Analysis of Unexpected Fault Current Limiter Operation using EMT Programs

M. S. Hibbert, *Connell Wagner PPI (Australia)*, K. S. Smith, *Mott MacDonald (UK)*

Abstract: The need for high security of electricity supply, common to many large industrial process plants, often results in the interconnection of a number of systems supplied by high capacity transformers. This can give rise to prospective fault currents which exceed existing circuit breaker ratings. One means of reducing fault currents is to use Fault Current Limiters (FCLs). These devices are designed to separate parts of the network when a fault occurs.

Unexpected operation of FCLs has been identified in the 11 kV distribution network of a mineral processing plant. To investigate this a full time domain model of the electrical system including the FCLs has been developed using ATP. Independent verification of the modelling approach was achieved by implementing an equivalent model using the PSCAD-EMTDC software. Extensive studies identified that fault initiation transients caused high di/dt values that, in conjunction with the complicated current summation tripping logic, resulted in unexpected tripping of one of the FCLs under certain conditions.

A number of alternative solutions were considered and simulated to determine if satisfactory operation could be expected. The chosen solution involved a network reconfiguration, the relocation of two reactors, and the installation of three additional FCLs. This enabled simpler tripping criteria to be adopted, which prevents the fault initiation transients from causing spurious trips.

The study demonstrates the benefits of using powerful simulation tools such as EMTP/ATP and PSCAD-EMTDC for analysing complex power systems and identifying the causes of problems that are generally impractical to find by normal measurements due to the need to capture information during faults.

Keywords: Fault current limiter (FCL), current limiting fuse, ATP, EMTP, PSCAD-EMTDC, fault level studies, transients, fuse modelling.

I. Introduction

Many large industrial processes have evolved from smaller establishments via staged expansions.

The distribution networks required to provide electricity to these plants are usually expanded by the addition of extra transformers. This gives rise to prospective fault currents that can exceed circuit breaker fault current ratings. In industrial applications it is usually the first peak of the fault current that presents the most onerous condition due to the contribution from many connected motors.

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Three common methods are used to avoid excessive fault currents, namely: i) split the system into groups of two or three transformers (depending on size), ii) replace switchgear with higher capacity equipment, and iii) utilise current limiting reactors. These options have disadvantages that in some cases are costly to overcome. For example: if a four transformer system with N-1 capacity is split into two pairs of transformers, each pair will be exposed to an N-1 load that is 50% greater than the rating of one transformer. Hence splitting a system that is already loaded to capacity often also requires the purchase of larger transformers to replace the now undersized units. Replacement of switchgear also has a cost implication, but more often than not replacement requires a prolonged shut down to part of the plant, and the cost of lost production can greatly exceed the capital cost of new plant.

The use of current limiting reactors is a common method of reducing fault levels. However the voltage drop across the reactor can often result in unacceptable voltage levels under certain operating configurations, for example operation with a transformer out of service where that transformer's load is supplied through a reactor.

A less commonly used alternative method of reducing fault levels is to employ FCLs.

II. Fault Current Limiter Operation

Fault current limiters are devices that are designed to separate parts of the network when a fault occurs. They are fast operating devices that commence operation within the first few milliseconds after a fault, and limit the first peak of the fault current to acceptable levels.

Fault current limiters consist of current limiting fuses operated in parallel with explosible links. The explosible link may be constructed from a brass tube fitted with an explosive charge. The tube is appropriately fissured to control its bursting performance, and is employed to carry the normal load current of the device. The construction and operating characteristics of this type of FCL are described in [1]. An alternative form of explosible link consists of a segmented copper bar, again appropriately fissured, which separates into a number of segments, again by the triggering of an explosive charge. This type of FCL is illustrated in [2].

On detection of a fault meeting the tripping criteria, the charge is detonated separating the explosible link, thus leaving only the current limiting fuse in the circuit. The fuse then operates separating the two parts of the network, effectively limiting the first peak of the fault current to that generated by the source on the faulted part of the network plus the let through current of the fuse. The principle of operation of current limiting fuses is well known and will not be expanded on here. It is understood, however, that the detailed design aspects of current limiting fuses for this application are somewhat different to those used for typical applications. In particular, for this application the rating of the fuse element is significantly smaller than the normal load current expected to be carried by the FCL, thus ensuring rapid operation.

III. Application of Fault Current Limiters

Fault current limiters were used in an industrial plant to manage fault levels after an expansion added two new 47 MVA 132/11 kV transformers to an existing four transformer system as shown in Fig.1. The addition of extra reactors to the system, which already had one reactor connecting each transformer to a common bus, was not practical due to the size of reactors that would be required, and the resulting voltage drops under transformer out conditions. Instead, two reactors were replaced with FCLs and a third FCL was installed in the tie cable to the new switchboard (busbars E, F and G).

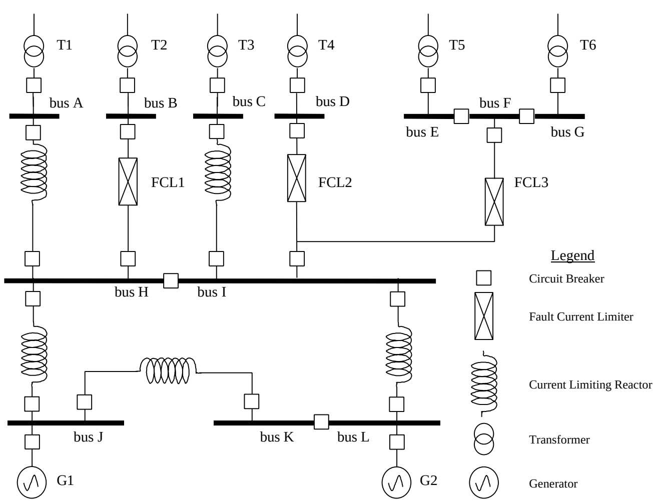


Fig. 1 Application of Fault Current Limiters

Two 12.5 MW steam turbine driven 11 kV generators also supply the system as shown, and fault current contribution from approximately 90 MW of connected motor load also added to the high prospective fault levels.

IV. Spurious Operations

The FCLs were configured to operate as shown in Table I. Since commissioning of the FCLs incorrect operation for faults on bus B and bus D had been experienced. In both cases FCL 3 operated but was not required to operate. The cause of these spurious operations was investigated.

V. Modelling Approach

The postulated cause of the spurious operations was transients interfering with the di/dt sensing. Review of [2] corroborates this theory, and hence a time domain model of the system was required to analyse the system in the first half cycle after fault initiation. References [3] and [4] provided some useful information on modelling of current limiting fuses, and after reviewing these it was decided to model the FCL using the Alternative Transients Program (ATP) software.

TABLE I CONFIGURATION OF FAULT CURRENT LIMITERS

Faulted Bus		**Fault Current Limiter Operation**		
Bus Name/Rating		**FCL 1**	**FCL 2**	**FCL 3**
Bus A	26 kA	No	No	Yes
Bus B	26 kA	Yes	No	No
Bus C	40 kA	No	No	Yes
Bus D	26 kA	No	Yes	No
Bus E	40 kA	No	No	Yes
Bus F	40 kA	No	No	Yes
Bus G	40 kA	No	No	Yes
Bus H	40 kA	Yes	Yes	Yes
Bus I	40 kA	Yes	Yes	Yes
Bus J	26 kA	No	No	Yes
Bus K	26 kA	No	No	Yes
Bus L	26 kA	No	No	Yes

A. Basic FCL Model

The explosible link was modelled using a type 12 switch (refer to [5] for details) which is controlled by a logical variable, and allows current chopping at any point in the waveform. The current limiting fuse element was modelled using a type 91 piecewise linear time varying resistor with a non-linear characteristic, which started its characteristic after the voltage across it exceeded a nominated value. As it was known that the design of the current limiting fuse element of the FCL was different to that of a standard current limiting fuse, it was decided that the characteristic should be derived from test data of these fuse elements. Oscillogram traces from [6] were studied and transposed to a spreadsheet where the non-linear characteristic was derived by simply dividing the voltage characteristic by the current characteristic. The resulting characteristic was similar to that shown in [4], although more approximate in the first two milliseconds, and is given below in Fig. 2, with the characteristic values following in Table II.

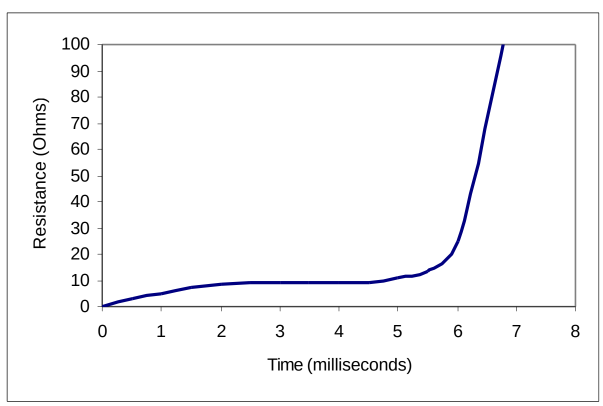


Fig. 2 Non-Linear Resistance Characteristic of Fault Current Limiter Fuse Element

TABLE II NON-LINEAR RESISTANCE CHARACTERISTIC

Time Milliseconds	Resistance Ohms
0	0.0025
0.5	2.94
1.0	4.71
1.5	7.06
2.0	8.24
2.5	8.82
3.0	8.82
4.0	8.82
4.5	9.01
5.0	11.18
5.5	13.53
6.0	25.00
7.0	125.00
8.0	250.00
8.5	375.00
9.0	500.00
10.0	1,000.00

A simple single phase network model was established to test the proposed FCL model, which in its simple form is shown below in Fig. 3.

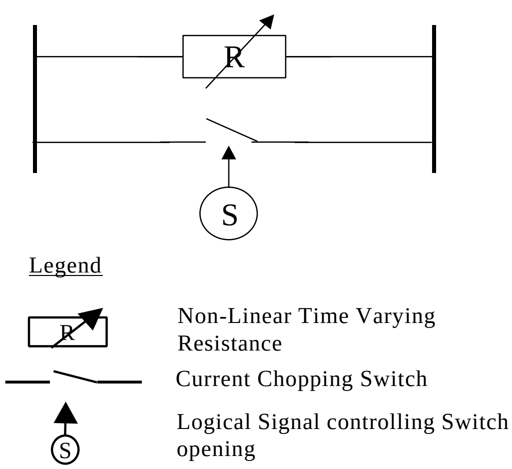
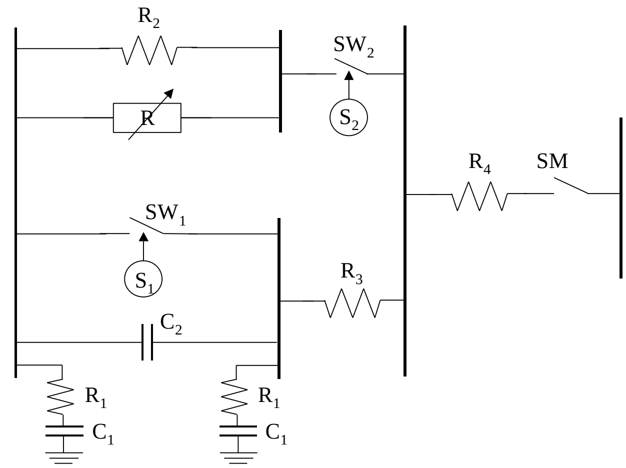


Fig. 3 Initial Fault Current Limiter Model

While this model worked, it suffered two drawbacks. Firstly the operation of the current chopping switch gave rise to a significant voltage spike and subsequent numerical oscillations. Secondly the non-linear resistor would allow current flow to continue past the current zero for certain switching scenarios. Modifications were made to overcome these problems and damp out the oscillations, resulting in the final model shown in Fig. 4. Switch SW_1 represents the explosible link and is triggered as soon as the tripping criteria are met. Switch SW_2 is used to interrupt the current through the time varying non-linear resistor as soon as it crosses the zero axis. This model resulted in acceptable results producing characteristic voltage and current waveforms similar to those presented in [3], as shown below in Fig. 5.



Legend

R_1	5 Ohm damping resistors
C_1	4 nF damping capacitors
R_2	10,000 Ohm damping resistor
C_2	0.6 µF spike damping capacitor after transition through current zero
R_3 & R_4	0.0001 Ohm resistors used for separation of switches
SM	permanently closed measuring switch

Fig. 4 Final Fault Current Limiter Model

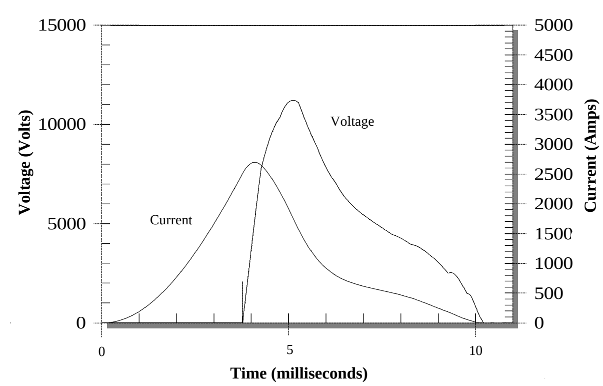


Fig. 5 Fault Current Limiter Simulation Result

B. Tripping Criteria

The MODELS subprogram was used to simulate the tripping criteria which were obtained from [7]. It should be noted that reference [7] is a confidential report to the client and is not available to the public, however similar information can be found among the references given in [1]. The tripping criteria were fairly complex, and are given below for FCL 3:

i) the instantaneous value of the current through FCL must be between nominated high and low gateway settings
ii) the absolute value of the time derivative of the current through the FCL must be above the nominated di/dt trip setting for the FCL
iii) the absolute value of the time derivative of the sum of the currents through all three FCLs must be above the nominated di/dt trip setting for the summation value
iv) all three of the above values must possess the same sign.

The satisfaction of the above four criteria will result in an operation of the FCL. This was detected using logical comparison statements in MODELS, which then triggered the operation of the current chopping switch SW_1 in Fig. 4. The piecewise non-linear time varying resistance characteristic commences as soon as the voltage across it reached 10 V (which was an arbitrary choice), and the operation of the FCL concluded when switch SW_2 in Fig. 4 opens following transition of the current through a current zero. This transition was detected using simple logic in MODELS followed by enabling of the opening signal S_2 (refer Fig. 4).

Numerical oscillations, although dampened by the resistors and capacitors R_1, R_2, C_1 and C_2, as shown in Fig. 4, were still a feature of the output waveforms. These had the potential to interfere with the correct simulation of tripping conditions. This aspect was dealt with by averaging the output every two time steps, and then operating on the averaged results in the MODELS logic to determine if the tripping criteria had been satisfied. MODELS was found to be a very powerful tool for comparing network values and their time derivatives and initiating switch opening sequences based on the results of those comparisons.

C. Network Model

The network was modelled using standard ATP components. The upstream 132 kV system was modelled as an infinite bus and three phase RLC source impedance connected to the local transmission substation via a number of overhead transmission lines. These transmission lines were represented as coupled Pi models with the matrices derived using ATP's "line constants" routine. The six star-delta 132/11 kV transformers were represented using the "BCTRAN" model, with the earthing transformers modelled using "XFORMER" (refer to [5] for details).

The generators were modelled using the Universal Machine Model UM1, assuming constant excitation and input torque, which is an appropriate assumption considering that operation over only a few cycles needs to be simulated.

All other connections in the network were by single core 11 kV cables which were represented as coupled Pi models with the matrices derived using ATP's "cable constants" routine. Motor contribution to the fault current was simulated by lumped motor models using the Universal Machine Model UM4 connected at 11 kV or at 3.3 kV and 415 V via lumped equivalent transformer (BCTRAN) models. The one peculiar feature about the plant that is worth mentioning is the fact that the cables from the transformer terminals T1 through T4 to busbars A through D respectively were approximately 200 m in length, and the tie cable between bus F and bus I was approximately 500 m in length. All other cable runs in the network shown in Fig. 1 were relatively short.

D. Model Verification

The FCL model was verified by the development of an alternative model that was implemented using the PSCAD-EMTDC software. The basic FCL representation of a switch in parallel with a variable resistance was implemented within PSCAD. Unlike the ATP model there was no need to use additional damping resistors in the PSCAD model. Numerical chatter is a time step to time step, symmetrical oscillation phenomenon inherent in the trapezoidal integration method used in the Dommel algorithm for transient simulation of electrical networks. It is usually initiated by the closing of a switch in a branch containing inductors. It does not matter if the switching occurs at a natural current zero, or elsewhere in the waveform. The PSCAD software includes a chatter detection algorithm to continuously detect such spurious oscillations and remove them if so required. It is believed this is the reason why damping resistors were not required in the PSCAD model. Chatter and its effects are discussed in Ref [8,9]. The PSCAD representation of the FCL confirmed the transient voltage and current waveforms predicted by the ATP model (as shown in Fig. 5).

The FCL tripping logic implemented in the PSCAD Continuous System Modelling Function Library was identical to that programmed using the ATP MODELS subprogram. The electrical network elements were modelled using the standard components available in the PSCAD library. The synchronous and induction machines were modelled using the PSCAD two axis models to give the correct transient fault currents.

For a number of test cases the PSCAD model was shown to behave identically to the ATP model. The asymmetric peak currents predicted by each model and the trip/no trip decisions reached by their tripping logic were the same. As both models were based on the same source data and developed independently of each other, this was taken to demonstrate the veracity of the programming of both models. The full system studies were then undertaken using the ATP model.

VI. RESULTS OF SYSTEM STUDIES

Simulations showed that spurious operation of FCL 3 could be expected for faults on bus B or D. Different phases of FCL 3 were affected depending on the point of wave at which the fault occurred. The following combinations were found to occur i) one phase only, A, B or C, ii) two phases, A and C only, and iii) under certain conditions correct operation (ie no operation of FCL 3) was seen to occur.

The cause of the spurious operation was traced to the existence of 20 kHz (approximately) current oscillations superimposed on the fault current waveform, commencing immediately after the initiation of a fault and lasting several milliseconds. An example of these fault initiation transients for one phase is shown in Fig. 6. It was clearly shown that these transients resulted in excessively high values of di/dt which were responsible for "confusing" the tripping logic.

The presence of these current oscillations at this high frequency gives rise to very high values of di/dt. This defeated the "same sign" criteria of the tripping logic as the time derivative of the current through FCL 3 and the time derivative of the sum of the currents through all three FCLs oscillated across both sides of the zero axis, and at one stage were of the same sign while all other criteria were satisfied, thus resulting in an unnecessary operation.

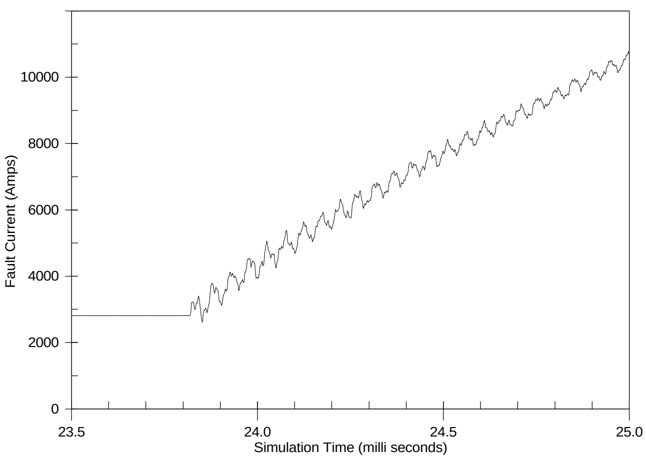


Fig. 6 Current Oscillations Following Fault Initiation

VII. SOLVING THE PROBLEM

Analysis of the factors leading to the unnecessary operation resulted in the following conclusions: i) it would be necessary to have less reliance on di/dt criteria and more reliance on instantaneous current criteria to avoid the problems caused by fault initiation transients, ii) higher tripping values would enable more time for oscillations to damp out which should make the detection circuitry more reliable, and iii) the above two conditions could not be met if FCL 3 was required to operate for faults in all buses listed in Table I.

More robust tripping criteria result if the FCL is only required to operate for faults in one particular zone. Operational requirements for the plant were also considered as were the limitation of 50 kA prospective fault current for numerous fused isolators in the network. A fault on the load side of these fused isolators, which were equipped with standard current limiting fuses, would result in the commencement of fuse melting before the detection time for FCL operation had commenced, and it was not possible to guarantee that the let through current of the FCL would not combine with the fault current from the source on the faulted side to exceed the 50 kA limitation of the downstream fuses, unless the prospective fault current was kept below 50 kA RMS. Simplification of the tripping criteria required each FCL to operate and protect one bus only, and the 50 kA limit on prospective fault current required the network to be split into three pairs of transformers. The four aged transformers vary in size from 28 to 40 MVA, and are all to be replaced with new 47 MVA units to enable N-1 capacity to be maintained.

An additional six-unit switchboard is to be installed and some reconfigurations are planned to enable different pairs of transformers to be connected together for increased security during transformer outages. The resultant system is shown in Fig. 7.

Two basic tripping configurations are required. One is shown in Fig. 8 below and applies to bus pairs A, D and B, C, both of which can be connected to the generator buses J, K and L. At the faulted bus shown in Fig. 8 the current through FCL 1 (I_2) is positive. Hence the summation current $I_S = I_1 + I_2$ is greater than the summation current at the adjacent bus, where I_5 is negative and equal to $I_4 + I_6$. This factor was used to provide an additional tripping criteria similar to a bus zone protection scheme, viz:

i) if the instantaneous value of current through the FCL is between the high and low gateway settings, and
ii) the time derivative of the current through the FCL is above its trip settings, and
iii) the time derivative of the summation of the incomer current and the FCL current is above its trip setting, and
iv) the sign of all three of the above is identical, and
v) the instantaneous value of the summation of the incomer current and the FCL current is above its trip setting.

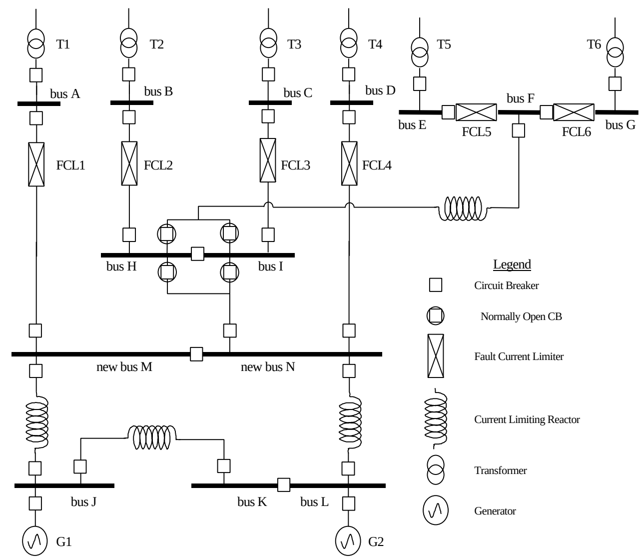
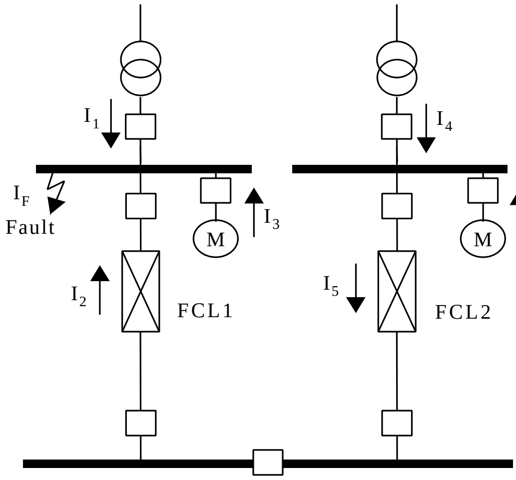


Fig. 7 Reconfigured System

If the above are satisfied, then operation of the FCL is required to occur. Without the last criterion, as I_2 and I_5 in Fig. 8 are the same, transient oscillations can result in the first four criteria being satisfied for both FCLs. The addition of the fifth criteria prevents this due to the fact that $I_5 = -(I_4 + I_6)$, and hence the sum of I_4 and I_5 will not reach the necessary instantaneous value to enable a trip to occur. The second tripping configuration applies to buses E, F and G and is shown below in Fig. 9. Fault current limiters FCL 5 and FCL 6 have similar tripping criteria to that discussed above for faults on bus E or bus G. For faults on bus F, an additional current summation tripping criteria $I_S = -I_2 - I_5 + I_8$, together with similar di/dt and instantaneous current tripping criteria, is implemented to trip FCL 6.

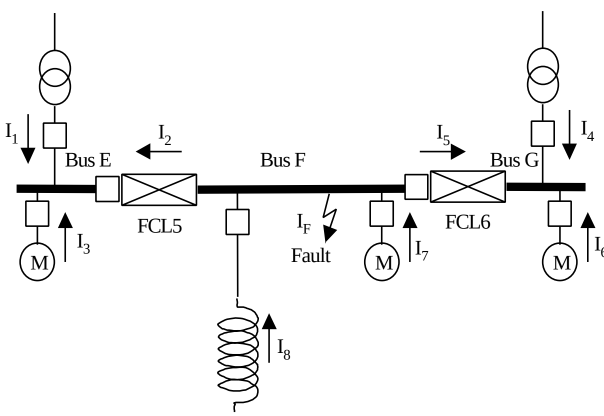


Legend

I_1	Transformer Incomer contribution
I_2	Current through FCL
I_3	Motor Contribution on faulted bus
I_4	Adjacent Transformer Incomer Contribution
I_5	Current through adjacent FCL
I_6	Motor Contribution on adjacent bus

Positive direction of current is towards protected bus

Fig. 8 Tripping Configuration for Bus Pairs A, D and B, C



Legend

I_1, I_4	Transformer Incomer Contribution
I_2, I_5	FCL currents
I_3, I_6, I_7	Motor contribution
I_8	Contribution from rest of system

Fig. 9 Tripping Configuration for Buses E, F and G

VIII. Conclusions

Spurious operations of FCLs have been known to occur due to the effect of transients resulting in satisfaction of the di/dt tripping criteria. This is further reinforced by the results of this study for a network where such incorrect FCL operations have occurred. This paper shows that such transients can be modelled using EMT type simulators such as ATP and PSCAD-EMTDC, which allow engineers to identify the cause of such events, and to plan, and test proposed remedial actions.

IX. References

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X. Biographies

Mark Hibbert was born in Harare, Zimbabwe in 1959. He received the B Eng and M Eng degrees from Queensland University of Technology in Brisbane Australia in 1981 and 1995 respectively. He worked in the electricity distribution industry in South-East Queensland from 1982 to 2002 spending the majority of that time undertaking technical investigations, including many time domain studies, and system planning studies. Currently he is a Senior Associate with Connell Wagner PPI, Brisbane, Australia, where he is responsible for the transmission and distribution sector of the business. Mr Hibbert is a Chartered Professional Engineer and a member of Engineers Australia.

Kenneth Smith was born in Perth, Scotland in 1966. He received the B.Sc.Eng. and Ph.D. degrees from the University of Aberdeen, Scotland in 1988 and 1992 respectively. Currently he is with Mott MacDonald’s Power Systems Division in Glasgow, Scotland where he is responsible for power system transient studies. Between 1992 and 2002 he worked in the University sector at the University of Aberdeen and later Heriot-Watt University, Edinburgh. During this period he carried out extensive work on the time domain modelling of electrical power system transients. Dr Smith is a Chartered Electrical Engineer (UK) and member of both the IEE and the IEEE.