 , No. 3, June 2011.

[2] H. Saadat, *"power System analysis,"*, 2nd Ed. New York: McGraw-Hill, 2004.

[3] L. Ye, L. Z. Lin, and K. P. Juenyst , *"Application Studies of Superconducting Fault Current Limiters in Electric Power Systems,"* , IEEE Trans. on Applied Superconductivity", Vol. 12, No.2, March 2002.

[4] V. Sokolovsky, V. Meerovich ,I. Vajda , *"Transient Stability of a Power System with Superconducting Fault Current Limiters,"* , Cryo Prague 2006 : Multi-conference : proceedings : July 17-21 2006, Praha, Czech Republic.

[5] S. B. Chul, and P., J. Wook, *"Study on a Series Resistive SFCL with Experimental Verification by Real-Time Digital Simulator."* , International Conference on Electrical Engineering, Okinawa, Japan, July 2008.

[6] B. C. Sung, D. K. Park, J. W. Park, and T. K. Ko, *"Study on a Series Resistive SFCL to Improve Power System Transient Stability: Modeling, Simulation, and Experimental Verification."*, IEEE Trans. on Industrial Electronics, Vol. 56, No. 7, JULY 2009.

[7] K. Yasuda , A. Ichinose , A. Kimura , K. Inoue , H. Morii , Y. Tokunaga , S. Torii , T. Yazawa , S. Hahakura , K. Shimohata and H. Kubota , *"Research and development of superconducting fault current limiter in Japan."*, IEEE Trans. Applied Superconductivity., Vol. 15, No. 2, pp.1978 -1982, 2005.

[8] Yazawa T., Ootani, Y. , Sakai, M. , Otsuki, M. ; Kuriyama, T. , Urata, M. , Tokunaga, Y. and Inoue, K., *"Design and Test Results of 66 kV High-Tc Superconducting Fault Current Limiter Magnet"*, IEEE Trans. on Applied Superconductivity, Vol. 16, No.2, March 2006.

[9] B. C. Sung , *"Study on Optimal Location of a Resistive SFCL Applied to an Electric Power Grid,"*,IEEE Transactions on Applied Superconductivity, Vol. 19 , Issue: 3, June 2009.

[10] Jin-Seok Kim, Sung-Hun Lim, and Jae-Chul Kim , *"Study on Application Method of Superconducting Fault Current Limiter for Protection Coordination of Protective Devices in a Power Distribution System,"*,IEEE Trans. on Applied Superconductivity, Vol. 22, No. 3, June 2012.

[11] J. S. Kim, S. H. Lim, and J. C. Kim , *"Study on Protection Coordination of a Flux-Lock Type SFCL With Over-Current Relay,"*,IEEE Trans. on Applied Superconductivity, Vol. 20, No. 3, June 2010.

[12] Almeida, M.E. ; Rocha, C.S. ; Dente, J.A. ; Costa Branco, P.J , *"Enhancement of power system transient stability and power quality using superconducting fault current limiters,"*, International Conference on Power Engineering, Energy and Electrical Drives, POWERENG '09, 2009.

[13] G. Didier, J. Lvłque, and A. Rezzoug , *"A Novel Approach to Determine the Optimal Location of SFCL in Electric Power Grid to Improve Power System Stability,"*,IEEE Trans. on Power Systems, Vol. 17, No. 2, 2012.

[14] D. K. Park ; S. E. Yang, *"Analysis of the Operational Characteristics of a Resistive SFCL by Using the YBCO Coated Conductor,"*,IEEE Trans. on Applied Superconductivity, Vol. 17, No. 2, June 2007.

[15] Y. Cai, S. Okuda, T. Yagai, M. Tsuda, and T. Hamajima , *"Study on Three-Phase Superconducting Fault Current Limiter,"*, IEEE Trans. on Applied Superconductivity, Vol. 20, No. 3, June 2010.

[16] Kozak, J.Majka, M. ; Kozak, S. ; Janowski, T. , *"Comparison of Inductive and Resistive SFCL,"*, IEEE Trans. on Applied Superconductivity, Vol. 23, No. 3, June 2013.

[17] Aly, M.M. ; Mohamed, E.A. , *"Comparison between resistive and inductive superconducting fault current limiters for fault current limiting,"*,International Conference on Computer Engineering and Systems (ICCES), Seventh International Conference, 2012.

[18] Lee, B.W.,Rhee, S.B. , *"Test Requirements and Performance Evaluation for Both Resistive and Inductive Superconducting Fault Current Limiters for 22.9 kV Electric Distribution Network in Korea,"*,IEEE Trans. on Applied Superconductivity, Vol. 20 , No. 3 , June 2010.

[19] Hye-Rim Kim, Chung Ryul Park, Seong-Woo Yim, Seung-Duck Yu, and Ok-Bae Hyun , *"Recovery Characteristics of Coated Conductors,"*,IEEE Trans. on Applied Superconductivity, Vol. 20, No. 3, June 2010.