A Pyrotechnic Fault Current Limiter Model for Transient Calculations in Industrial Power Systems

T. C. Dias, B. D. Bonatto, J. M. C. Filho

***Abstract*-- Isolated industrial power systems or with high self-generation, both with generators electrically close to the loads, have characteristics of high fault currents and X/R ratios. This characteristic represents higher electrical and electromechanical stresses on the systems' components such as switchgears, busbars, circuit breakers and current transformers (CTs). These high fault currents may result in the specification of more expensive equipments and make the investment inviable. In this context the fault current limiters (FCLs) are used.**

The objective of this paper is to present a model of a pyrotechnic device (PD) for transient calculations. Through this proposed model is possible to verify the voltages and currents' behavior during the FCL operation and evaluate the performance of the system related to transient recovery voltages (TRVs), CT saturation, electromechanical stresses on busbars and protection relay's operation and coordination. The model was used in a simple generic power system to check its behavior during fault conditions alone and with a reactor in parallel.

The model of this PD FCL was developed on the Simulink platform and the results were compared to the ones presented in the literature, with accurate current behavior.

***Keywords*: Pyrotechnic fault current limiter, industrial power systems protection, EMTP, transients calculations.**

I. INTRODUCTION

WITH the increasing electric energy prices, reduction of generation systems' costs, and demand for high reliability of power supply, industries have been investing in self-generation, especially in cases where the source used for power generation is already available as part of the industrial process (e.g. oil refinery). For grid isolated power systems, where connecting to the utility is not viable or not even possible, the use of self-generation is mandatory (e.g. offshore platforms, marine vessels, etc). During staged expansions, industrial plants may require the installation of additional power transformers and/or transformers with higher capacity.

All three situations mentioned before result in high short circuit (SC) currents and, typically in systems with self-generation, the X/R ratios are also high. These conditions lead to high electromechanical and thermal stresses in the system's components (switchgears, busbars, CTs, circuit breakers etc) [1-2]. For industrial plants in expansion, the SC currents may surpass the installed devices designed capacity, demanding additional investments in new ones. For new industrial plants, the need for high capacity devices may result in a financially inviable investment. This context represents the main application of FCLs, reducing the SC currents to acceptable levels and making the investments cost-effective.

Therefore, the objective of this paper is to present a model of a pyrotechnic fault current limiting device for transient calculations. In section II, the main impacts of high SC currents in industrial power systems are commented. In section III, the main FCLs technologies are presented. In section IV, the developed Simulink model is discussed. Finally, in section V simulations results are shown to illustrate the model functionality and accuracy.

II. MAIN IMPACTS OF HIGH SC CURRENTS AND X/R RATIOS IN INDUSTRIAL POWER SYSTEMS

Switchgears, busbars, fuses and circuit breakers are usually specified based on the symmetrical SC current and X/R ratio of the equivalent circuit. The technical standard used in the device's design establishes the maximum X/R ratio for which the correct operation is guaranteed for the specified symmetrical SC current.

Higher X/R ratios imply in DC components in the SC current with slower decay and higher peak values. This results in electromechanical and/or thermal stresses that may exceed the capacity of the device. For example, high-voltage circuit breakers designed based on the IEEE standard are tested for an X/R ratio of 17 (time constant of 45ms) in 60Hz [3]. In power systems with higher X/R ratio, a derating factor has to be used to verify if the currents' requirements are still fulfilled. The same idea works for switchgears (tested for a time constant of 45 ms [4]) and fuses (time constants vary depending on the class [5]).

For CT specification the main problem is related to AC and DC saturation. High symmetrical SC currents may cause AC saturation which reduces the current RMS value on the CT secondary due to the waveform distortion during steady-state, as shown in Fig. 1(a). High X/R ratio causes severe saturation during the transient period due to the current's DC component, as shown in Fig. 1(b). Once the signal distortion reduces the RMS value measured by the associated relay, overcurrent

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protections might misoperate [6] (e.g. delay in the instantaneous overcurrent protection during the transient), and this may result in miscoordination or damage to the protected equipment. To minimize the DC saturation, it can be used a oversizing factor of 1 + X/R [6]. However, in some cases this factor results in expensive CTs that may not fit into the switchgear.

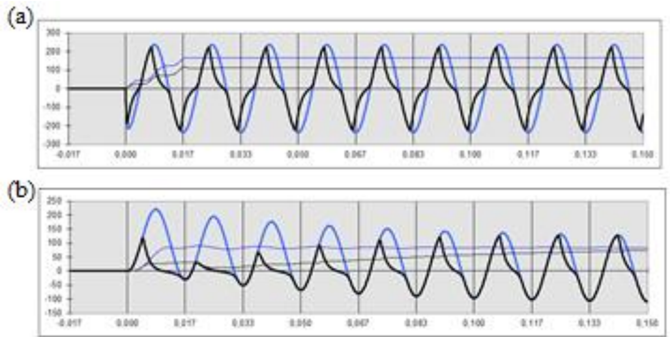

Fig. 1. (a) AC CT saturation; (b) DC CT saturation. In blue is the current signal without saturation, and in black is the real measured signal, both instantaneous and RMS. Adapted from [7].

These practical and economic issues justify the application of FCLs in industrial power systems. However, it is important to study the impacts of the FCL installation. The interaction of the system with the FCL affects the protection system [8-9]. Modifications in the system topology and the decrease of the SC current have direct impact in overcurrent and distance protection operation and coordination. In industrial power systems that vary their topology continuously depending on the plant operation, detailed SC studies are necessary to verify the conditions in which the FCL have to be operational and if there are conditions where it may be disabled. Electromagnetic transients' studies are important to analyze the voltage behavior due to the FCLs operation.

The next section presents the main technologies of FCLs and justifies the choice of the pyrotechnic device.

III. Main Technologies of FCLs

Many FCL technologies have been developed and are consolidated in industry and utility power systems (e.g. pyrotechnic devices and reactors). Some novel approaches are under development (e.g. superconductors and "driven-arc" type) [2]. This section briefly introduces the main technologies of FCLs.

A. Reactor

Reactors are the simplest FCLs. They are passive devices which introduce a reactance in series with the power source, increasing the system's impedance and limiting the fault current. They are normally built as air-cored coils due to the no-saturation characteristic of the core, since the reactance must remain constant in fault conditions.

The reactors are connected to the power system permanently, and so they have side effects such as modification on the system's power flow and voltage levels (especially during high power motor starting). Even though this is a simple and low cost solution, its side-effects may degrade the systems performance and physical space limitations in the substation can make it a not possible solution.

B. Superconductors

FCLs based on superconductors exploit the superconducting materials' characteristic of transiting from zero resistance to finite resistance [2]. Superconductors have very low resistivity below its critical temperature and critical current density. The current increase during a SC heats the material, surpassing both the critical temperature and current density, causing a fast resistivity increase and consequently reduces the total current.

Due to its inherent characteristic, this device comes close to the ideal FCL, zero resistance during normal operation of the system and on fault condition operates as a self-triggered with fail safe device (high impedance in case of superconductivity loss).

The main disadvantage of this technology is related to the high cost due to the necessity of cooling (critical temperatures of high temperature superconductors are up to 135K), not viable for industry applications.

C. Power electronics based

Power electronics based FCLs show as an interesting alternative for high voltage power systems. For example, Fig.2 presents a Thyristor Controlled Series Capacitor (TCSC) used for series compensation of transmission lines. In fault condition, the firing angles of the thyristors are adjusted so that the equivalent impedance of the TCSC is inductive, increasing the total line impedance and decreasing the SC current.

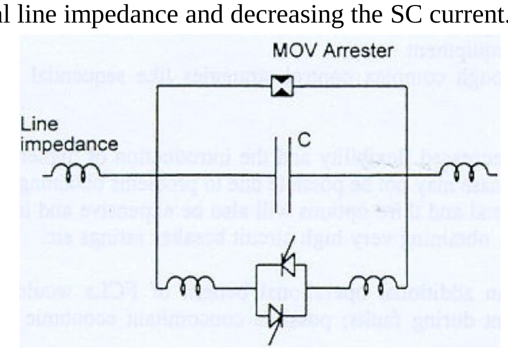

Fig. 2. Typical TCSC circuit diagram [2].

The cost of power electronics FCLs exclusively for current limiting are high, however incorporating this functionality to Flexible AC Transmission Systems (FACTS) devices is a good technical and economic solution for power grids [10]. The investment in this type of technology is not justifiable for industry applications, since they are not commonly used in normal operation.

D. Pyrotechnic devices

PDs work as an extremely fast switch. It consists of two parallel conductors. The main conductor carries the device's rated current. During a SC the rate of current rise detector triggers an explosive charge that destroys the main conductor, forcing the current through the parallel fuse (second conductor) which limits the current and opens the circuit in less than half-cycle [2].

During normal conditions, the PD does not have any impact on the system's operation. The main issue is related to the necessity of replacement after operation. Because of this particular problem, hybrid solutions with reactors in parallel with the PD can be found.

The cost, reduced physical dimensions and functionality make the PD an attractive solution for industry. There are not many models for electromagnetics transients calculations of PD in the literature; in [11] an ATP and PSCAD model is introduced. Based on these facts, a Simulink model was developed and it is described in the next section.

IV. Proposed Model for Electromagnetic Transients Calculations

The proposed model for the PD FCL is composed by an ideal switch in parallel with a fuse. The fuse model for electromagnetics transients calculations was developed based on [12] and [13]. Fig. 3 presents the used power circuit model.

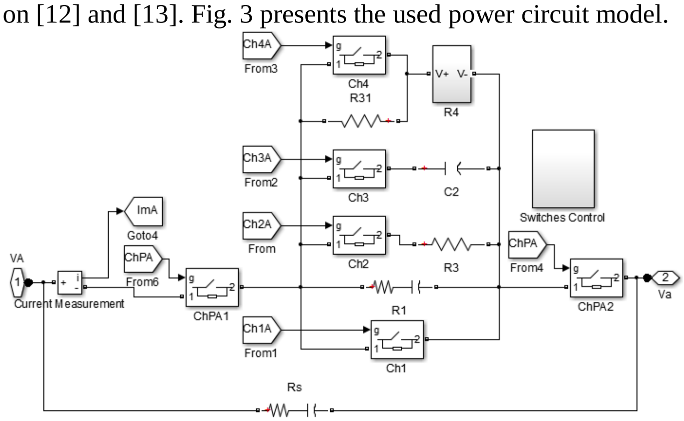

Fig. 3. Proposed power circuit model.

The switches ChPA1 and ChPA2 are used for the connection and disconnection of the FCL to the circuit. The RC branches named "Rs" and "R1" are used as snubbers for voltage spikes attenuation during current variations and numerical stability. The switch Ch1 represents the main conductor and starts closed. The three branches above the R1 branch model the fuse.

In the fuse model, Ch2 closes to start the operation. R3 is a small resistance used for current measurement and I²t calculation. Once the I²t value surpasses a predetermined value (varies for each fuse), Ch3 closes and Ch2 opens. C2 models the voltage rise at the fuse terminal during its melting. When the voltage exceeds the threshold named transition voltage (obtained in experimental tests), Ch4 closes and Ch3 opens inserting the non-linear resistance R4 that models the fuse characteristic during the arc extinction. A high resistance R31 is connected in parallel to Ch4 to avoid numerical errors during simulation. The non-linear resistance R4 model is presented in Fig. 4.

Simulink does not have a non-linear resistance block. To model this element it was used a voltage controlled current source. Using the test data presented in [13], the current as a function of voltage equation was derived through a quadratic regression method. Since this model was developed to be used to simulate the system behavior at any instant, the non-linear resistance characteristic has to work on both possible quadrants (positive voltage and current or negative voltage and current). The "Transfer Fcn" blocks are used to break algebraic loops during Simulink compilation.

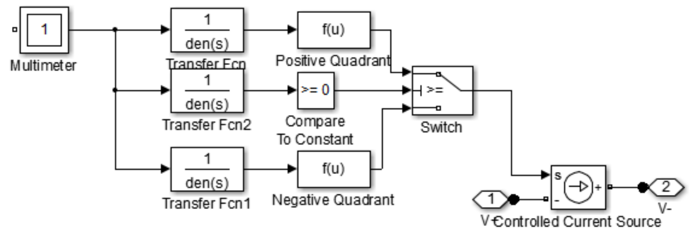

Fig. 4. Non-linear resistance modelled in Simulink.

The control block for the switches is represented in Fig. 5. The first stage is a rate of change detector that opens Ch1 and closes Ch2.

The "Multimeter" measures the current through the R3 branch which is integrated for I²t calculation. When I²t surpasses the threshold Ch3 closes and Ch2 opens.

The block "Multimeter1" measures the voltage on C2 and compares the value to the transition voltage. When the measured voltage exceeds it, Ch3 opens and Ch4 closes. In the moment that the first zero current crossing is detected while Ch4 is closed, both ChPA switches are opened and the FCL is disconnected from the circuit, extinguishing the current.

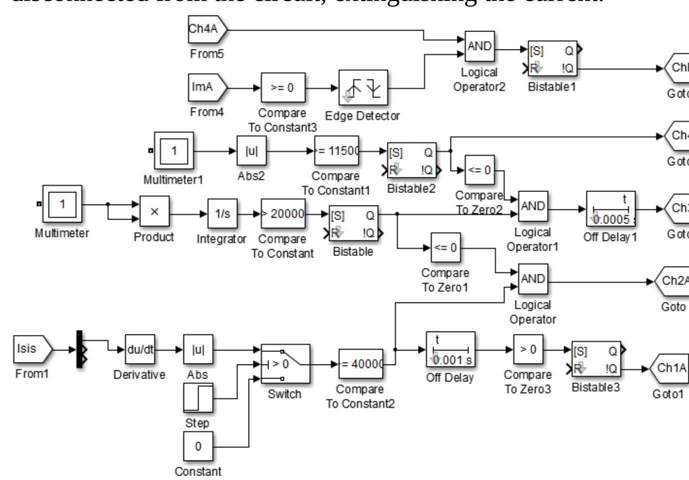

Fig. 5. Switches control algorithm.

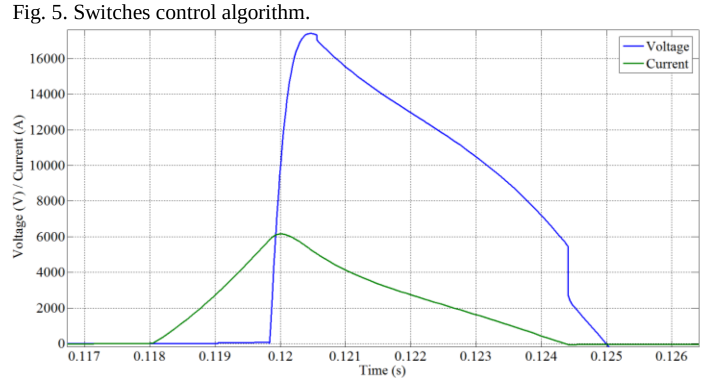

Fig. 6. Voltage and current during the FCL operation.

To check the results obtained with the proposed model, a simple simulation of the FCL operation was developed. Comparing the waveforms and values obtained in Fig. 6 with the ones presented in [11], [12] and [13], as shown in Fig.7, it is possible to observe coherent results and behavior of the proposed FCL model. The voltage and current values shown in Fig.6 cannot be compared with the ones presented in Fig.7 since the system's and fuse parameters were not the same. But the voltage and current waveforms are reasonably similar.

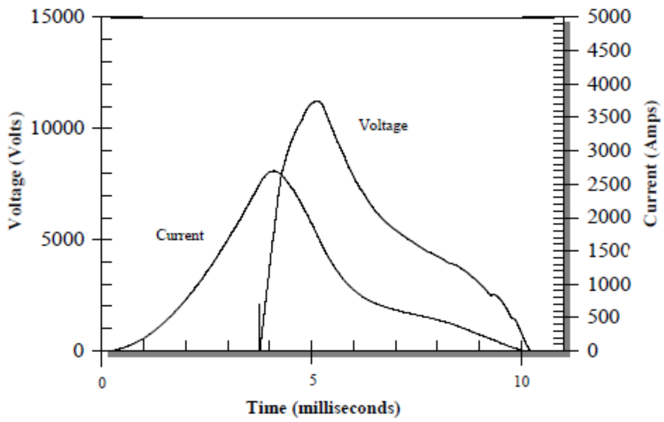

Fig. 7. Voltage and current waveforms presented in [11].

V. Simulation Results

To test the proposed model, three different situations were simulated in the system of Fig. 8(a). The power source was modelled as an ideal source in series with a resistance and a reactance. The equivalent source is a 200MVA SC power in 13,8kV with X/R ratio of 20. Fig. 8(b) shows the three-phase fault results without the FCL to be used for comparison.

The maximum instantaneous SC peak current obtained is around 20kA for the condition without the FCL and the AC current component has an RMS value of approximately 8.4kA.

The three test cases with the FCL are: same condition of Fig. 8(b); single-phase-to-ground fault at 116ms; and three-phase fault with a reactor in parallel.

Fig. 9, Fig. 10 and Fig. 11 show the current and voltage at the source connection in each case and Table I summarizes the results.

TABLE I
Results Comparison for All Cases

Simulated Case	Maximum Peak Current	RMS AC Current
Without FCL	20kA	8,4kA
Three-phase Fault with PD FCL	7 kA	NA
Single-phase-to-ground fault with FD FCL	7 kA	NA
Three-phase Fault with PD FCL and reactor	8 kA	3,2kA

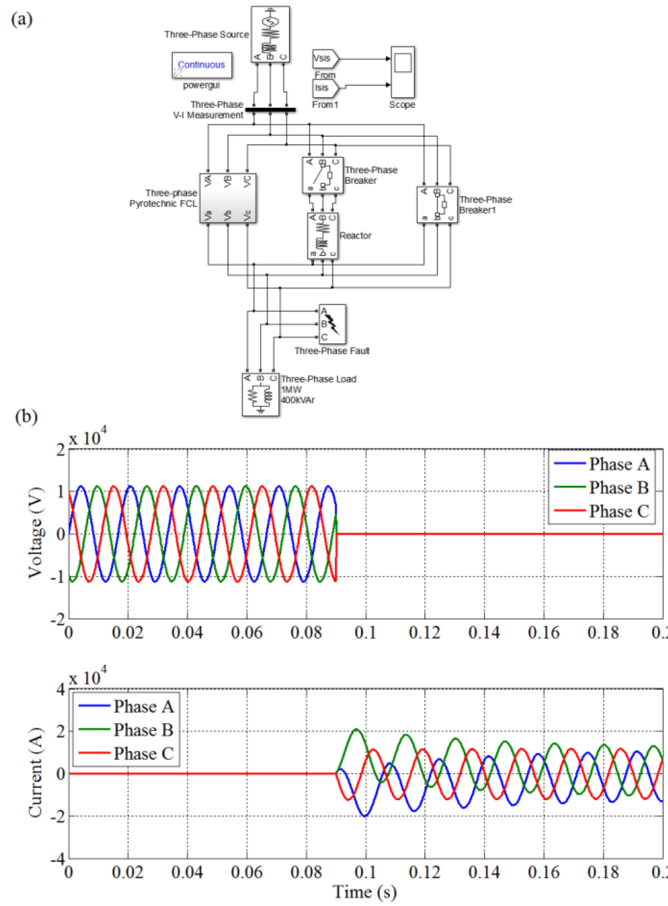

Fig. 8. (a) Simulated system; (b) Three-phase fault.

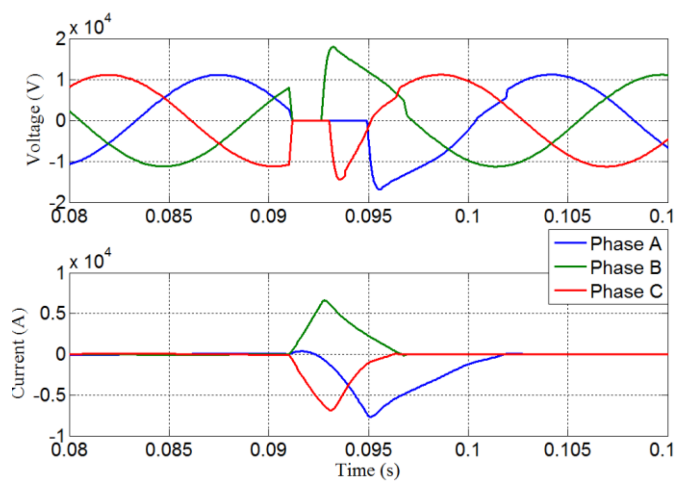

Fig. 9. First case: three-phase fault.

The results has shown the functionality of the proposed model, working correctly as a three-phase FCL with independent phase operation for different fault conditions and time instants.

In this simple example, the maximum peak SC current is limited in approximately 35% of the expected value for the system without FCL, illustrating its application. The voltage and current transients during the FCLs operation can also be analyzed.

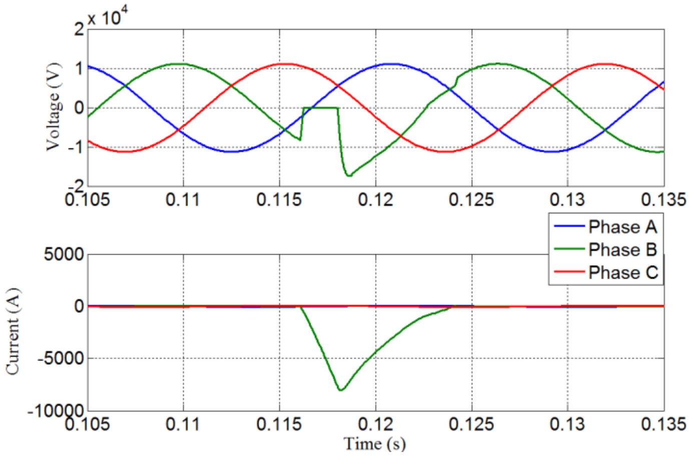

Fig. 10. Second case: single-phase-to-ground fault.

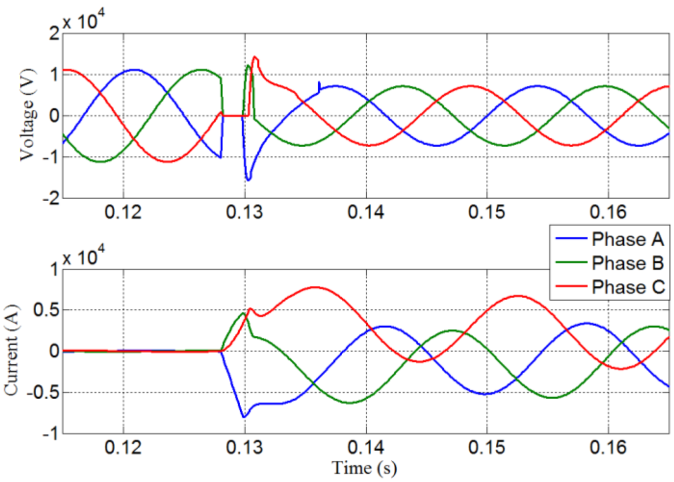

Fig. 11. Third case: three-phase fault with a reactor in parallel.

VI. Conclusions

This paper briefly presented the context of FCL applications in industry, and proposed a PD FCL model for transient calculations using Simulink.

The advantages of the proposed model are the possibility of applications in various systems' topologies. It works for all types of faults at any time instant, and it is easy to modify and simulate different tripping logics. The main disadvantage is the restrictions and complexity of modelling big power systems in the Simulink.

The next step of this work is to adapt this model to the RSCAD platform for real time simulations using the RTDS, for comparing and further validating the model performance in this hardware-on-the-loop computer platform. This work is being developed along with a Master Thesis related to FCL applications in industry, involving a case study of a real offshore oil platform in order to analyze the equipment's specifications and protection system's performance in real time simulation.

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