

White paper on Fault Current Limiters (FCL's) – Impedance study of FCLs in relation to increase in power generation of the system.

Prepared by Olsen Rodrigues and Victor Temple – May 26th 2009

Abstract

This paper describes the functioning of the FCL and the amount of series impedance needed to limit fault current. Typically the FCL impedance needs to limit fault current value down to a level for circuit breakers to safely interrupt. This impedance increases as source impedance decreases, i.e. more power generation is added in the source to meet load demand. Therefore an FCL is designed keeping in mind the projected increase in generation and allowing for increasing FCL impedance over a period of time. One case we will go into in detail is a projected doubling of generation coupled with a doubling of short circuit current.

Introduction

Fault current limiters (FCL) are used in power lines to protect circuit breakers in event of a short-circuit fault on power lines. Different technologies have been employed to design FCLs such as turn-off of a solid state switch to using superconductors that respond with increasing resistance in event of fault current.

In this paper, we are concerned with the operation of FCLs and the amount of impedance they are required to insert in series with the transmission line. In its normal mode of operation, it behaves like a switch turned ON so as to appear like a transmission line. Whenever a fault occurs downstream of this line, the FCL switch is opened and in its place a series impedance is inserted to limit the fault current to an acceptable value that downstream circuit breakers can handle to trip.

Since FCL's are installed in each phase of the line, the fault is viewed in perspective of per phase. For the purposes of this study, we consider phase to ground fault and phase to phase fault scenarios.

Case study of a line to ground fault in a transmission line

Consider Fig. 1, in which many power generating sources (represented by the single generator with equivalent source impedance) connected to a 69kV three-phase transmission line through a Delta-Wye transformer, that feeds a static load. This is a general representation of a tie between two networks, into which an FCL can be placed. This tie line has a per phase to ground short circuit fault current of 40kA due to existing generation at the source, which is within the capability of the system fault control

equipment (breakers, transformers, etc.). Mid-section in this diagram, the single line is transformed into a three-line diagram to highlight the phase undergoing fault. The source impedances of all generating stations collectively determines the fault current value. It is possible, then, from additional generators added to meet ever increasing load demand, that the source impedance of the line could be significantly reduced, therefore leading to higher fault currents. The occurrence of a fault downstream can then lead to currents that exceed the ratings of currently installed 40kA rated circuit breakers. It is then necessary that the utility replace these breakers with those of higher short circuit current ratings to avoid long term outage of the line. All this comes at an increased operational cost to the utility company. By inserting an external impedance into the line, during fault, the short circuit current is brought down to a value that can be safely interrupted by the existing circuit breakers without having to replace them. This series impedance can be introduced incrementally into the line, depending on the condition of the source impedance of the line, i.e. whenever additional generation causes the source impedance to fall, increasing values of series impedance in the FCL can be inserted to match the fault current to the safe limit.

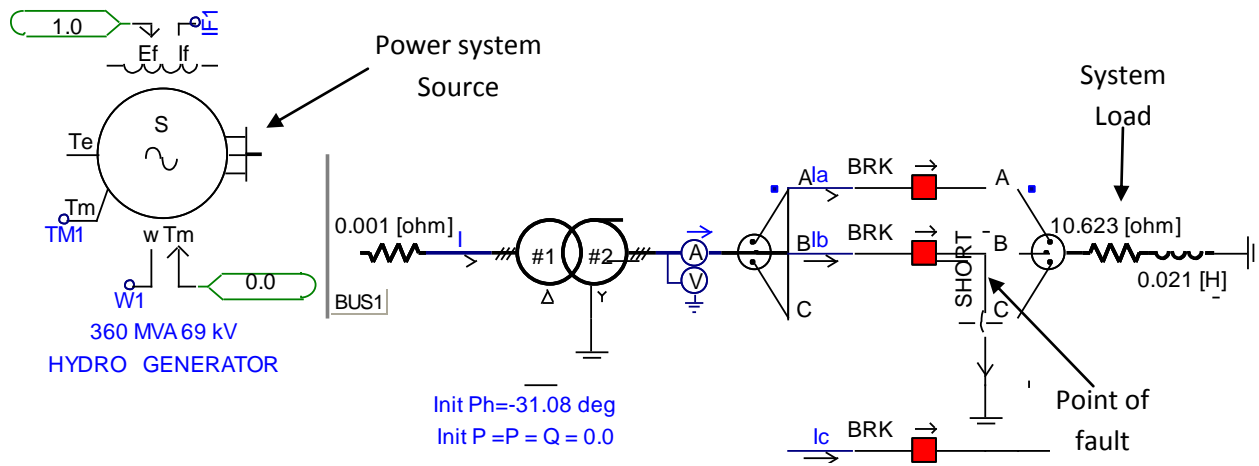


Fig. 1 – Diagram of a tie-line with a source and load and point of line-to-ground fault in the system.

It is calculated that the system impedance of this line is $\frac{69kV}{\sqrt{3} \cdot 40kA} = 1\Omega$. Suppose the generation to this line is increased by 25%. We then have a short circuit current of 50kA and the source impedance is 0.8 Ω . Since this is beyond the SC rating of the breaker in place, the FCL would then have to insert an impedance of 0.2 Ω to limit the current back to 40kA.

The following table shows the decrease in source impedance and incremental FCL impedance needed to limit to 40kA, depending on percentage increase in generation.

	Fault current (kA)	Source Impedance (Ω)	Impedance to be added (Ω)
Existing generation	40	1.0	0
25% increase	50	0.8	0.2
50% increase	60	0.667	0.333
100% increase	80	0.5	0.5

Table. 1

Fig. 2 shows the vector diagram of impedance, that displays the amount of impedance to be added for the increase in generation highlighted in the table above. Z_f is the original source impedance for the 40kA fault current. Z_{s1} , Z_{s2} , Z_{s3} corresponds to source impedance of 50kA, 60kA and 80kA and Z_{a1} , Z_{a2} , Z_{a3} corresponds to the limiting impedance required in these three cases. The resultant impedance as shown for these cases is exactly equal to the magnitude of the original source impedance, an arc is drawn with center at origin and at same radius to show this. Since resistance R is very small compared to the reactance X , the resistance scale is expanded many times to show the slight differences in load angle of the resultant impedance. Here series resistance R is very small, close to zero. So the R scale is expanded many more times compared to X . Figs. 3,4 and 5 show how the short-circuit current is reduced with respect to the prospective fault current of the system for the 3 cases.

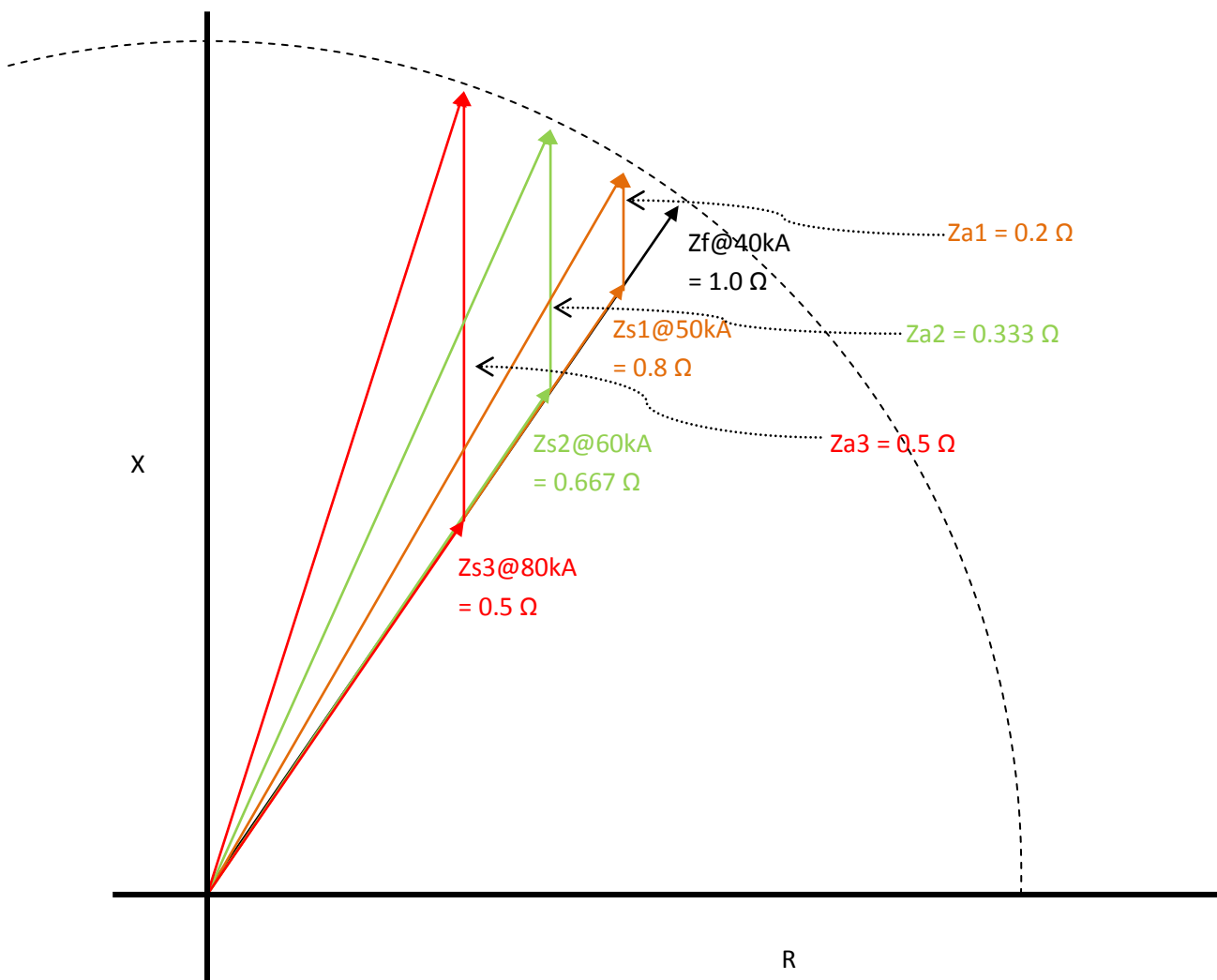


Fig. 2 – Vector diagram of impedance for the values of fault current shown in Table 1

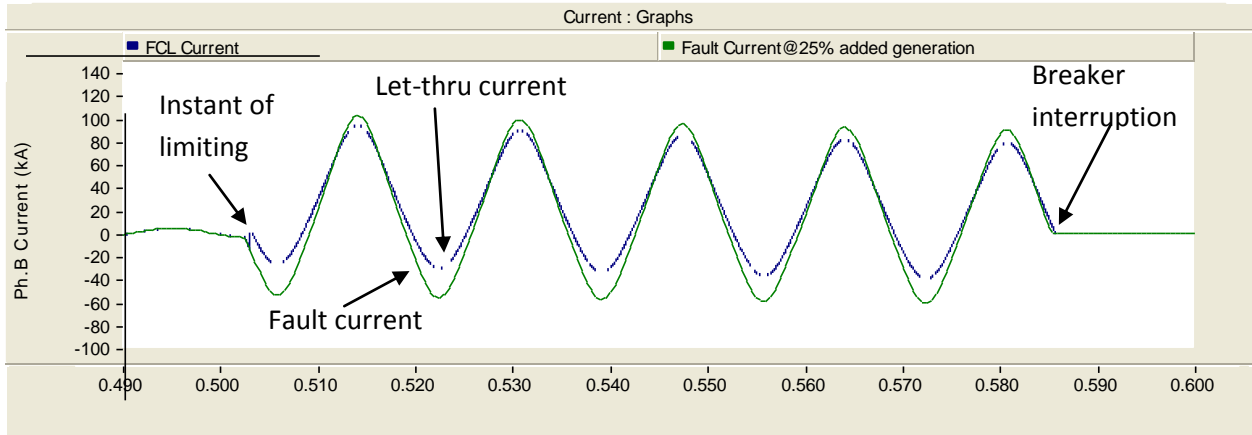


Fig.3 – for 50kA fault current with and without inserting a 0.2Ω FCL impedance.

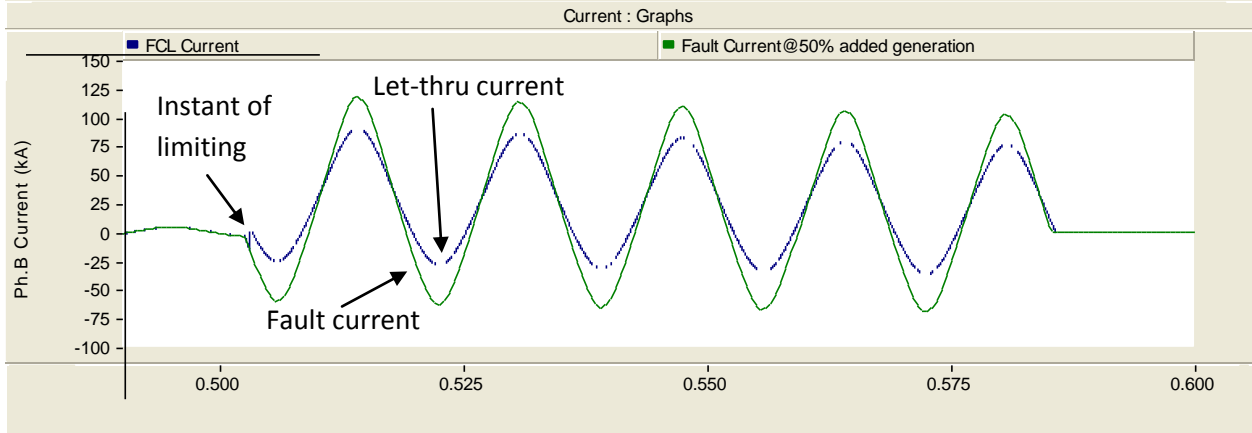


Fig.4 – for 60kA fault current with and without inserting a 0.33Ω FCL impedance.

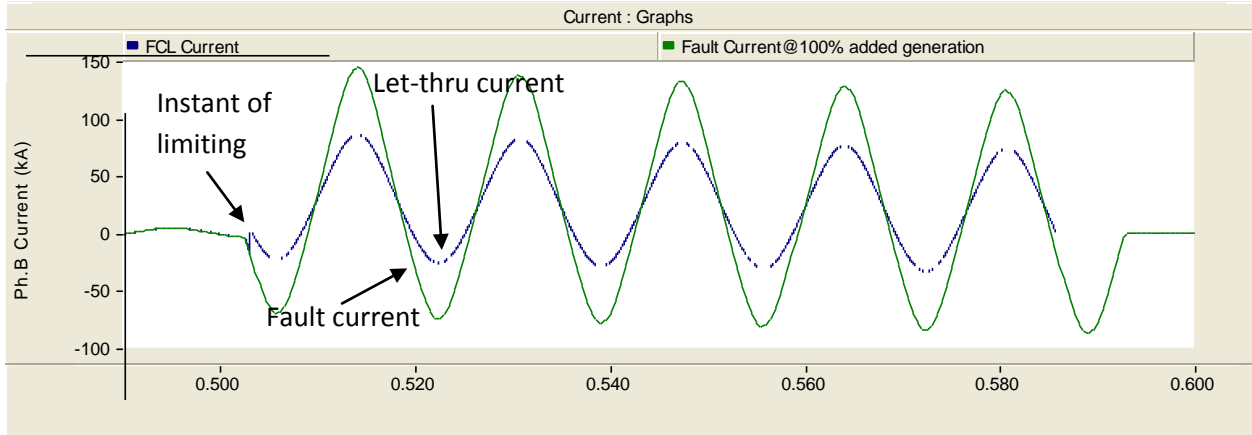


Fig.5 – for 80kA fault current with and without inserting a 0.5Ω FCL impedance.

Case study of a line to line fault in a transmission line

Consider Fig. 6 in which case there is a line-to-line fault downstream of the circuit breaker. In this case both breakers on phases B and C have to trip. Then, knowing the system impedance, the fault current in these two phases is $\frac{69kV}{(1+1)\Omega} = 34.5kA$.

The following table shows the decrease in source impedance and incremental FCL impedance needed to limit to 40kA, depending on percentage increase in generation.

	Fault current (kA)	Source Impedance (Ω)	Impedance to be added (Ω)
Existing generation	34.64	2.0	0
25% increase	43.3	1.6	0
50% increase	51.96	1.334	0.2
100% increase	69.28	1.0	0.333

Table 2

Suppose the generation to this line is increased by 25%. We then have a short circuit current of 43.3kA and the source impedance is 1.6 Ω . Theoretically, no series impedance need be added to limit fault current. However, since the FCL is configured to limit 50kA line to ground fault current, an impedance of 0.2 Ω is inserted anyway. This limits fault current to 34.64kA. This is because the FCL limiting impedance inserted was based on the worst-case scenario which is the line-to-ground faults. Fig. 10 shows the vector diagram of impedance for the line-line fault case.

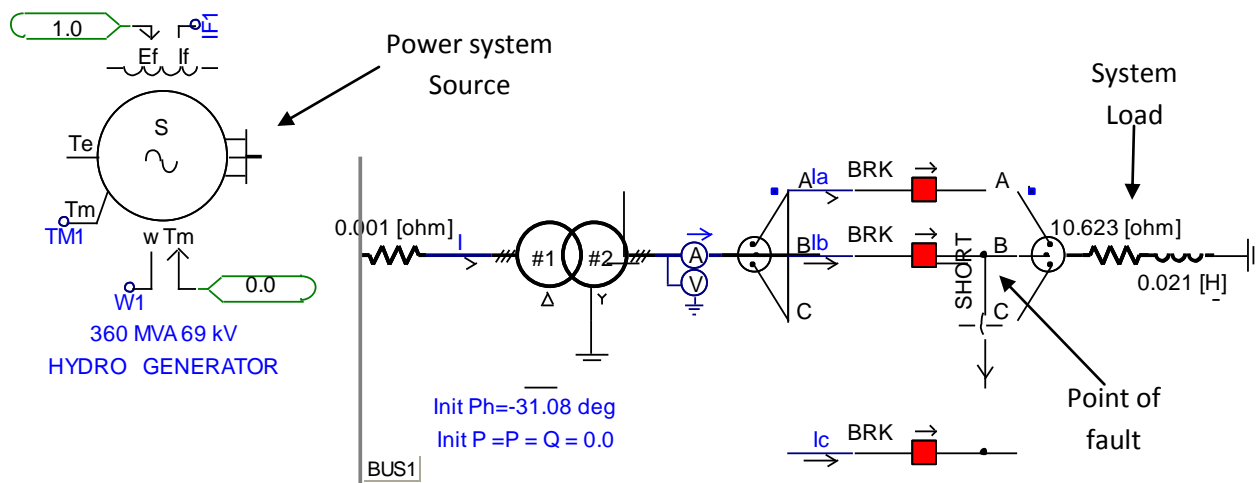


Fig. 6 - Diagram of a tie-line with a source and load and point of line-to-line fault in the system.

Modular level based fault current limiter

FCL's are modular series blocks of AC switches. Each AC switch or level is capable of turning OFF and transferring short circuit current to a parallel impedance by itself. The required FCL impedance to be inserted can be broken down into a number of smaller blocks of inductors in series, each of which is in parallel to the level AC switch. Each level consists of a limiting inductor that has a solid-state switch in parallel that is turned ON to behave like a transmission line and turned OFF during fault to transfer the short circuit current to the inductor. The level also has 4 parallel varistors to clamp overvoltage across the switch during turn-off.

For each level, we look at the varistor's ability to clamp at a certain energy rating. Consider the case if there is 80kA fault in the system. That means from the above table that we need to insert 0.5Ω or 1.326mH into the system. If we fix the number of levels at 12, then the inductance per level is 110.5μH. In order to justify the amount of levels needed, we look at the voltage across inductor and see if the varistor ratings can match this. Each varistor has a rating of 3800J at 2ms and a clamp voltage of 3200V at 1000A. Therefore, time taken to clamp during turn-off of 6000A is, $t = \frac{110.5\mu H}{3200V} 6000A = 207\mu s$.

So, energy during turn-off is $E = \frac{6000A}{4} * 3200V * 207\mu s = 995J$ at 207μs., which is well within the ratings of the varistor. Also for 39kV phase to ground voltage, the FCL drops about 20kV in this case, which means each level blocks 2357V per level. At this voltage, the varistor conducts ~ 100mA of current, according to the specifications and is practically an open circuit compared to the let through current through the level inductor.

Since is desirable to have redundancy in the system, in case of failed levels in the FCL system, we choose to have N+4 redundancy. This will round off the total number of levels to 16.

It then follows that at different increases in generation, one or more installed levels might well be shorted by replacing the level inductor by a bypass, while still maintaining the ability to introduce sufficient impedance to limit to 40kA let-thru current. We can then have, for a 16 level FCL installed at a substation, the following amount of levels to be functional for effective current limiting as shown in table below.

	Fault current (kA)	Source Impedance (Ω)	Impedance to be added (Ω)	Functional Levels required
Existing generation	40	1.0	0	None
25% increase	50	0.8	0.2	5+4
50% increase	60	0.667	0.333	8+4
100% increase	80	0.5	0.5	12+4

That means for a 25% increase in generation at the line, 5 active levels would be sufficient to reduce the let-thru current below 40kA. It would be conceivable that until we had more than a 50% increase in generation that a single 10-level stack be all that we install, which would give us an N+5 design at 25%

increased generation and an N+2 capability at 50% increased generation. Even at 100% increase in generation the appropriate series levels we require for an N+3 design is only half a stack (5 levels).

Conclusion

With increase in generation, comes an increase in short-circuit current in a transmission line during faults. Utilities usually predict how much fault current exists in the line and can forecast its increase over a period of time. By controlling the amount of impedance introduced in the line, we can say that a modular level based FCL can insert required impedance depending on existing fault current conditions on the line. This would reduce the number of levels needed to limit current. Additional levels can be incrementally added whenever line conditions change that reflect higher short circuit current values. The result is a lower cost system that is smaller and has much lower losses.