# WHAT CAN FUSES OFFER TO SURVIVE THE NEXT CENTURY

Andrzej Wolny
Technical University of Gdańsk
Gdańsk - Poland

***Abstract*** A short survey of most important kinds of fuses and current limiters, accompanied by evaluation of impact of the observed trends in fault-current protection is concluded with examination of three technologies: substrate fuses, HCLID and VAF considered promising for the next century.

## I. INTRODUCTION

It seems to be the right time to raise such a question, since the rapid development of power semiconductor devices, increasing role of computerisation in protection techniques, and first of all, the change in preferences of people can cause reduction in demand for fuses. Not only for those conventional. Can some features of fuses be considered „unbeatable"? If the answer were positive efforts of researchers should be centred on them.

## II. THE PRESENT STATE

Over more than a century, fuses play a role of the fastest, most reliable and relatively low-cost current protection devices. Their unquestionable success is undoubtedly due to the idea of application of sand filler, which offered to the fuses the current limitation features, difficult to achieve with other methods over many decades. Hence, in spite of the development of many systems of arc quenching, applicable also to fuses, the sand-filled fuse remains the most popular kind, and probably will, for a few decades more, although the automation and demand for maintenance-free equipment will probably limit their importance. At DC currents, sand fuses have little competition. Hence, e.g. in electric traction the demand for them looks quite stable.

Low prise and easy manufacturing make the expulsion fuses still attractive in some areas of application. For instance, the miniature fuses (MF) are manufactured for protection of electronic circuits, and automobiles. However, the traditional application of expulsion fuses in household power systems in America, and in the protection of distribution transformers against internal short-circuits is shrinking. It is imaginable that the latter area can even disappear in not a distant future.

Some old designs like the liquid-filled fuses, or the simple air fuses with ceramic chambers have probably reached their limit, if not an unexpected break-through in technology or demand occurs. It is true that the former are well suited for mounting inside oil tanks of transformers and for protecting them, however the interest in oil transformers is reducing, for safer dry resin-cast designs are on the market.

In the era of fast development of vacuum and $SF_6$ contact arc quenching devices, the idea of application of the same methods to fuses surfaced [1-3]. However, the new constructions of fuses fail to revolutionise this area, mostly due to their high cost. Moreover, vacuum and $SF_6$ are best suited to HV application, where demand for fuses is relatively low.

The most interesting and promising idea seems to be a substrate, or thin film fuse [4-10]. It facilitates far-reaching reduction in volume of current limiting fuses, and permits to avoid utilisation of sand filler. The sand is unpleasant for manufacturers, due to its adverse effect upon the reproducibility of fuse characteristics and automation of production.

A special field of fuse application is current limitation. There are many ideas on taking advantage from melting, overheating or rupturing of a segment of current path, due to the effect of a fault current, which should be interrupted, limited or commutated into a parallel device. Some relatively new ideas emerged.

Presently, such current limiters as $I_s$-Limiter of Calor Emag, Ultrup Fuse of Fuji, or PPF of Mitsubishi [11-15], can be called conventional. In these cases, the melting or mechanically disrupted part of the current path is merely used to current commutation into a parallel device, and the final current interruption may be completed by an additional switch.

Effective fault-current limitation and its interruption can also be performed by means of current commutation from an operating fuse into a parallel device, such as a varistor. In such application, the role of the fuse is only to generate an arc voltage high enough to force the current through the parallel varistor.

As a new idea of fuse-like current limiters, a superconductive device can be mentioned [16], which operates by virtue of a sudden increase of its resistance, due to a heating of a fuse-element-like current path above the critical temperature. Some researchers express their expectations with respect to this kind of current limiters.

Another CLID, which cannot be strictly referred to as a fuse is a hybrid current limiting and interrupting device (HCLID), presented by Zyborski [17,18]. HCLID is related to fuse-similar current limiters since, common features with $I_s$-Limiters of Calor Emag or Ultrup Fuses are noticeable. In place of explosives used in $I_s$-Limiters for the current path interruption, in HCLID a magnetodynamic drive deforms a "one-shot contact" to make a gap facilitating current commutation into a TCB, which substitutes for a parallel HBC fuse used in the former device.

The above-presented short survey of devices, which should pretend to be called fuses, makes it clear that the classical and intuitive definition of fuse needs some modification to embrace all the mentioned kinds of current limiters.

## III. CONDITIONS OF FUSE APPLICATION

There are some new factors influencing fuse application, which are mainly connected with the new possibilities offered by broadly understood computers and power electronics, facilitating automation of protection, drastic reduction in labour-force, and changes in peoples preferences. On the other hand, quality of transformers, machines and other equipment has increased significantly, thus internal errors occur so seldom that investment in very developed protection systems seems to be unreasonable. The opinion becomes common (not only in the field of protection) that it is more economic letting complete destruction of a device and next replacing it, than preventing (thanks to the protection) far-reaching deterioration and next fixing the faults. Such reasoning would lead to a simplification of protection: only the indispensable means should be left, those preventing disastrous economic effects of faults, and reducing danger to human life. First to remove would be some kinds of fuses owing to their inherent inability to be included in automatic protection system, and the necessity of maintenance.

There is also a different thinking. Cost of undelivered energy increases due to the rise of efficiency of manufacturing. Therefore, any fault should be localised and cleared in the shortest time possible. The break in electric power delivery, due to a fault, should be limited to as few consumers as possible. Such ideas are opposite to the presented above. They will result in application of a fast individual protection just to cut off devices and appliances being out of order. In such a case a simple and reliable "one shot" protection, such as a fuse, is perfect.

Another factor to take under consideration is connected with fault current limitation, which is very important for many devices sensitive to high currents, among others semiconductor power devices and contactors, as well as for systems with very high short-circuit currents. In such cases fuses are almost unbeatable. They are also well suited for the "last resort" protection.

Summing up, factors exist, both reducing and stimulating demand for fuses. These factors will affect, the field of fuse implementation. Undoubtedly, fuses remain attractive as current limiters and individual protection, preventing extensive cutting off in power delivery. However, in all cases when fuses can be replaced by other maintenance-free current breaking devices, or distance controlled protection, probably they will be removed.

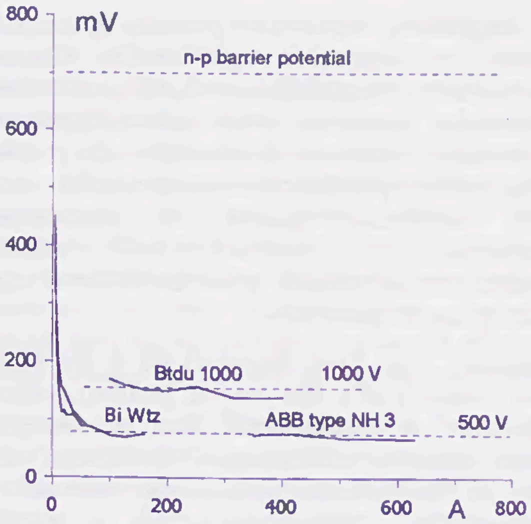


**Fig. 1.** Voltage across terminals of variety of sand filled fuses versus the rated current. Polish make fuses and ABB are compared, both power and semiconductor types.

## IV. SOME OTHER FUSE FEATURES

Some advantageous features of fuses, such as a small volume compared with that of contact CBs, low cost, as well as low power losses (although higher than those of CBs, significantly lower than losses of semiconductor devices) affecting their demand, should also be mentioned. In Fig. 1 voltage drop across fuse terminals of a variety of Polish make and ABB fuses are compared. It is noticeable that typically, the voltage produced over fuses is lower by a factor of several than that of a n-p barrier potential. Only substrate fuses generate higher voltages across terminals [8] at rated currents. For the same sand fuses, in Fig. 2. power losses are shown, and in Fig. 3. a unit volume per ampere. Except for low rated fuses, the voltage drop across fuse terminals and the unit volume per ampere of fuses of the same rated voltage differ insignificantly each other. Consequently, the power losses are proportional to the rated current of fuse and its rated voltage.

Low volume, low cost, as well as power losses and voltage drop lower than those of semiconductor devices are other features stimulating and facilitating application of fuses [16].

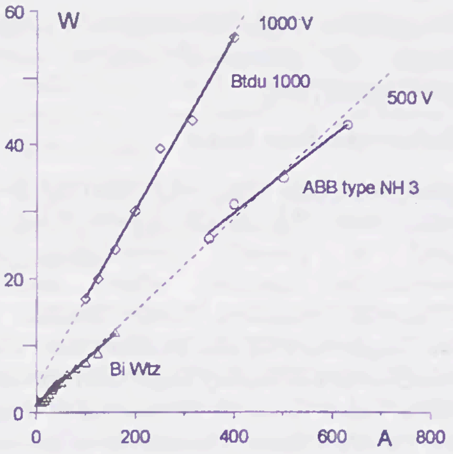


**Fig. 2.** Power losses of a variety of sand filled fuses versus the rated current. Polish make fuses and ABB are compared, both power and semiconductor types.

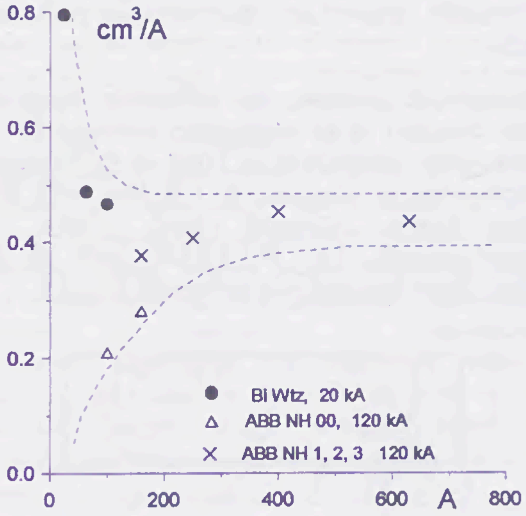


**Fig. 3.** Unit volume of a fuse link per ampere of a variety of sand filled fuses versus the rated current. Polish make fuses and ABB are compared, both power and semiconductor types.

## V. PROSPECTIVE TECHNIQUES

The above presented concise discussion shows that fuses in some fields of application increase their competitiveness by improvement of such appreciated features as: miniaturisation, current limitation, and technology enabling automation of manufacturing. Presently, only special current limiters such as PPF, Ultrup Fuse, or HCLID can be though of as fuses applicable to, gaining popularity, automatic protection systems.

Examples of developing technologies and ideas are discussed below. The superconductor current limiters extensively presented on previous ICEFA are not surveyed again [16].

### V.1 Substrate fuse links

Technology of thin film, or substrate fuses is relatively new [4]. Such fuses have been designed to protect developing power semiconductor devices, when sand-filled fuses almost reached their limits. Small thermal capacities of the thinner and thinner semiconductors of costly high current diodes, thyristors and power transistors required shorter thermal time constants of protecting devices. This implied a significant reduction in the fuse-element mass of a given rating fuse, which was only possible by significant increase in cooling conditions. The fuse should also display good current limiting characteristic, and its Joule integral should be readily less than that of the protected device.

Although, at present, the substrate fuses are often thought of as miniature semiconductor fuses, they exemplify a kind of technology, which may be applied to full-size and full-range fuses. Already, such fuses are manufactured, e.g. FULLRAN, and in the future their ratings will probably extend.

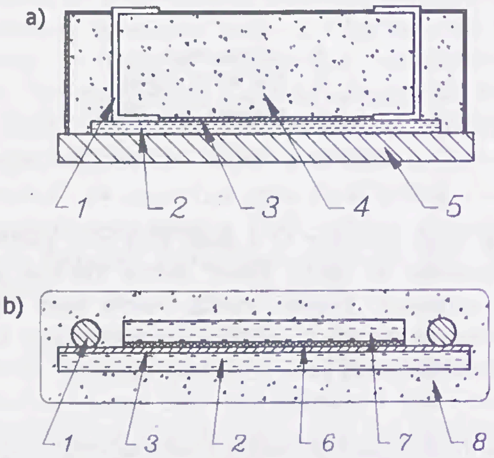


**Fig. 4**. Substrate fuses: a) substrate, sand filled fuse with copper base [8]; b) substrate fuse with cover plate (MLF) [10]: 1- connection, 2 - substrate, 3 - fuse element, 4 - sand, 5 - copper plate, 6 - glaze, 7 - cover plate, 8 - resin

Competitive efforts to substitute a different grain filler for quartz sand [18-22], and this way to improve cooling conditions failed to bring expected results. However, this cannot be surprising, since any porous material is unable to improve significantly thermal conductivity. Hence, the idea of fuse element deposition upon a well heat conducting substrate, seems presently the most attractive. Typically this substrate is made from alumina, quartz or pyroceram. Sometimes, to improve heat transfer conditions the ceramic plate is soldered upon a thick metal base [8].

Typically, the fuse element of a substrate fuse consists of a few layers, printed, vapour deposited or galvanised. The intermediate layers improve adhesion of the main silver layer to the ceramic plate. Good adhesion is particularly important at sudden overcurrents due to, e.g. motor starting, when the temperature can change in a short time, say by 200 °C. Features of the layers influence ***t-I*** characteristic of a fuse, and can be considered a tool in its formation.

Thickness of the fuse element is very important. The thinner the fuse element, the better its cooling, however, the steeper its ***t-I*** characteristic. Presently, layers of a fuse element are approximately of 1 μm in the thickness, and investigations are in progress on creation of even thinner ones. The problem consists in homogeneity and uniformity of the fuse element. Known methods produce thin layers slightly porous, so their resistivity is readily higher that that of a typical wire or strip.

Formation of fuse elements of substrate fuses is performed by means of similar methods to those used in the technology of integrated circuits. Hence, precision of their shapes is high, and the reproducibility of fuse features depends basically on the thickness and homogeneity of layers. In substrate fuses rated current density acquires unbelievable values. It can exceed 6 kA/mm$^2$ [8]. Application of laser technology in fuse element formation is also attractive [23,24].

It is interesting, that the technology of manufacturing of fuses tends to resemble that of integrated circuits, and not long ago the success of vacuum arc quenching devices was based on the zone refining method also developed for semiconductors.

In some substrate fuses [4-8], the fuse body, with the ceramic plate inside, on which the fuse element is deposited, is filled with quartz sand. The filler helps to quench the arc and to recover the post-arc withstand in the same way as that in conventional sand-filled fuses. The basic difference consists in the significantly lower quantity of metal vapours in substrate fuses. Application of a sand filler is inconvenient, since the homogeneity of the filling affects fuse characteristics, and it is not easy to ensure perfect reproducibility of filling parameters. Moreover, in the manufacturing process special care must be taken to avoid adverse effects of sand grains on operating machines.

Therefore, a next important step has been done by substituting another ceramic plate for the sand [9,10]. In such a case the fuse element is placed in a very narrow slot, causing the arc pressure increase and the arc voltage rise. Unlike in sand filled fuses, metal vapours of the decomposed fuse element have no chance to escape rapidly from the arc zone. So, they must be absorbed and bound chemically with the ceramic plates, to ensure sufficient recovery withstand. Thus, the plates material must be carefully selected. It should be chemically active, binding metal vapours of the fuse element, and creating non-conductive compounds. The conventional metal-oxide ceramic fails to meet such requirements. Ossowicki and Sulikowski [9,10] applied for their MLF (miniature layer fuse) plates from a special kind of glass covered with a material reacting endothermically with metals.

In substrate fuses, due to the very high current density, the volume of metal vapours is small compared to the conventional fuses, which facilitates reduction in the fuse volume. Therefore, the fuse sealing becomes easy, and a possible application of additional gas filling, improving current-interruption features of fuses, looks simple.

In conventional sand filled fuses the fuse-element length is due to conditions of overcurrent breaking. Fuse elements of substrate fuses are at least by an order of magnitude shorter than those of sand fuses. This fact positively affects dimensions of MLF.

On the other hand, the voltage drop across the fuse and power losses at rated current may increase, due to the very small cross-section area of the fuse element. Hence, it would be beneficial undertaking efforts to reduce these values.

Substrate fuses display some advantageous features, due to their technology, improving their reliability and reproducibility of characteristics, compared to conventional fuses. First of all:

- the state of the fuse element notch is practically independent of assembly conditions,
- the possibility of mechanical damage, while repeated overloads, e.g. by motor starting, (stress due to dynamic forces and dilatation) to notches of the fuse element is notably limited, which prevents changes in the ***t-I*** characteristic.
- automation of manufacturing is simpler than in the case of sand filled fuses.

Summing up, the conclusion can be formulated that thin film technology may be a similar milestone in the history of electric fuses, as the application of quartz sand filler was a century ago. This technology not only enables a dramatic reduction in the volume of fuses increasing this way their predominance compared to other protection devices, but also improves stability of their characteristics, and facilitates automation of manufacturing, which helps reducing prices and strengthening their economic advantage, despite of complexity of production processes. Moreover, the degree to which a fault current can be limited, as well as the low let-through Joule integral allow for considering them as the best semiconductor fuses.

Presently MLF are exclusively used to protect semiconductors. At 250 V, typically, a single notch is applied. Hence, high voltage designs with several notches in series are expected in the future.

### V.2 Current limiting devices (CLD)

Fuses are considered the most effective and economic current limiting devices (CLD), especially in the case, when high short-circuit currents appear in LV circuits of high rating currents, or at moderately high voltage and relatively low rated currents. In the former case, exploding current limiters, and PPF are applicable, and in the latter one, typically, sand fuses are used.

However, new possibilities emerge. E.g. at low voltages HCLID [17,18], akin to the exploding CLD, can be used, and at high voltages, current commutation to a parallel varistor, in a varistor assisted fuse (VAF) assembly [25,26] can be beneficial.

### V.2.1 HCLID assembly

The hybrid current limiting and interrupting device (HCLID) was developed by Zyborski [17], based upon the concept of DHR circuit breaker presented by Collard and Pellichero in 1989 [28]. In both devices, there are contacts and a thyristor circuit breaker (TCB) connected in parallel. This way, significant power losses due to a high voltage drop across the TCB are avoided. Also the thyristors can be selected smaller.

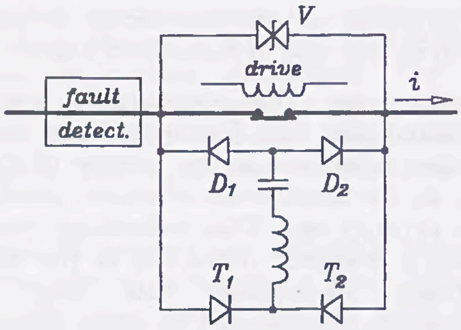


**Fig. 5**. Simplified diagram of HCLID [17]

On opening contacts, the current is commutated into the parallel TCB and interrupted as soon as possible. The interruption energy is absorbed by a varistor, Fig. 5. If the commutation takes place shortly after a fault has occurred, the fault current will be limited. Thus, the span of time between the fault initiation and contacts opening is crucial for current limitation. Therefore, in place of a heavy mechanical switch used in HDR, Zyborski applied a special contact system with reduced mass and inertia, driven by an electromagnetic drive, operating in less than 100 µs. To speed up the operation, the contacts are simply bent by the force of the drive at a moment selected by a fault detection system (SDS), Fig. 5.

The adequate control of magnetodynamic drive and TCB thyristors is the basic problem. The state off should be reached after the gap between open contacts gains full recovery withstand. The current commutation proceeds thanks to the rising voltage across the contacts. To limit fault current effectively, the latter should be triggered as soon as possible, however never before the electrical withstand of contacts gap is enough to withstand the transient voltage. Zyborski used the delay of 220 µs. In Fig.6. the oscillogram of Czucha, Pikon and Zyborski [18] is reproduced, showing traces of the current and the voltage across contacts of their HCLID. In this model IGBT was used in place of TCB.

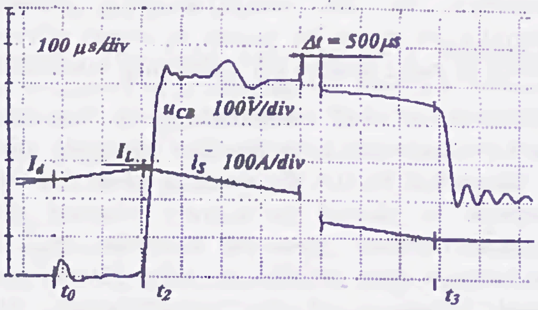


**Fig. 6**. HCLID: traces of contacts current and voltage. $u_{CB}$ the voltage across contacts, $t_o$ the moment of fault discrimination, $t_2$ the moment of TCB triggering, $t_3$ the fault current off.

The current limitation and reduction of the let-through Joule integral achieved are comparable in a broad range with those of semiconductor fuses. Presently, the investigations have been carried on substitution of IGBT for the TCB. More detailed information concerning HCLID is provided in the paper of Zyborski in this proceedings.

The point of this short examination of HCLID is a demonstration that methods based upon current commutation used in conventional CLDs like PPF, Ultrap Fuse, or Is-Limiter are still actual, however new elements are also being involved, e.g. such as semiconductor devices, and that their presence must be taken into consideration in the future current limiters designs.

### V.2.2 Varistor assisted fuse (VAF)

Varistor assisted fuse (VAF) was presented a few years ago by Wolny, Stokes and Kacprzak [25]. Its idea was born on comparison of operation costs and features of a sand filled fuse and that of expulsion type. A question surfaced: must current limitation cost so much, if current interruption by an expulsion fuse needs only a fraction of this amount? Moreover, unlike HV sand-filled fuses, expulsion fuses have typically full range features. The problem consists in the current interruption energy. Just after the arc ignition, in expulsion fuses the gas evolving confinement walls are still relatively cold, and time is needed to increase the pressure, causing gas stream flow efficiently cooling the fuse arc. Therefore, typically, expulsion fuse fail to limit fault currents. However, if the current is commutated into a parallel varistor during the fuse-arc ignition period, the varistor will limit the current, forcing it to zero. The energy deposited in the fuse reduces by an order of magnitude or more [25]. Typically, the energy deposited in a current commutating fuse during the process of commutation is approximately the same as that in the period of arc ignition [27]. This facilitates simplification of the fuse design, and lowers its cost. In Fig.7. typical assemblies of VAF are presented, in which the diagram b) shows that in some cases, typically for HV application, or when ***u-I*** characteristic of the varistor is far from rectangular, an additional switch can be welcome to avoid through-varistor currents after the fault clearing.

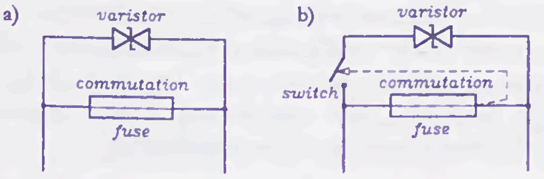


**Fig. 7**. VAF: a) $U_v / E >> 1$; b) $U_v / E \geq 1$

A bulk of the current interruption energy is deposited in the varistor. Dimensioning of the latter depends on the relationship between the varistor threshold voltage $U_v$ and the system voltage $E$ (peak value). The higher the varistor voltage the lower the energy deposited in the varistor. This energy $W_v$ equals to the energy stored in the magnetic field at the moment of current commutation $W_{mag}$, and that additional taken from the system $W_s$ [25].

$$W_v = W_{mag} \cdot \frac{U_v / E}{(U_v / E) - (I_f' / \omega)} \qquad (1)$$

where $I_f'$ is the normalised rate of fault current rise at the cut-off point, and $\omega$ is the frequency.

The magnetic field energy $W_{mag}$ depends on cut-off current and the reactance of the fault circuit, which in turn is related to the prospective fault current. The maximum energy $W_{mag,\,max}$ calculated for the peak value of the prospective current is inversely proportional to the inductance of fault circuit:

$$W_{mag,\max} = \frac{E^2}{2\omega^2 \cdot L} \qquad (2)$$

This implies that the component $W_{mag}$, of the energy $W_v$ under the worst conditions reduces as the prospective current rises.

It is evident that the maximum energy $W_{v,max}$ is deposited in the varistor when current commutation occurs at the peak of current wave. In such a case $W_{v,max}$ is given by the formula [25]:

$$W_{v,\max} = 0.05E \cdot \frac{U_v / E}{U_v / E - 0.72} \sqrt{S_f} \qquad (3)$$

where $S_f$ is the cross-section area of the fuse element. This equation demonstrates that the maximum energy deposited in the varistor is independent of the prospective current. However, $W_{v,max}$ rises as the system voltage and the square root of the cross-section area of fuse element, which shows that on application of fuses with reduced cross-section area of the fuse element, e.g. a substrate fuse, a reduction in varistor dimensions should be achieved.

Having in mind the fact that the increase in prospective current is due to reduction in the inductance of fault circuit, it can be demonstrated that the energy deposited in the varistor decreases inversely as the prospective current, Fig. 8., [25].

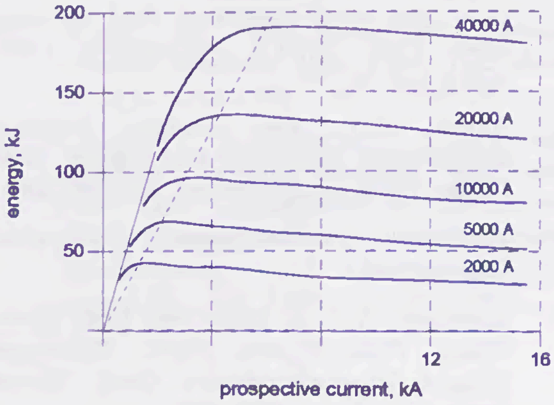


**Fig. 8**. Energy deposited in the varistor of VAF at $U_v$ = 18 kV, $E$ = 11 kV

Equation (3) also yields another important conclusion, indicating the importance of a proper selection of the varistor voltage $U_v$. If the ratio $U_v/E$ is high enough, the varistor only absorbs the energy stored in the magnetic field, and this energy can be significantly reduced by selecting a commutating fuse with small $S_f$. e.g. a substrate fuse.

The analysis given in [27] shows that the energy deposited in the fuse, during current commutation process, is approximately equal to the energy of the fuse element disintegration, Fig. 9., which is almost independent of fault conditions. However, it is proportional to $S_f$. This implies that a decrease in $S_f$ facilitates reduction in both the fuse and the varistor dimensions, without adverse effects on breaking capacity.

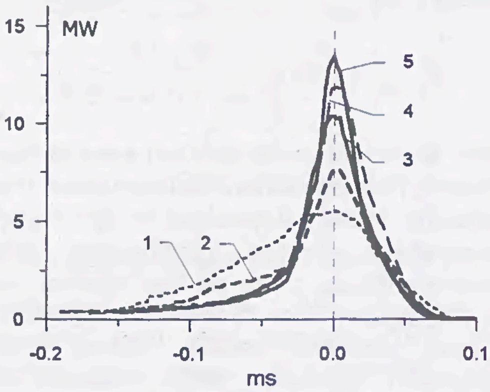


**Fig. 9**. Power deposited in the current commutating fuse at various prospective currents: 1 - 1 kA, 2 - 2.2 kA, 3 - 4.4 kA, 4 - 8 kA, 5 - 12 kA; for copper fuse element Ø 0.36 mm; $U_v = 6$ kV

The above discussion demonstrates that:

- any VAF has almost unlimited current breaking capacity,
- reduction in the cross-section area of a VAF is very beneficial,
- application of substrate fuses in VAF assemblies would be advantageous.

## VI. CONCLUSIONS

Further development of automatic, computerised protection systems, rising importance of automatic manufacturing, increasing reliability of transformers, machines and other devices, and changes in peoples preferences affect the demand for conventional fuses.

Since most kinds of fuses are considered very effective current limiters at LV and medium HV, their application is often associated with the limiting features. However, at LV in some areas they compete with semiconductor CBs.

Special kinds of current commutating fuses can improve current limitation technique at both LV and medium HV.

Possible extension of parameters of substrate fuses to higher voltages and currents can increase their application. Combination with ablation effects should not be excluded. It may happen that substrate fuses replace sand filled fuses in some applications.

Thin films technology, ablation effects, and new current commutation techniques seem to be interesting areas of the future development.

## REFERENCES

[1] Wang Jimei: Research on horse-shoe core type axial magnetic field vacuum fuse. Proc. ICEFA Nottingham (UK), 1991, pp. 33-36

[2] Akers, D.J.: $SF_6$ designs improve distribution switching and fusing, 1989 Power Technology Intern., pp. 267-268.

[3] Yorkshire Switchgear: Dyscon Interrupter

[4] Marriage, A.J., B. McIntosh: High speed Thick Film Fuses. Proc. European Hybrid Microelectronics Conf. Stresa (Italy), 1985, pp. 282-287.

[5] Harrison, R.D., I. Harrison, A.F. Howe: Ageing of film fuses on substrates. Proc. ICEFA, Nottingham (UK), 1991, pp. 85-91.

[6] Takahashi, H., K. Hirose: A semiconductor fuse-link on a ceramic substrate. Proc. ICEFA, Nottingham (UK), 1991, pp. 92-95.

[7] Lindmmayer, M., M. Luther: Fusing and short-circuit interruption bahaviour of metal film fuses. Proc. ICEFA, Nottingham (UK), 1991, pp. 107-113.

[8] Harrison, R.D., I. Harrison, A.F. Howe: Thin film fuse link. Proc. ICEFA, Ilmenau (Germany), 1995, pp. 169-175.

[9] Ossowicki, J., J. Sulikowski: Bezpieczniki warstwowe na pod³o¿u szklano-krystalicznym. Zeszyty Naukowe Wydz. Elektr. Politechniki Gdanskiej, No. 9, 1996, pp. 95-99.

[10] Ossowicki, J., J. Sulikowski: Postepy w rozwoju bezpiecznikow topikowycho charakterystyce ultraszybkiej. Zeszyty Naukowe Politechniki Poznanskiej, No. 44, 1997, pp. 201-208.

[11] Itoh T., Miyamoto T., Wada Y., Mori T., Sasao H.: Design considerations on the P.P.F. for a control center. IEEE Trans., vol. PAS-92, No.4, pp.1292÷1297, 1973.

[12] Wada Y., Takagi Y., Mori T., Hamano S., Miyamoto T., Itoh T.: Usefulness of permanent power fuse in control centers with molded case circuit breakers. IEEE Trans., vol. IA-16, No.1, pp.30÷39, 1980.

[13] Nakayama H., Fukazu T., Wada Y., Shinozaki Y., Ibuki K.: Development of high voltage, self-healing current limiting element and verification of its operating parameters as a CLD for distribution substations. IEEE Trans., vo. PD-4, No.1, pp. 342÷348, 1989.

[14] Brückner, P.: Ein neuartiges Schaltgerät mit äßerst kurzen Schaltzeiten. 1958, ETZ-A. vol. 78, pp. 33-40.

[15] Böttger, C.: The application of $I_s$-Limiters in three phase systems. Calor-Emag Eletrizitäts - Aktiengeselschaft D-403 Ratingen (Germany)

[16] Lindmayer, M, M. Schubert: Current limitation by high temperature superconductors and conducting polymers. Proc. ICEFA, Ilmenau (Germany), 1995, pp. 1-14.

[17] Zyborski, J., T. Lipski, S. Hassan, J. Wittstock: A new hybrid AC current limiting interrupting devicefor semiconductor converter protection. Pro. European Conf. on Power Electronics and Application EPE'95, Vol. 3, 1995, Seville (Spain), pp. 3.117-3.120.

[18] Czucha, J., M. Pikon, J. Zyborski: Ultra rapid IGBT-contact current limiting interrupting device of very high breaking capacity. Inter. Symposium on Short-Circuit Currents in Power Systems. Brussels (Belgium) 1998, pp. 219-222.

[19] U.S. Patent, Jan. 9, 1990, No. 4,893,106 (solidified sand)

[20] Eliade, R., E. Budascu: Contributions concerning new extinction media in ultra-fast fuses up to 2000 V a.c. Proc. ICEFA, Nottingham (UK), 1991, pp. 81-84.

[21] Lipski, T.: Behaviour of stone-sand fuses in short-circuit conditions. Int. Conf. on Gas Discharges and Their Appl., Swansea, (UK), 1992, pp. 204-207.

[22 Lipski, T., J. Ossowicki: Some aspects of application of stone-sand arc-quenching medium in H.B.C. fuses. Int. Symp.on Switching Arc Phenomena, £ódŸ (Poland), 1993, pp. 231-235.

[23] Pawlak R.: Optimization of conditions of laser alloying of silver surface layer. Proc. SPIE: Laser Technology IV, vol. 2202, Bellingham, 1994.

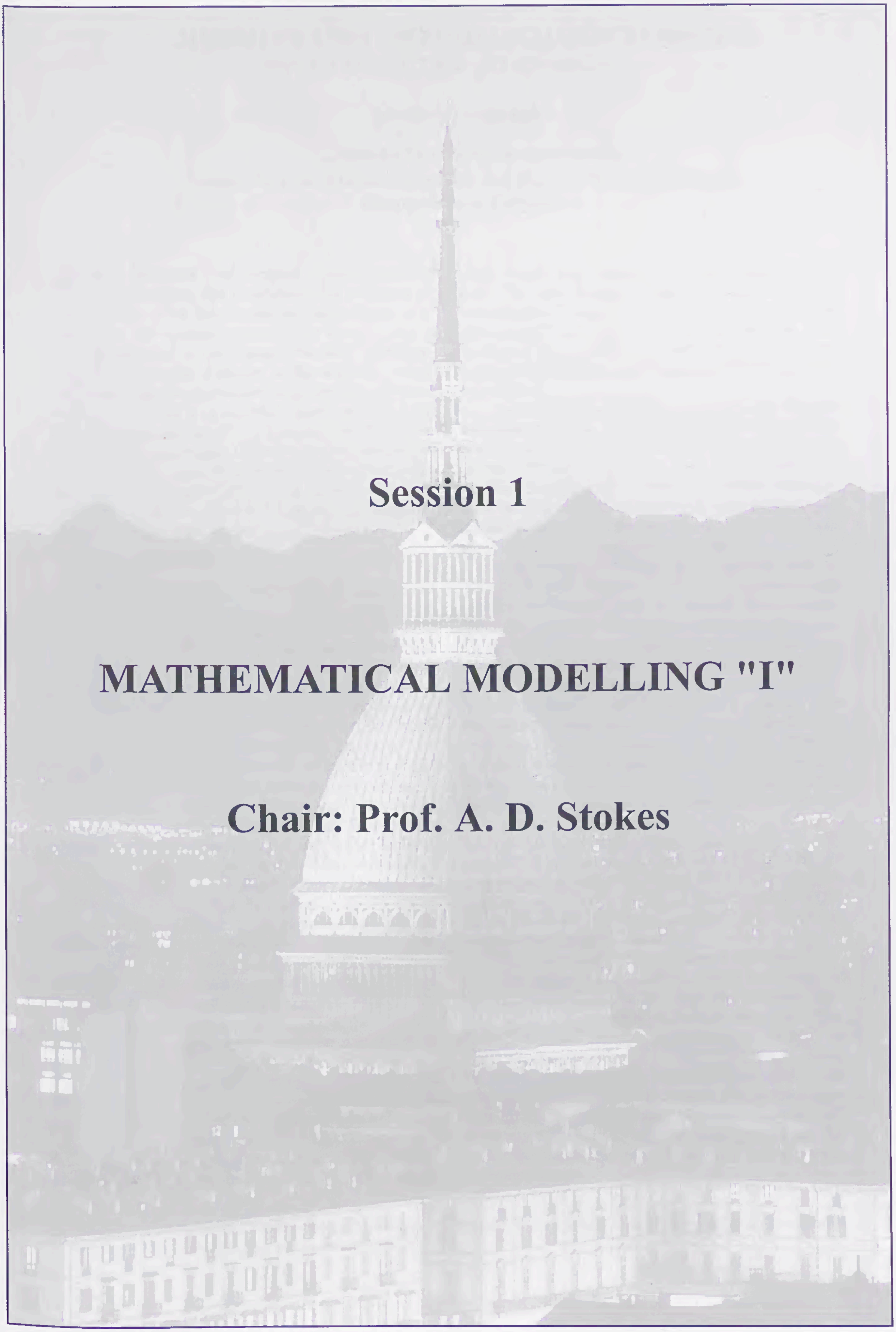
[24] Pawlak R, Raczyñski T.: Selected properties of surface layers of metals alloyed with pulsed laser. Materials Science and Engineering 1993, A168, pp. 67-70.

[25] Wolny, A., A.D. Stokes, B. Kacprzak: High voltage fuse behaviour with varistor commutation. Proc. IEE, Gen., Transm., Distrib., vol. 141, No. 1, pp. 33-37, **1994**.

[26] Wolny, A., A.D. Stokes: Varistor assisted fuse current breaking. Int. Symp. on Switching Arc Phenomena, £ódŸ, s. 245-248, **1993**.

[27] Wolny, A.: New protection means: varistor assisted fuse. Proc. ICECAAA, X'ian (China) 1997, pp. 524-528.

[28] Collard, P., S. Pellichero: A new high speed DC circuit breaker: the DHR. Proc. IEE, Colloquium on Electronic-aided Current-limiting Circuit Breaker Developments and Applications, IEE Digest No. 137, 1989, London (UK).



# Session 1

# MATHEMATICAL MODELLING "I"

Chair: Prof. A. D. Stokes