Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Reliability evaluation of HV substations in the presence of Fault Current Limiter

I. Rahmati, and M. Fotuhi-Firuzabad, *Senior Member, IEEE*

***Abstract*--Short circuit current is one of the major threats for power system stability. Power system should have the ability to detect and clear these faults within a specified time. The protection system can clear the faults only if the interruption capability of the circuit breakers is higher than the fault level. Expansion of the grid and installation of new power on the scale that is envisaged will require practical solutions to a number of technical challenges. One of the technical challenges is fault level management as system expansion often results in increased fault levels beyond the design limits of the existing switchgears. Replacing the old equipments particularly circuit breakers with the new ones having higher interruption capability is one way to overcome this problem. This, however, is not a cost-effective management of fault levels. Using Fault Current Limiters can be an alternative to avoid this high investment cost. In this paper, application of fault current limiter in substation reliability enhancement is presented. The result of the investigations carried out to assess the impacts of FCL application on substation reliability.**

***Index Terms*--Fault Current Limiter, HV Substation, Reliability Evaluation.**

I. INTRODUCTION

NOWADAYS the need for electrical energy is increasing and every day of our life becomes more dependent on this kind of energy. To respond to this rapid growth, Power systems should be expanded in generation, transmission and distribution sections. One of the problems related to these expansions is the fast increase in the short circuit level. This increase causes the following effects:

1. Overheating the series devices in the fault path.
2. Increase transient and recovery voltages produced by cutting off the increased current, and this can damage insulation systems.
3. Producing very high mechanical forces in the devices containing coils (like transformers, generators, reactors,…)
4. Depends on the magnitude of fault current and clearing time, system stability may be lost.
5. Because of the growth in the fault current amplitude it is possible that the circuit breakers installed in the past can not interrupt the fault current anymore and need to be replaced and this needs extra investment in time and money. To avoid these extra costs we may have restriction in paralleling the power transformers to reduce system interconnectivity and this also reduces transmission capacity and system reliability.
6.
7. By increasing the fault current, following corrective actions take more time and this means more interruption time and more commercial loss.
8. To decrease in reliability of electrical network

The above effects can be harmful for any power systems. Basically, there are 3 solutions to alleviate these effects:

1. To design and build power network in a way that probability of occurring a fault be as low as possible.
2. To use the circuit breakers that can cut off the increasing fault current and replace the weak circuit breakers with ones having higher interruption capability.
3. Make changes in power network in order to reduce the short circuit level.

A combination of the above solutions is normally used to design an optimum network while maintaining system reliability within acceptable margins. It is clear that probability of occurring a fault can never be removed completely. On the other hand, designing power apparatuses based on increasing short circuit currents is not commercially reasonable. The 3rd solution can be categorized into the following items:

1. Reduce system interconnectivity (e.g. Bus splitting)
2. Fault Current Limiter application

Substituting circuit breakers with ones having higher interruption capability is a very expensive solution and in some cases is not applicable. Furthermore, protection system has a delay in fault detection depending on the relay specification. Operation of circuit breaker and extinguishing the arc are not instantaneous and this causes another delay (3 to 5 cycles) to remove faults completely [2]. Because of these delays, fault current can't be usually interrupted before 2-8 cycles after the fault. In this duration, a very high current is flowing through the series devices in the fault path and this high current can be destructive even in this short duration. This is particularly true in the first cycles when the fault current is extremely high due to the presence of the DC component of the fault current.

Bus splitting and reducing system interconnectivity can be considered as the two options to alleviate this problem.

M. Fotuhi-Firuzabad is with the center of Excellence in power system control and Management Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran (e-mail: fotuhi@sharif.edu).

I. Rahmati is with the Privatization Bureau of Ministry of Energy of Iran, Tehran, Iran. (email: rahmati@moe.org.ir).

They, however, bring other operational difficulties like decreasing transmission capacity, changing the power flow in the network, increasing losses, etc [1].

And this is why FCLs come to this aspect. In short, the need for the FCL is to protect costly, underrated equipments [4]. In general, all the proposed FCL strategies are based on inserting high impedance in the series path when a fault occurs, and only the procedures are different [1]. Normally, the desired specifications of an ideal FCL are:

1. Having very low impedance in the normal condition of power system
2. Inserting high impedance when a fault occurs
3. Fast operation to restrict DC component of fault current
4. Having capability for multiple operation in a short time and self recovery
5. not to insert harmonics in power systems
6. Preventing transient over voltage as far as possible.
7. Having a high reliability

II. RELIABILITY OF FAULT CURRENT LIMITERS

According to the above discussions, generally two major reasons can be considered for FCL application in a substation:

1. To avoid the costly solution of replacing the installed breakers by the ones with higher short circuit capability.
2. To keep substation topology and avoid bus splitting because of operating or reliability issues.

Unfortunately, the authors couldn't find a reliable source or reference about FCL's reliability characteristics so in this research we try to analyze this problem by considering the technological characteristics. Some FCLs have a very complex technology and this may lower their reliability characteristics. There are various kinds of FCLs among them resonance link and super conductive FCLs are more famous.

A. resonance link FCL

Up to now many configurations for resonance link FCL have been proposed. They can generally be categorized in *Series Resonance Link FCLs* and *Parallel Resonance Link FCL*. Resonance Links have many good characteristics for fault limiting application. Some of them are:

- action without current interruption
- fast reaction to the fault
- able to carry short circuit current for the fault duration
- resetable

Resonance link FCLs are typically constructed of many parts. The overall reliability of the FCL is dependent on correct operation of its components. Furthermore, some of Resonance Link FCLs need an external device for triggering. This means that additional parts are needed to sense the short circuit and perform triggering and this makes the functionality of the FCL more complicated, hence less reliable. It is, therefore, clear that self-triggered FCLs are more reliable.

B. Superconductive FCLs

In contrast to resonance link FCL, super conductive FCLs don't need many parts and are self-triggered. The fault limiting strategy and procedure are very simple and are based on the natural behavior of super conductive materials.

As we know, super conductivity exists only in very low temperatures and because of this, the super conductive FCLs need additional devices for refrigerating and this needs extra investment that makes this technology very expensive. However in this paper we don't see the problem from the commercial point of view and the concept presented in this paper is only limited to evaluate the effects of a FCL application on the transmission substation reliability.

III. FAILURE MODES OF FCLs

Like other parts in a high voltage substation, FCLs have different failure modes which should be considered in reliability evaluation of transmission substations containing FCL. In this section, we're going to compare different kinds of FCLs from the failure rate point of view. In general, there must be a basic relationship between the reliability of a complete system and the number of sub-systems which must operate properly in order to achieve the desired total function [4].

A. Active Failure Modes

Some failure modes of FCLs are active failure modes and cause the change in the status of other apparatus. For example, an internal short circuit in FCL is considered as an active failure and the protection system must respond to it.

FCL, regardless to the type, is a high-tech apparatus that usually is made very carefully and well-constructed. So, this device is very well insulated and failures like short-circuit are very improbable.

B. Passive Failure Modes

Another failure mode is malfunction mode that means unnecessary action of FCL, inserting high series impedance when there is no fault. This failure is referred to a *Passive failure* because it doesn't affect the status of other parts. This failure can occur because of malfunction of the triggering system (in external triggered FCL) or because of transient high currents when the device setpoint is not properly adjusted.

Passive failures are more common in super conductive FCLs. The most probable failure mode for a super conductive FCL is failure in the cooling system. Cooling system is an external device which has a modern technology that should be kept working continuously and without interruption to achieve enough low temperatures. Higher operating temperatures (HTS)[1], perhaps approaching that of liquid nitrogen, would soften utility opposition to deploying cryogenic systems and greatly improve cryo system reliability. The current reliability associated with cryocooler / reliquifier is another area of

[1] High Temperature Superconductivity

concern, as they may have problems during hot summer weather. The design must be extremely reliable for operation in unmanned substations.

C. Stuck Failure Modes

Another failure mode associated with a FCL, is stuck failure mode in which FCL will not react when a fault occurs. So, it doesn't insert any impedance into the fault path and fault current is not restricted. Such failure is extremely fatal as the circuit breakers are not able to interrupt the unlimited fault current. Generally 3 reasons can be considered for this failure:

1. Mistake in adjusting the activating current level.
2. Failure in triggering system (External triggered FCLs only)
3. Failure in responding to the activation signal

It's clear that those FCLs which need triggering system (external triggered FCLs) have a higher stuck mode occurrence rate. In general, every FCL employing a triggering system or commutation involves sequential operation of multiple switching devices, carefully synchronized and coordinated with other difficult functions. Device complexity is therefore substantially greater than those of conventional circuit breakers [4]. In resonance link FCLs (both external and self–triggered), stuck failure mode can occur because of changes in resonance component characteristics. Changes in characteristics are due to variations in operating conditions like temperature. Working in unrated conditions may also result in change in characteristics.

Stuck failure mode is not a problem in superconductive FCLs. A superconductive FCL may have stuck failure mode only if it is over-cooled. This condition does not normally happen. So, it can be said that super conductive FCLs don't have this failure mode at all. In most cases, the superconductive FCL can be designed with predictable parameters and can withstand thousands of activation and recovery cycles. In addition, using a smaller FCL instead of a big one, can increase both reliability and limiting capability [3,4]. Table I shows a brief comparison between the rate of different failure modes among various kinds of FCLs.

IV. SUBSTATION STRUCTURE

The sample substation shown in the picture below is used to assess the impacts of implementing FCL on substation reliability. As we know, use of Bus-sectionalize circuit breaker in order to manage the protection plan and improve the flexibility of substation configuration in case of repair and maintenance process is very common. If the fault current level of the substation is over than the interruption capability of the circuit breakers, replacing this bus-sectionalize circuit breaker with a FCL can be a solution. In fact, Inter-Bus is one of the most interesting application of FCL.

TABLE I.
Rate of occurrence of different failure modes

TYPE	FAILURE RATE		
	Active failure λ_a	Passive failure λ_p	Stuck probability P_c
Ex.trig. resonance link	Low	Medium	high
Self-trig. Resonance link	Low	low	low
Super conductive	Low	Medium	very low

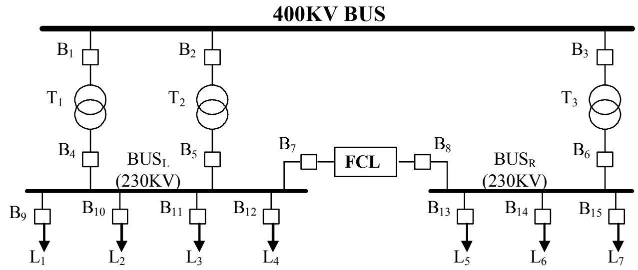


Fig. 1. A sample substation

V. STUDY RESULTS

In our analysis all the loads connected to each one of the 230KV buses are assumed identical. Hence, we focus on the reliability assessment of the Load #1 at the left 230KV bus, and Load #5 at the right 230KV bus. Reliability of the loads is expressed using the following indices:

1. loss of load probability (λ)
2. annual outage time (U)

We consider 400KV bus fully reliable. In order to skip unnecessary calculation, we do not consider failure modes containing more than 3 simultaneous failed components. Since the rate of such failure modes is very small, this assumption doesn't create noticeable error.

Table II shows the failure rates and repair time of the components. For the first step, reliability indices associated with the left 230KV bus are calculated. For wise and complete comparison we have to calculate reliability indices for load points L_1 to L_7. But since the loads are similar and connected to the same bus they will have similar failure modes. So we only calculate indices for load point 1 (L_1) on the left bus and for load point 5 (L_5) on the right bus.

TABLE II
Failure rates and repair time of the components

Device	λ_p [f/yr]	Switching time [hour]	λ_a [f/yr]	Repair timr [hour]	P_c [f/yr]
B_1, B_3, B_5	0.001	3	0.004	15	0.004
T_1, T_2, T_3	0.001	2	0.001	200	-
B_2, B_4, B_6	0.0001	1	0.0009	10	0.001
B_7, B_8	0.0001	1	0.0009	10	0.001
$B_9 - B_{15}$	0.0001	1	0.0009	10	0.001
BUS_L, BUS_R	-	3	0.000001	300	-
FCL	0.00009	-	0.00001	50	0.0

As stated above we use two probabilistic indices for our analysis: loss of load probability (λ) in [f/yr] and annual outage time (U) in [hrs/yr].

For a single failed component we have:

$$U = \lambda \times T_r \tag{1}$$

The equivalent failure rate (λ_{eq}) , average outage time (T_O) and annual outage time (U_{eq}) for the case of second simultaneous outages are expressed below:

$$\lambda_{eq} = \lambda_1 \times \lambda_2 \times (Tr_1 + Tr_2) \tag{2}$$

$$T_O = \frac{Tr_1 \times Tr_2}{Tr_1 + Tr_2} \tag{3}$$

$$U_{eq} = \lambda_{eq} \times Tr_{eq} = \lambda_1 \times \lambda_2 \times Tr_1 \times Tr_2 \tag{4}$$

And for third level of simultaneous outages we have:

$$\lambda_{eq} = \lambda_1 \times \lambda_2 \times \lambda_3 \times (Tr_1 \times Tr_2 + Tr_2 \times Tr_3 + Tr_1 \times Tr_3) \tag{5}$$

$$T_O = \frac{Tr_1 \times Tr_2 \times Tr_3}{Tr_1 \times Tr_2 + Tr_1 \times Tr_3 + Tr_2 \times Tr_3} \tag{6}$$

$$U_{eq} = \lambda_{eq} \times Tr_{eq} = \lambda_1 \times \lambda_2 \times \lambda_3 \times Tr_1 \times Tr_2 \times Tr_3 \tag{7}$$

Considering all the failure modes, Total failure rate and Total annual outage time can be calculated as follows:

$$Total\ \lambda = \sum_{i=1}^{N_f} \lambda_{eq_i} \tag{8}$$

$$Total\ U = \sum_{i=1}^{N_f} U_{eq_i} = \sum_{i=1}^{N_f} \left(\lambda_{eq_i} \times T_{O_i}\right) \tag{9}$$

Table III shows the result of reliability analysis for load 1.

Table III
Results of Load point 1

Interruption rate (λ) [per yr]	Repair time (R) [hr]	Total annual interruption [hr/yr]
0.0221186	5.24713	0.116059

Now, the same calculation is done for the lines on the other 230KV bus. Table IV shows the results associated with load point L_5.

Table IV
Results of Load point 5

Interruption rate (λ) [per yr]	Repair time (R) [hr]	Total annual interruption [hr/yr]
0.0210205	6.69293	0.140689

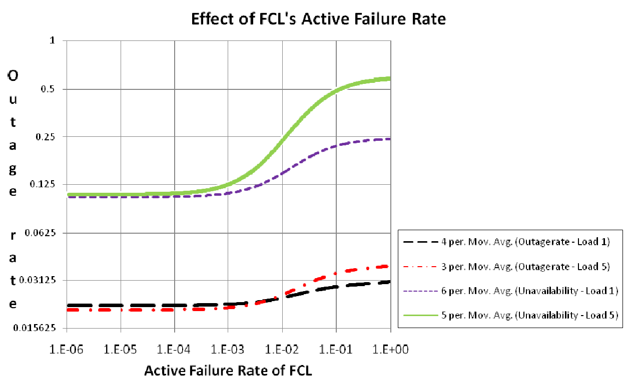


Fig. 2. Impacts of FCL's active failure rate on reliability indices of the loads

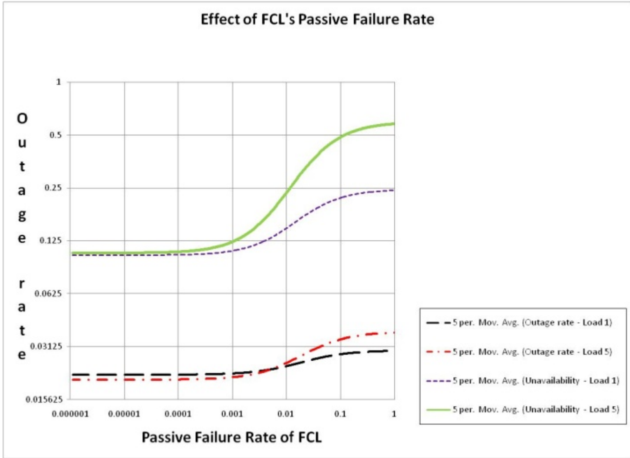


Fig. 3. Impacts of FCL's passive failure on reliability indices of the loads

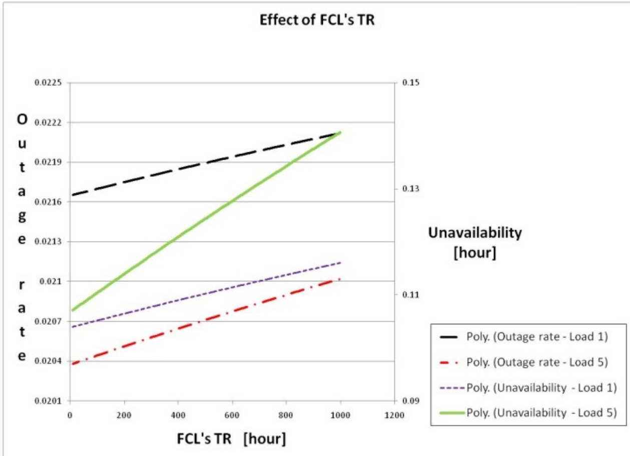


Fig. 4. Impacts of FCL's repair time on reliability indices of the loads

VI. CONCLUSION

Application of fault current limiter in substation reliability enhancement was presented in this paper. The mathematical model and the procedure used in reliability calculations were explained. The proposed procedure was applied to a sample substation. The results of the investigations carried out to assess the impacts of FCL application on substation reliability. The results presented indicate that the substation reliability is improved by implementing FCL. A sensitivity analysis was conducted to examine the impacts of various parameters such as FCL active failure rate, FCL passive failure rate and FCL repair time on the reliability indices.

VII. REFERENCES

[1] J. Cerulli, "Requirements for a Superconducting Fault Current Limiter in the Utility Bus-Tie Location", *Power Engineering Society*, Winter Meeting, IEEE, Vol. 2, 31, pp. 950 – 955, Jan-4 Feb 1999.

[2] E. M. Leung, "Superconducting Fault Current Limiters", *Power Engineering Review*, IEEE, Vol. 20, Issue 8, pp. 15 - 18, 30, Aug. 2000.

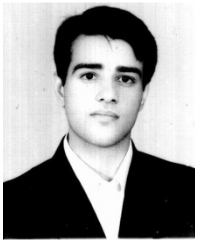
[3] Attila Gyore, Sandor Semperger, Laszlo Farkas, Istvan Vajda, "Improvement of Functionality and Reliability by Inductive HTS Fault Current imiter Units", *IEEE Transactions on Applied Superconductivity*, Vol. 15, No. 2, June 2005.

[4] P. Barkan, "Reliability Implications in the Design of Fault Current Limiters", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, No.5, Sept/Oct 1980.

[5] M.Takasaki, S.Torii, "Performance Verification of a Practical Fault, Current Limiter using YBCO Thin Film, *IEEE Transactions on Applied Superconductivity*, Vol. II, No I , MARCH 2001.

[6] Lin Ye, "Behavior Investigations of Superconducting Fault Current Limiters in Power Systems", *IEEE Transactions on Applied Superconductivity*, Vol. 16, No. 2, June 2006.

VIII. BIOGRAPHIES



Iman Rahmati was born in Tehran, Iran on September 2, 1980. Obtained B.S. from Tehran Water & Power Institute of Technology in 2003, and M.S. from Tabriz University in 2005. His special fields of interest include Power system reliability, Ancillary services and Power System Restructuring. Presently he is head of Market Design & Development group of Ministry of Energy of Iran. He also has affiliation with the secretariat of Iran Electricity Regulatory Board since 2004.

Mahmud Fotuhi-Firuzabad (SM'1999) was born in Iran. Obtained B.S. and M.S. Degrees in Electrical Engineering from Sharif University of Technology and Tehran University in 1986 and 1989 respectively and M.S. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan in 1993 and 1997 respectively. Presently he is head of the Department of Electrical Engineering, Sharif University of Technology. Dr. Fotuhi-Firuzabad is a member of Center of Excellence in Power System Management and Control in the same department.