by Tom Keim

Developments in Pyrotechnic-Assisted Fuses

Every electric power engineer has some familiarity with electrical faults and technologies for fault mitigation. The basic problem presented itself to the earliest workers in electric technology, and the basic solutions have been present essentially from the beginning, and many are used with great effect to this day.

In some applications where essentially the same protections are required in millions of instances per year, very cost-effective solutions are common. Mainstream automobiles (i.e., setting aside for the moment battery-electric and hybrid-electric vehicles), for example, are largely protected by simple electrical fuses, which are technically effective at very low cost. Residential electrical systems at one time used fuses, too, but these have mostly been supplanted by resettable electromechanical circuit breakers. In this case, the chosen technology is also extremely technically effective. Whereas the cost per unit is far greater than for an automotive fuse, the technology is also economically quite satisfactory.

One technology that is receiving substantial attention for use in electric automobiles and in other applications is pyrotechnic current interruption. In situations where very rapid current interruption is desired, one option is to use a small explosive charge to literally blow away a formerly solid electrical conductor. At first blush, the idea seems dramatic, over the top. But thinking just for a moment about arcs and arc interruption, one realizes that explosives and the act of current interruption by mechanical separation of contacts or intentional melting of a conductor as in a fuse are not that different in audacity.

An apparent leader in this development is Mersen, which includes a company formerly known as Ferraz Shawmut. At the Applied Power Electronics Conference and Exposition 2018, their booth offered a brochure that described a product line, the Xp series, which claims to be able to switch up to 12 kA at up to 1,000 V. The Xp series device is electrically gated. The device is essentially an electrically triggered, fast-acting, one-time disconnect. At the International Power Electronics Conference (IPEC) in Niigata, Japan, in May 2018, representatives of the company presented a compelling paper, focused on near-term requirements of battery-electric vehicles. In this paper, they discussed a proposed product designated the Xp-ST. Whereas this product is similar to the Xp series, it replaces the external gating capability with a self-actuating configuration. This device is very similar in overall functionality to a conventional fuse but with a different principle of operation.

It appears that what is attracting new attention to this concept is increased market interest in current interrupting performance that cannot be obtained, or cannot be obtained as economically, by alternative means. The referenced Mersen paper cites a good example. The authors cite a particular automotive battery system with a nominal voltage of 900 V and a current rating of 500 A. The mainstream overcurrent protection solution for such a power source is the series combination of a mechanical contactor and a fuse. But in the case under consideration, the highest-rated contactor available from a major supplier of automotive grade contactors, combined with a fuse that is capable of interrupting the current available in the event of a solid short circuit, cannot clear all possible overloads. The contactor can interrupt up to 650 A. The fuse cannot be relied upon to interrupt anything under 1,200 A. Even at 1,200 A, the fuse could take up to 200 s to act.

One solution to this problem might be a more capable contactor. If such a contactor is not available or not available in a suitable time or at a suitable price, this solution may not be acceptable. Another solution is one or the other of the products offered by Mersen.

The fundamental construction and operation of the Xp series product was explained by Dr. Jean-Francois de Palma, innovation and research and development vice president at Mersen. The device is the parallel combination of a pyroswitch element and a conventional fuse, schematically illustrated in

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Figure 1. The pyroswitch element is a robust copper conductor with a few areas of reduced cross section, assembled with a small explosive element. In normal operation, the conductor in the pyroswitch has far lower impedance than the fuse; essentially all of the current flows in the pyroswitch. When a fault is detected, the explosive is ignited, and the conductor in the pyroswitch element is very quickly removed from the circuit. In at least one case, the fault current begins to collapse within 300 μs of the trigger event. When the conductor is removed from the circuit, the fuse becomes by far the lowest impedance in the device, and essentially all of the current transfers to the fuse. The voltage across the place where the pyroswitch element formerly was is kept low by the presence of the fuse, and any arc there is quickly extinguished.

The fuse element is now carrying a current far in excess of the lowest current required for it to act, so it quickly melts and commences to interrupt the current. The voltage rating of the fuse is above the voltage of the source, so the fuse has no difficulty extinguishing the current. The key to fast action in all cases is that the fuse in this device has a current-carrying capability far lower than rated current. This is possible only due to the presence of the pyroswitch element.

According to Project Manager Dr. Pierric Gueguen, although the built-in fast action is the primary benefit, the configuration of Figure 1 also offers some additional advantages. When a fuse is the only current-interrupting element in use, it experiences thermal transients any time there is a change in operating current or a short overcurrent not resulting in circuit interruption. These thermal transients degrade the capability of the fuse to carry normal operating current, to the point where fuses have a finite life even in normal service. Because the fuse is essentially bypassed in the pyrotechnic-assisted device except during operation, no important degradation occurs during normal operation.

Also, there is much more flexibility to choose the conductance of the element that carries current during normal operation. It is normal for literature on these devices to suggest that the conductor is copper, and except for a number of mechanical weak places, there is little restriction on its cross section. As a result, it is reasonable for a pyrotechnic-assisted fuse to have far lower on-state losses than a conventional fuse for the same current. It is further practical and desirable to include both the parallel elements of Figure 1 inside the same mechanical package.

The electrical triggering function can be an advantage or a disadvantage, depending on the needs of the system designer. If it is desirable to use complex logic to decide when to actuate the device and when not to do so, the function is desirable. If the desired triggering decision is very simple, e.g., trigger immediately if current rises above 120% of rated current, the need for a separate triggering device, which has a separate power supply and therefore can fail to function for reasons unrelated to any failure of the

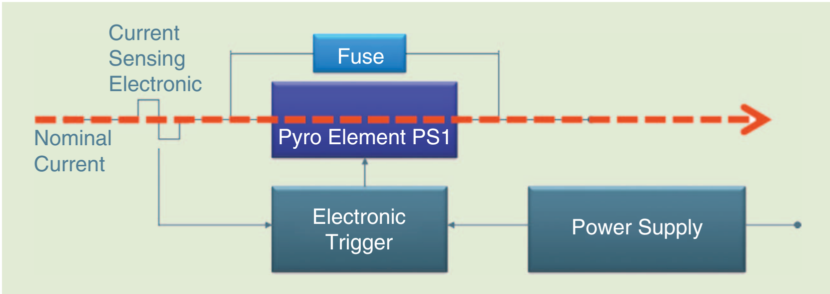

FIG 1 The overall topology of pyrotechnic-assisted fuse. (Figure courtesy of Mersen.)

switching product, the separate trigger may be an undesirable feature.

For these cases, Mersen plans to offer an Xp-ST product, described in the IPEC paper. This product additionally places a fuse in series with the components of the Xp product, as shown in Figure 2. This series fuse is underrated for the voltage of the system but is designed to act at an overcurrent high enough to prevent spurious tripping. When the series fuse opens, it does not extinguish the internal arc that results, because of its low voltage rating. Instead, the voltage across the fuse is used to trigger the pyroswitch, which without further delay opens the circuit by the process described previously. This configuration is protected by an issued French patent, and patent protection in major world markets is being pursued.

Additionally, Mersen has under development a product called *Xp-STT*, which includes the triggering mechanisms of both the Xp and Xp-ST devices. This device is hinted at, but not named, in the final paragraph of the IPEC paper. The authors point out that it is desirable to perform a precautionary disconnect of the battery in cases where no overcurrent exists, e.g., a serious collision or the occurrence of a fire. If such a device were specified, the best use may be to program the gate trigger for every conceivable case, reserving the slower self-triggering case as a backup in case of a failure of the primary triggering mechanism.

Pyrotechnic-assisted current interruption is receiving renewed interest not only for high-power dc systems but also in ac generation and distribution systems. Swedish power systems component manufacturer ABB produces a line of pyrotechnic-assisted devices for use in medium-voltage 50- and 60-cycle power systems. A line of products based on the same principle described previously, i.e., that of an explosively removable conductor paralleled by a fuse, has been available under the brand name I_s-limiter since

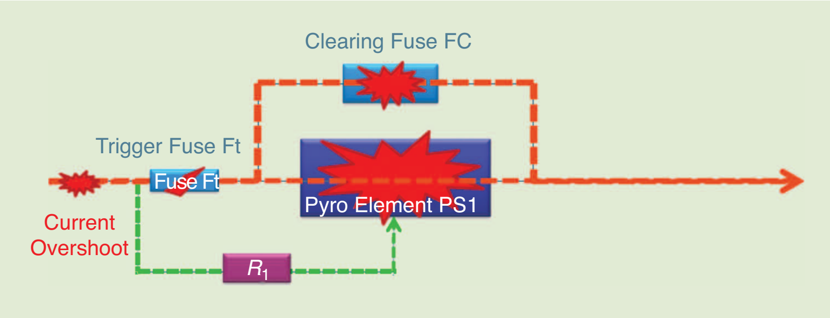

FIG 2 The fuse in series is underrated versus the voltage of the application. It is designed to act at an overcurrent high enough to prevent spurious tripping. (Figure courtesy of Mersen.)

1958. Late in 2016, a new product was launched, under the trademark FC-Protector. The new product includes modernized trigger circuitry and appears to use revised power components, but the operating principle is unchanged. Technically, the difference between the pyrotechnic-assisted products and more conventional circuit breakers is that the former interrupts the current before the first half-cycle current peak that would otherwise occur. Circuit breakers do not so dramatically chop fault currents but instead extinguish the current over a few cycles.

The current-events aspect of this product is not so much the new technology as the renewed interest in promoting the purchase and use of the product. The relevant parts of ABB's website have for the most part been revised recently, and in some cases, quite recently.

This makes sense as does the introduction of the modernized product. It is well established that fault current levels in medium-voltage electrical distribution systems have increased over time and continue to do so, as the amount of electrical power used per block in areas of high population density has increased. There is a conflict between the desire to feed a given area by a number of redundant, parallel paths, for increased reliability, and the need to keep fault current within the capability of the interrupting equipment at hand. ABB has a white paper on its website explaining how the fast response of a pyrotechnic-assisted fuse can be used to good advantage to increase the up-time of a data center at favorable equipment cost.

A very interesting article with the title "Using Pyrotechnic Current-Limiting Devices" appeared in the September/October 2017 issue of *IEEE Industry Applications Magazine* [1].

The lead sentence of the article postulated a trend toward electrical rather than mechanical drivers for large offshore installations. The article provides an overview of the implementation of pyrotechnic current-limiting devices from the design stage through precommisioning, commissioning, and operation. Plus, it explains the pertinent techniques to use a small number of such devices to enable the entire installed power system on an offshore oil platform to operate in synchronism, despite the fact that the prospective fault current of such a connection would otherwise exceed the interruption rating of available switchgear.

The article ran with the subtitle "A Case Study of What Went Right." Of course, not everything went right. This particular offshore rig (called a *floating production storage and offloading vessel*) is powered by six 25-MW gas turbine generators and has electric motors as large as 14 MW. The design of the electric power system is clearly a major engineering project. A system this large could supply a city of approximately 100,000 people in the United States. The generators are paired, with two feeding each of three buses. The buses are interconnected through two sets of pyrotechnic fault current limiters, each in series with a circuit breaker. During normal operation, one generator experienced a major internal fault, and the pyrotechnic devices worked exactly as they should have, separating the buses in under half a cycle. Contrary to plan, all generation on the vessel was lost, but that was not because of the operation of the pyrotechnic devices. The story of what went wrong did involve one of the pyrotechnic devices, but the problem resulted from device abuse, a consequence of either inadequate system operating instructions or a failure to follow instructions.

A reader can imagine that these lessons can be applicable beyond large offshore installations (or alternatively, that the lessons could have been learned by an awareness of land-based practice for power systems of similar voltage and power levels). The article is certainly recommended reading for anyone who wants a good starting point on how these devices can benefit a system at 13 kV with challenges due to fault currents.

About the Author

Tom Keim (tkeim@alum.mit.edu) is a late-career engineer and a longtime Member of the IEEE. His specialty is high-performance electromechanical systems and the power systems that drive and control them. He has worked for a worldwide conglomerate, for a small (50 employees) innovative research and development company, for a major research university, and for an engineering consulting company. He has 50 publications and 11 patents and is currently active as an author, inventor, and consultant.

Reference

[1] T. Hazel, J. Lavaud, and B. Leforgeais, "Using pyrotechnic current-limiting devices," *IEEE Ind. Appl. Mag.*, vol 23, no. 5, pp. 50–59, Sept.-Oct. 2017.