A FUSE USED AS AN ARC QUENCHING CHAMBER GENERATES A NEW CONCEPT OF POWER CIRCUITS PROTECTION

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ABSTRACT : The description and the application of a new current limiting device using a fuse as an arc quenching chamber are described. This new device consists of a current carrying bypass switch and of a parallel fuse. The role of the bypass switch is to provide a large current rating and the fuse's role is to handle the arc ignition and extinction. Therefore the fuse replaces the arc quenching chamber of traditional circuit breakers, and has generated a new range of current limiting devices faster than any existing circuit breaker.
This new device represents an important technological breakthrough in protection of electric and electronic power circuits.

1. INTRODUCTION : The need for a new ultra high speed current limiting device appeared several years ago in the field of static converters protection as well as in the field of distribution systems. An example is the protection of medium voltage variable frequency drive using many SCR's in series and parallel. Another example is the protection of equipment where available short circuit currents have grown and surpassed the breaking capacity of the existing protective devices. For these protection problems it is not realistic or even impossible to design multi-parallel fuses in order to carry large continuous current and still provide current limiting and I2t protections, and moreover circuit breakers are not fast enough.

For such problems a new current limiting device (the PYROBREAKER) offers economic and operating advantages for both AC and DC protection.

2. DEFINITION AND DESCRIPTION OF THE PYROBREAKER :

2.1. Definition : the PYROBREAKER is one component of a system (the PYRISTOR SYSTEM). In this system the pyrobreaker is the part which actually opens the circuit at a very fast speed. The PYRISTOR SYSTEM is described in paragraph 3.
A pyrobreaker consists of two parts (see figure 1) :
- a very fast opening percussion operated bypass switch using pyrotechnique material,
- a limiting fuse connected in parallel accross the bypass switch.
These two are integral parts of a unit and cannot be separated.

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2.2. Roles of the bypass switch and the fuse :
- The role of the bypass switch is to provide a low power loss path through which the required continuous current load current flows. The bypass switch is not designed to open the circuit by itself (no provision for arc extinction incoporated in the bypass switch).
- The fuse's role is to handle the arc and absorb the whole interrupting energy. The fuse's role is also to provide a prearcing duration long enough to let the bypass switch build an insulating distance that prevents any arcing inside the switch.

2.3. Description (see figure 2)
- motor (1) : this motor contains the explosive charge and a detonator. The detonator is activated by an electrical discharge supplied by the other components of the PYRISTOR SYSTEM described in paragraph 3.
- piston (2) : this is a part of the motor and is forced out violently by the explosion inside the motor.
- solid copper bar (3) : this bar carries the current and has very low power losses. It is a solid monoblock machined from a single copper bar which means that unlike traditional systems, current does not have to flow through any soldered joints or contacts held together under pressure.
- reception chamber (4) : when the piston strikes the center of the bar, a copper rod is sheared and propelled and lodges in the conically shaped reception chamber.
- copper connections (5)
- body (6)
- fuse (7) : this is a high-breaking capacity ultra fast-blowing fuse whose design is based upon the quality and advanced techniques of semi-conductor protection fuses.

3. DESCRIPTION OF THE PYRISTOR SYSTEM : Figure 3 shows the four main components and the basic interconnections required in the PYRISTOR circuit protection system. These components are :
- pyrobreaker : this is the part which actually opens the circuit to be protected. It is triggered by an electrical discharge.
- controller : it supplies the electrical discharge to the pyrobreaker and it monitors and processes a signal coming from a sensor.
- transformer : it is a pulse transformer designed to isolate the controller from the pyrobreaker.
- sensor : this is a measuring device which continuously monitors a circuit parameter.

4. PYROBREAKER OPERATION : the parameter to be monitored (temperature, current, di/dt, etc...) is detected by the sensor. The controller continuously monitors and processes the measured signal. As soon as the signal reaches a preselected "fault value", the controller supplies the electrical discharge which triggers the pyrobreaker.
Figures 4, 5, 6 and 7 show the main stages in the operation of the pyrobreaker. The main stages are :

4.1. Explosion inside the motor and shearing (figure 4) : the explosion occurs 5 microseconds after the start of the electrical discharge supplied by the controller. At this moment the piston begins moving out from the motor to strike the copper bar. A copper rod (8) is sheared from the copper bar.
Figures 5, 6 and 7 show how the copper rod (8) moves away and lodges

inside the reception chamber (4).
Note : the time from the beginning of the explosion to the end of shearing is only 100 microseconds (approximately).

4.2. End of piston stroke and fuse prearcing (figure 5) : the piston travels only 5 mm. Its role is to shear the copper (8) and to propel it. At the moment the thrust ends, the copper rod is moving towards the reception chamber at a speed of 45 m/second. At this time the current is no longer flowing through the bypass switch but through the fuse. At the end of the fuse's prearcing process current limit Ic has been established.

4.3. Arcing period (figure 6) : the copper rod has already travelled a distance "d" at the moment the arc appears in the fuse. The distance "d" is interconnected to the prearcing time since it must be reached to prevent the development of arcing inside the bypass switch.

4.4. End of arcing period, circuit completely open (figure 7) : the arc has developed in the fuse which alone ensures its extinction. At this moment the current has dropped to zero and the pyrobreaker remains open. It can be seen that the sheared copper rod (8) has reached and is lodged inside the reception chamber.

5. DETAILED DESCRIPTION OF CURRENT LIMITING FUNCTION : figure 8 shows how the current is interrupted in 5 stages. These stages are :

5.1. TS : time period required to reach the triggering current ID max, measurement tolerance included. ID max is a maximum value considering ID as a minimum and 1.1 ID a maximum including tolerance.

5.2. TF : time period required by the controller - approximately 50 microseconds.

5.3. TR : mechanical response time of the pyrobreaker. That includes the mechanical inertia of the motor and the time required to shear the copper bar. This is about 100 us.

5.4. TP : fuse prearcing duration. This is a few hundreds microseconds.

5.5. TA : fuse arcing duration. This is 5 milliseconds or less.

We can therefore write the following equation :

$$IC = ID + (TF + TR + TP)\, di/dt$$

Where di/dt represents the fault current rate of rise.

6. IMPORTANCE OF THE FUSE : the fuse must be designed to provide
- a sufficient prearcing time to allow the copper rod to establish enough insulating air gap and prevent arcing in the bypass switch,
- a sufficient chamber length and volume to allow the absorption of the whole interrupting energy.

6.1. The prearcing duration : immediately after the end of the shearing operation inside the bypass switch, the current is diverted to the fuse. At this moment the current value is (see figure 8) :

$$IR = 1.1\, ID + (TF + TR)\, di/dt$$

It can be seen from figure 9 that :

$$IC - IR = TP \cdot di/dt$$

This means that the prearcing I2t (adiabatic since TP is only a few hundreds microseconds) must have a minimum value K :

$$K = TP \cdot \frac{IC^2 + IR^2 + IR.IC}{3}$$

Then $$TP = \frac{3K}{IC^2 + IR^2 + IR.IC}$$

The fuse has been determined from ID, di/dt and the working voltage so that TP has the predetermined value.
It is then important to see that :
- if during operation the fault to be interrupted is as expected, the fuse prearcing time will be TP,
- if the current ID is lower, or if the maximum fault di/dt is lower than expected, time TP will therefore increase. This means that the isolating distance in the bypass switch has increased with respect to that expected and that therefore no danger exists.
- conversely, if ID or di/dt are higher than expected, time TP will decrease and the pyrobreaker will operate incorrectly.

6.2. Interrupting energy absorption : since the arc is totally handled by the fuse, the corresponding energy Wa must be fully absorbed inside the fuse chamber. The Wa value and the working voltage are taken into account to determine the fuse dimensions.
It is well known that :

$$Wa = \frac{1}{2}LIC^2 + \int_{TA} e(t).i(t).dt - \int_{TA} R.i^2(t).dt$$

where : L : inductance of the circuit
R : resistance
e(t) : source voltage versus time
i(t) : current versus time
IC :peak let through current of the pyrobreaker as shown in figure 7
TA : arc duration

It is common to get Wa values around or above 10^6 joules.

7. SOME CHARACTERISTICS OF THE PYROBREAKERS : the pyrobreakers are available for various voltages and current ratings. There are 6 models as shown in table 1. The ultra high speed of the devices is demonstrated by the duration ΔT between the triggering signal appearance and the moment when the current is limited.
Therefore $\Delta T = TF + TR + TP$ (see figure 7)
ΔT varies with the working voltage. Table 1 gives, for each model, the ΔT value corresponding to the rated voltage and the minimum value of ΔT with the corresponding working voltage value. For lower working voltages the ΔT value remains equal to that minimum (see table 1 on the next page).
- Breaking capacity : the breaking capacity is function of the following :
. Nature of voltage : AC or DC
. Under AC conditions : . F frequency
. U voltage
. ID triggering current, or the current value in the circuit when the triggering parameter value is reached.
. Under DC conditions : time constant (= L/R)
ID triggering current, or the current value in the

circuit when the triggering parameter value is reached.

For example the breaking capacity of the 7200 V 4000 A model is :
- 220 KA at 50 hertz or 180 KA at 60 hertz with ID = 18000 A and U = 7200V
- 100 KA at 50 hertz or 80 KA at 60 hertz with ID = 27000 A and U = 7200V

TABLE 1

VOLTAGE RATING AC or DC (KV)	CURRENT RATING (KA)	ΔT (microseconds)	WATTS LOSS AT RATED CURRENT (W)
2,5	2,6	260 µs at 1,2 KV 400 µs at 2,5 KV	120
2,5	4,5	300 µs at 1,2 KV 440 µs at 2,5 KV	220
2,5	8 in AC 10 in DC	330 µs at 1,2 KV 560 µs at 2,5 KV	320
7,2	4	480 µs at 2,5 KV 1050 µs at 7,2 KV	230
11	4	900 µs at 6 KV 1500 µs at 11 KV	230
20	3	530 µs at 4,6 KV 1400 µs at 20 KV	320

8. OSCILLOGRAM : figure 10 gives an oscillogram with test conditions and results.

9. APPLICATIONS AND ADVANTAGES OFFERED BY THE PYROBREAKERS : the pyrobreaker is ideal for the protection of both low and medium voltage equipments designed for high continuous applications and requiring fast action in the event of faults. The pyrobreaker offers technical and financial advantages.

9.1. Applications : the pyrobreaker is well adapted for the protection of power static converters and the protection of distribution systems. For example, it already protects the following :
- Rectifiers on AC and DC sides, such as :
1400 VAC rectifiers used to supply large current pulses to electromagnet.
1000 VDC trimmer rectifiers
- Cyclo converters, on AC or DC sides (see figure 11)
- Variable frequency drives on input and output (see figure 12) such as :
. 1500 V 3500 A drive
. 10000 V 2000 A drive
. 15500 V 1500 A drive
- DC motor protections
- Distribution panels fed by 2 sources coupled in parallel (see figure 12) at 11 KV

- Distribution circuit of plants : in order to upgrade the breaking capacity of existing circuit breakers.
etc...

9.2. Technical and financial advantages : the following advantages are offered by the pyrobreaker.
- adjustable triggering value (or another type of signal)
- peak current limited to very low values
- very low let through I2t
- low watts loss
- breaking capacity as high as several hundreds kiloamperes
- the equipment size and components size can be reduced to handle the low stress associated with the I2t and peak current limited by the pyrobreaker
- costly replacement of old circuit breakers is avoided by using a pyrobreaker
- costly current limiting reactors can be replaced by a pyrobreaker
- watts loss of current limiting reactors are drastically reduced by a pyrobreaker mounted in parallel accross them
- for a new equipment that requires a current limiting reactor in order to delay the shut down, the pyrobreaker in parallel also allows the diminution of the reactor dimensions and cost.

10. CONCLUSION : the pyrobreaker is an economical solution for the protection of high power equipment in commercial and industrial electrical power generation and distribution systems. It is sometimes the unique solution for the protection of semi-conductors in medium voltage systems.

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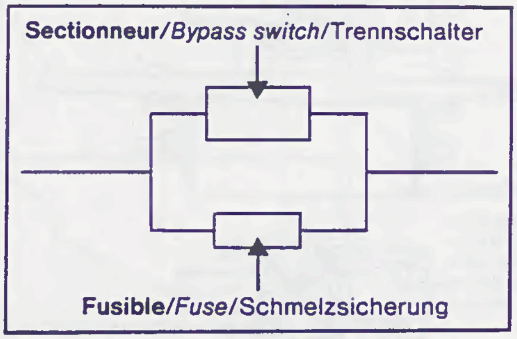


Fig. 1

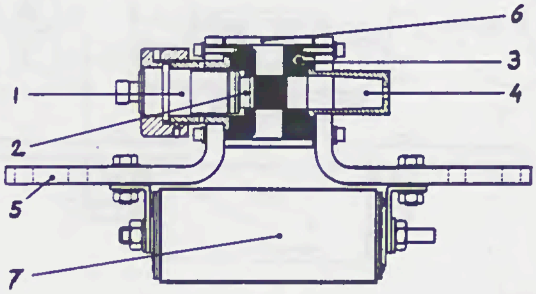


Fig. 2

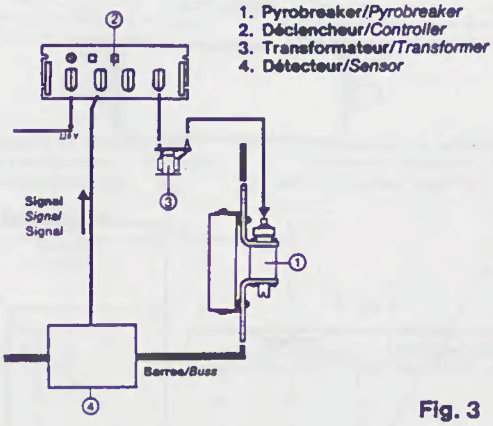
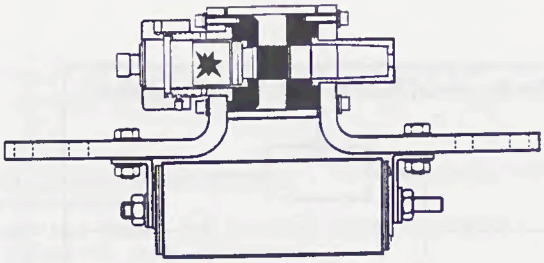


Fig. 3

Fig. 4



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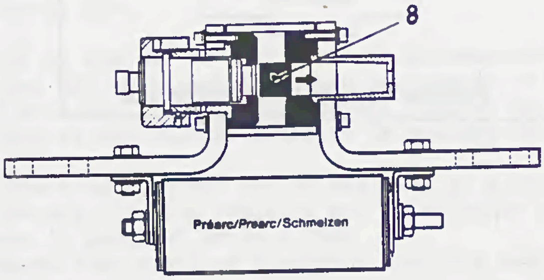


Fig. 6

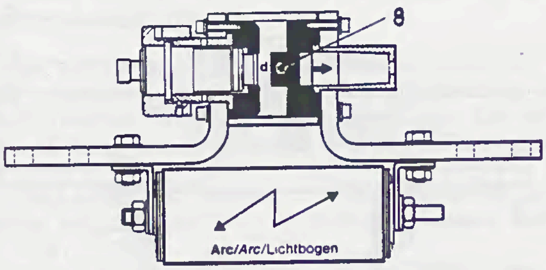
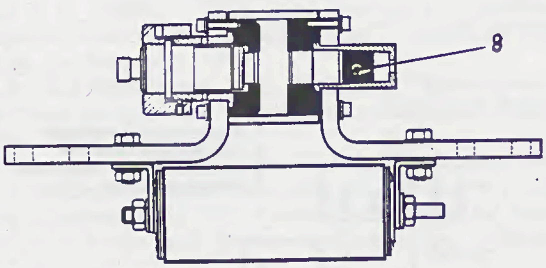


Fig. 7



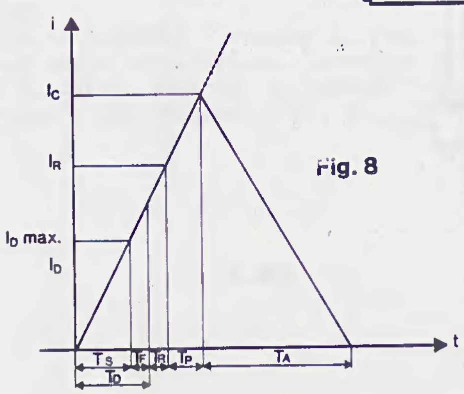


Fig. 8

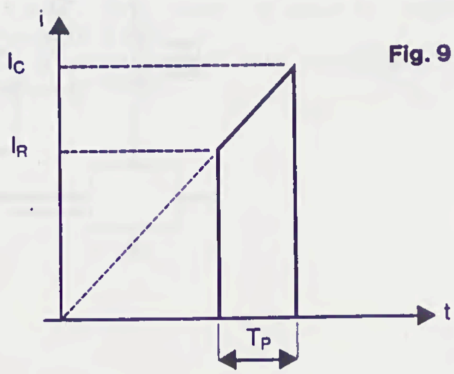


Fig. 9

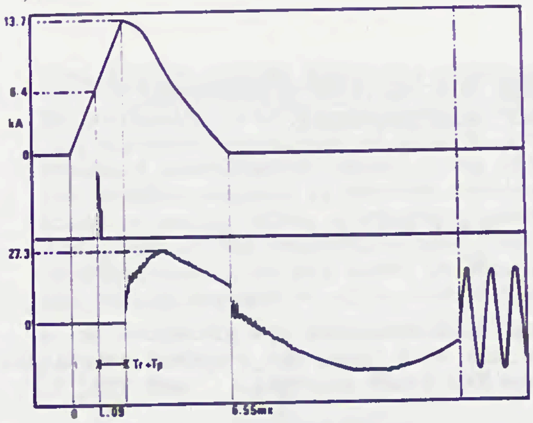


Fig. 10

Test conditions

U	*= 13 500 V (voltage)*
I_p	*= 14.5 kA (prospective fault current)*
Θ	*= 55 degrees (closing angle)*
Cos	*= 0.06 (power factor)*
I_D	*= 6 400 A (triggering current)*

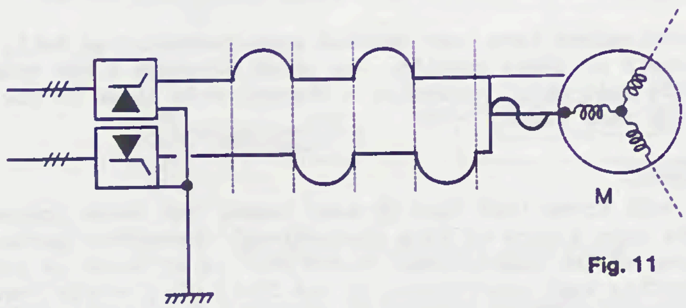


Fig. 11

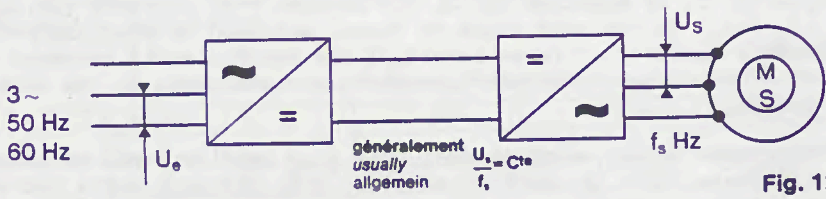


Fig. 12

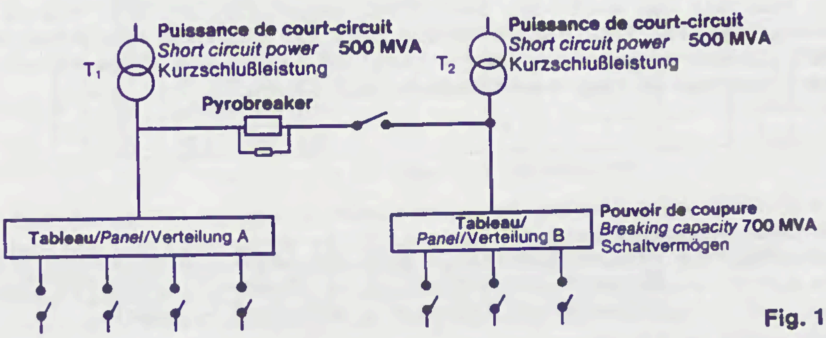


Fig. 13