Thermal analysis and temperature calculation for the nv melting fuse

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Abstract

This research discusses the NV melting fuse, which is used to protect various types of circuits because of its good properties. The calculation is based on the 3D finite element (FE) analysis that is conducted with the software Vector Fields Opera. Current field analysis has been conducted from which Joule losses are determined along with static and transient analysis of thermal field of NV melting fuse. Analyses have been carried out for a different melting fuse current and for different shape of perforation of melting fuse. The obtained results provide necessary information on distribution of Joule losses and temperatures for cases of different currents.

Keywords: NV melting fuse, finite element method, current field calculation, thermal field calculation.

1. Introduction

There are many different ways to protect electrical devices and users against overload and short circuits. One of the first examples of protection of electrical power grid has already been used in the pioneer years of electrical engineering. In 1890, Thomas Edison, as part of his electric energy distribution system presented and patented a melting fuse. Its concept of functioning is fairly simple. The functioning is reliable and that is the reason why it is still utilized nowadays. The operation is based on Joule losses, which occur in melting element of the melting fuse. When the current throughout the melting element is higher than the nominal current, the Joule losses increase to a value, which heats up the melting element up to the melting point. Turn-off characteristic of a melting fuse is directly dependant on the Joule losses in a melting element and its heating. Heating is than dependent from heat transfer to other parts of a melting fuse. With intention to know the exact process in a melting fuse, the measures of current field has been conducted, on the basis of which the Joule losses have been evaluated. Those measurements have been used later on for the calculation of a thermal field as a thermal source. Analyses have been conducted on a NV type of a melting fuse with a nominal current of 160 A and for two types of perforation of melting elements.

2 Construction of the NV melting fuse

NV melting fuses [1] are used for short circuit protection of low voltage power grids. Despite various types of currents and fault voltages, NV fuses guarantee a short circuit protection, when a fuse is choen correctly based on the turn-off characteristics as well as maximum reliable and cost rewarding prices.

During its operation, a NV melting fuse terminates the current in less than 5 ms [2]. This means an extremely quick turn-off efficiency of a breakdown, which is for a 50 Hz grid, less than a quarter of a time period.

NV melting fuse is made of a number of electrical conductive and non-conductive parts (Fig.1). Melting element (1) is the most important part of the fuse. It is made out of a thin copper strip that is used for a more precise positioning of Joule losses and therefore it contains a number of perforated parts (2). Perforated spots cause the narrowing of conductive areas for electrical current. Because of such, ohm resistance increases in these areas. Many consecutive areas of perforation, in relation to a current direction, assures at the same time that during the melting of a melting element, the arc distributes into many shorter parts. Hence, a quicker and more reliable extinguishing of an arc is assured as well as a consecutive termination of circuit.

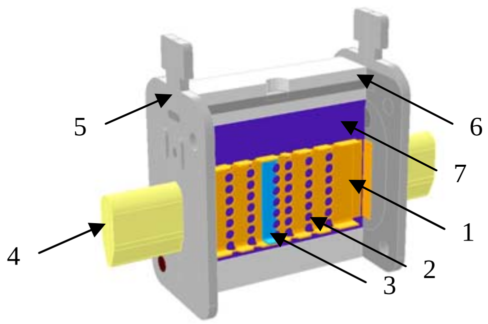

Fig. 1: NV melting fuse.

With the perforation of a melting element and additionally with a layer of low temperature melting alloy in the area of one perforation segment (3), it is possible to influence on the turn-off characteristic. Melting element is welded at the ends onto contact knives (4), which are impressed into the lids (5). The lids are fastened onto a fuse housing (6), which is made out of steatite. Steatite respectively soapstone is very good as an electrical insulator and it is basically magnesium silica in its structure. Area between the housing and the melting element is filled with pure silica sand (7), which has exactly defined chemical and granular structure. The sand with its thermal conductivity in considerable amount influences on the turn-off characteristic of the fuse. At the same time it influences on the time of extinguishing the arc. The fuse also has a built in indicator that interrupts the melting elements, which makes it easier to identify destroyed fuses as well as their replacement.

3. Mathematical description of the current and thermal field

3.1 Current field

Current field is a special example of a static electric field, which is observed only in electrical conductive areas. It is defined with an electric static potential ▯ [3]. Electric field strength **E** is given with (1).

$$\mathbf{E} = -\nabla \varphi \quad (1)$$

Current density **J**, in conductive areas is described with an equation (2), in which σ is specific electrical conductance:

$$\mathbf{J} = \sigma \mathbf{E} \ . \quad (2)$$

Since the current field is without a source, than the divergence of current density **J** equals to zero (3):

$$\nabla \cdot \mathbf{J} = 0 \ . \quad (3)$$

By taking into consideration (1) and (2) in (3), the Laplace equation of current field is easily obtained (4):

$$\nabla \cdot \left(\sigma \nabla \varphi \right) = 0 \ . \quad (4)$$

Upon the known distribution of electric field strenght and current density in electrical conductive region the Joule losses *p* can be calculated as (5):

$$p = J \cdot E \ . \quad (5)$$

and overall Joule losses for volume *V* are equal (6):

$$P = \int_V J \cdot E \, \mathrm{d}V \ . \quad (6)$$

3.1 Static thermal field analysis

Static thermal field occurs when the input thermal energy is equal to the dissipated one. At that time, in the observed area, there are not any changes in thermal energy. Thermal field can be presented with the use of temperature *T* as a scalar potential [4], [5]. Density of thermal current *q* is given with (7)

$$\mathbf{q} = -\lambda \cdot \nabla T \ , \quad (7)$$

where λ is thermal conductivity. Divergence of thermal current density offers density of thermal sources *Q* (8).

$$\nabla \cdot \mathbf{q} = Q \quad (8)$$

By combining equations (7) and (8), Poisson's equation is obtained for temperature distribution:

$$\nabla \cdot \lambda \nabla T = Q \ . \quad (9)$$

The corresponding boundary conditions determine whether thermal current flow is based on convection or radiation.

3.2 Transient analysis of thermal field

Transient analysis of thermal field is necessary when accumulated thermal energy varies with time. The change of thermal energy is equal to the difference between generated heat and dissipated heat, which is transferred over the areas of analysed region. It is described with (10), where ρ stands for mass density and *C* is heat capacity [4], [5].

$$\rho C \frac{\partial}{\partial t} T = Q - \nabla \cdot \mathbf{q} \quad (10)$$

By joining the equations (7) and (10), the temperature distribution is obtained (11).

$$\rho C \frac{\partial}{\partial t} T - \nabla \cdot \lambda \nabla T = Q \quad (11)$$

The boundary conditions of the analysed region need to be taken into consideration for the transient analysis.

4 Analysis of current and thermal field for the NV melting fuse

4.1 Geometric model of the NV melting fuse

Numerical analysis is based on 3D FE model of the melting fuse. The cross section of the model is shown in figure 1. FE analysis is conducted with programme tool Opera - Vector Fields [6]. The model contains all elements that are crucial for the description of current and thermal field. Very thin layers and perforations cause difficulties during the discretization of the model. Analysis is carried out for two different fuse models. The difference between them is in the shape of perforations whereas one contains round and the other square perforations. The most narrow portion between perforations of the melting element is equal in both cases. However, higher ohmic resistance occurs in the case of round perforations.

The material (thermal and electric) properties are given in table I [7]-[9]. The melting element is made out of copper, contact knives are made out of brass, the lids are from cold rolled alloy of aluminium and magnesium and solder is alloy of tin and copper. The melting point of solder is much lower than the melting point of a copper strip. The non-conductive areas also impact on the turn-off characteristic of the fuse. Silica is extremely important, because it is located between the melting element and housing. It prevents the arc from spreading and absorbs the heat. The housing is made out of steatite, which is characterized by high thermal resistance and very high dielectric constant as well as mechanical hardness.

Boundary conditions are scalar electric potentials that are set up on the surface (4) of the contact knife (Fig. 1). The potential difference between contact knives is chosen to ensure the expected current. Temperature values set up at the boundary of the domain specify the values a solution needs to take on the infinite surfaces.

Table I: Electric and thermal properties of used materials

Material	Specific conductivity ⍰ (S/m)	Thermal conductivity λ (W/m/K)	Specific heat *C* (J/kg/K)	Density ρ (kg/m^3)
Brass CuZn37	$16 \cdot 10^6$	120	376	8550
Steatite	10^{-12}	2.9	920	2710
AlMg3	$20 \cdot 10^6$	140	960	2650
Cu	$59 \cdot 10^6$	388	385	8920
SnCu1	$9.1 \cdot 10^6$	67	217	7310
Silica	10^{-15}	1	1201	830
Air	0	0.0257	1005	1.205

4.2 Current field calculation for the NV melting fuse

Heat source of the NV melting fuse is Joule loss. The current density is not equally distributed along the melting element. Therefore, the current field needs to be calculated in order to determine power loss. Current density along the melting elements is shown in Fig. 2. Figure 3 shows the coordinate dependence, which is perpendicular to the narrowing of the melting element area.

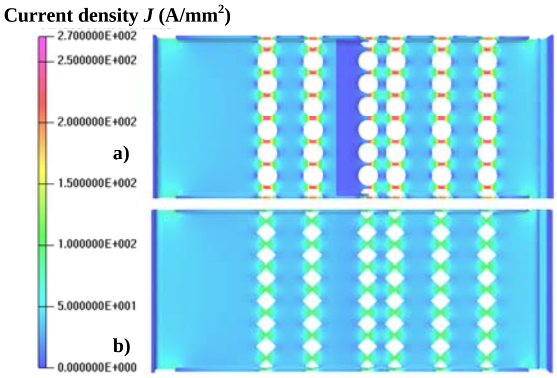

Fig. 2: Current density distribution in the melting element for current of 200 A: a) round perforation, b) square perforation.

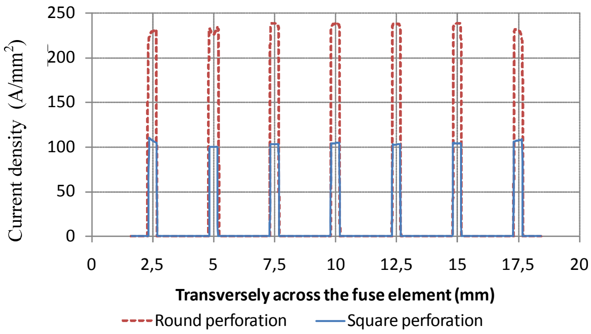

Fig. 3: Current density distribution in the melting element along the perforation line at the current of 200 A.

Distribution of Joule loss is calculated on the basis of the current field calculation (Fig. 4). Each FE contains an amount of current density that is further implemented as a heat source for thermal field calculation. Total power dissipation at the current of 200 A is 11.78 W for round perforation and 8.36 W for square perforation.

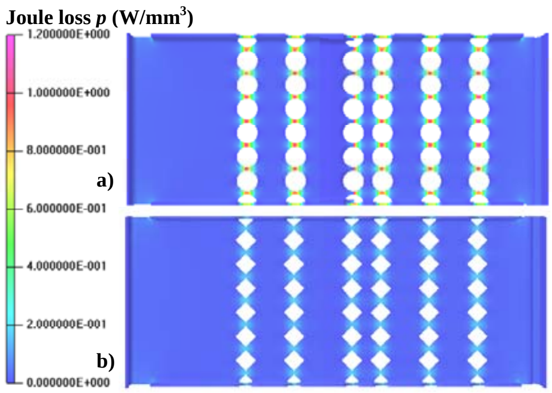

Fig. 4: Distribution of Joule loss for the melting element at the current of 200 A: a) round perforation, b) square perforation.

Figure 5 shows the distribution of electric potential along the melting element for both perforation shapes.

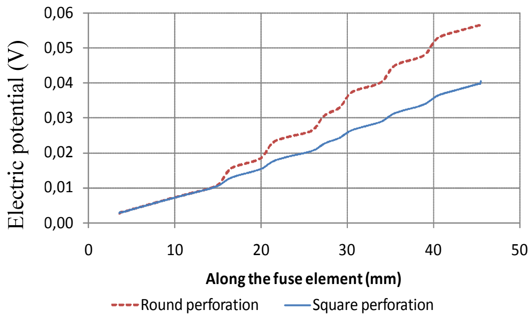

Fig. 5: Electric potential along the melting element at the current of 200 A.

4.3 Calculation of static thermal field at the current of 200 A

During the calculation of static thermal field, the same discretization is used as in current field calculation.

Therefore, the calculated Joule loss of each FE can be used directly as an individual source of heat that is further applied in thermal field calculation. The room temperature is 25 °C. The current of 200 A represents the upper limit for both the solder and the melting element.

The temperature distribution for the fuse cross-section along the melting element is shown in Fig. 6 and includes a round and a square perforation.

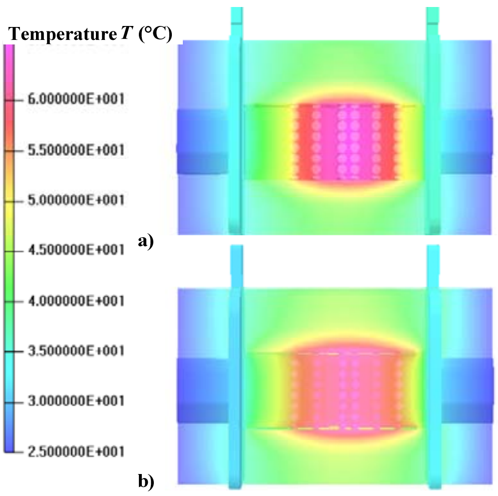

Fig. 6: Temperature distribution throughout the NV melting fuse at the current of 200 A for the static analysis; a) round perforation, b) square perforation.

4.4 Calculation of transient thermal field at the current of 800 A and 2000 A

Transient analysis of thermal field shows how the fuse behaves when exposed to the short circuit current. Because of such, the simulations have been carried out for 800 A and 2000 A. For both current values, the heat sources are calculated from the current field, which, of course, does not depend on the temperature. Temperature distribution along the thickness of the melting element is shown in Fig. 7, as well as for the solder and round perforation. The previously mentioned temperature distribution is for a particular moment in time when the temperature of the solder reaches the melting point, which is 240 °C. That critical point is reached in 4.6 s at the current of 800 A (Fig. 8). In the case of 2000 A, it is reached only in 0.17s. Figure 7 also confirms that the heating at 2000 A is mostly adiabatic. The short time needed for heating indicates that the heat does not transfer onto other parts of the melting fuse.

Figure 8 shows how fast the melting element area located beside the solder heats up with respect to time when the current equals 800 A.

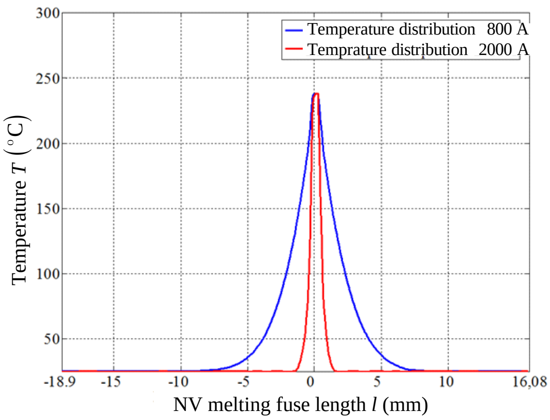

Fig. 7: Temperature distribution along the perpendicular direction of the melting element at the current of 800 A and 2000 A for round perforation; note that it is given for a particular moment in time when temperature reaches 240 °C.

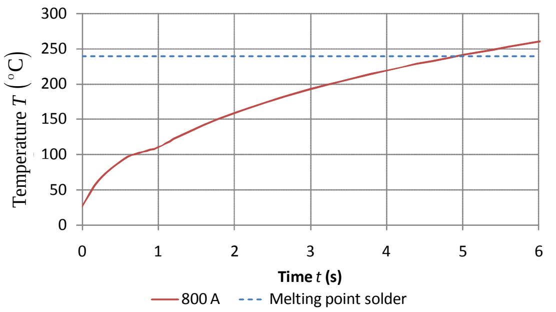

Fig. 8: Transient thermal behaviour of the fuse with the round perforations of the melting element, at the current of 800 A.

5. Conclusion

The experimental way to conduct the fuse analysis is not always suitable and most welcome. The problems occur when the turn-off characteristic varies among different fuse samples. The other more significant difficulty is the following: when testing the melting element once, the solder melts and it is impossible to repeat the experiment with the same sample. Therefore, it is very useful to apply accurate simulations and obtain the corresponding results.

The accurate simulation for current and thermal field requires a 3D numerical model as well as to posses the exact electric and thermal properties of the used materials. Thermal properties of the silica are varying with the purity and granulation and therefore, can cause problems in simulations.

Calculations and simulations confirm that the actual working conditions of the fuse can be presented and even under the different current supply and different surroundings. All results have not been experimentally verified except the case of current 256 A. The temperature of all crucial construction parts of the fuse has been measured with corresponding thermo couples. The time needed for the solder to melt has been measured as well. The transient analysis confirms that short-circuit currents that are few times larger than the nominal current, cause the heat to accumulate in the melting element, before the solder melts. In such case, the heat transfer to the remaining construction parts of the fuse is negligible. On the other hand, its role is important when the operating current of the fuse is just a little bit above the nominal value. The analysis shows as well that the perforation shape has an impact to the released heat inside the melting element. Joule loss is higher in the case of round perforations, because the conductive areas are smaller and therefore, the electric conductivity is lower.

References

[1] http://www.eti.si
[2] Martin Bizjak, Janez Kovač, Mitja Koprivšek: "The Phenomena Controlling the Melting Phase of a Fuse Element During a Break". *MTAEC9*, Ljubljana, 2004, p.123.
[3] Matthew N.O. Sadiku: "Elements of Electromagnetics". Thired Edition, Oxford University Press, Inc., New York, 2001.
[4] Frank P. Incropera, David P. DeWitt: "Introduction to Heat Transfer". Thired Edition, John Wiley & Sons, Inc., New York, 1996.
[5] Gorazd Horvat, Anton Hamler "Determination of heat circumstances in the motor protection switch considering air flow". IEEE trans. magn., vol. 42, No. 4, apr. 2006, p. 1071.
[6] Opera-3d: Reference manual user guide, version 12, 2007.
[7] http://www.metallurgy.nist.gov/phase/solder/cusn.html
[8] http://www.insaco.com/MatPages/materials.asp
[9] http://www.engineeringtoolbox.com

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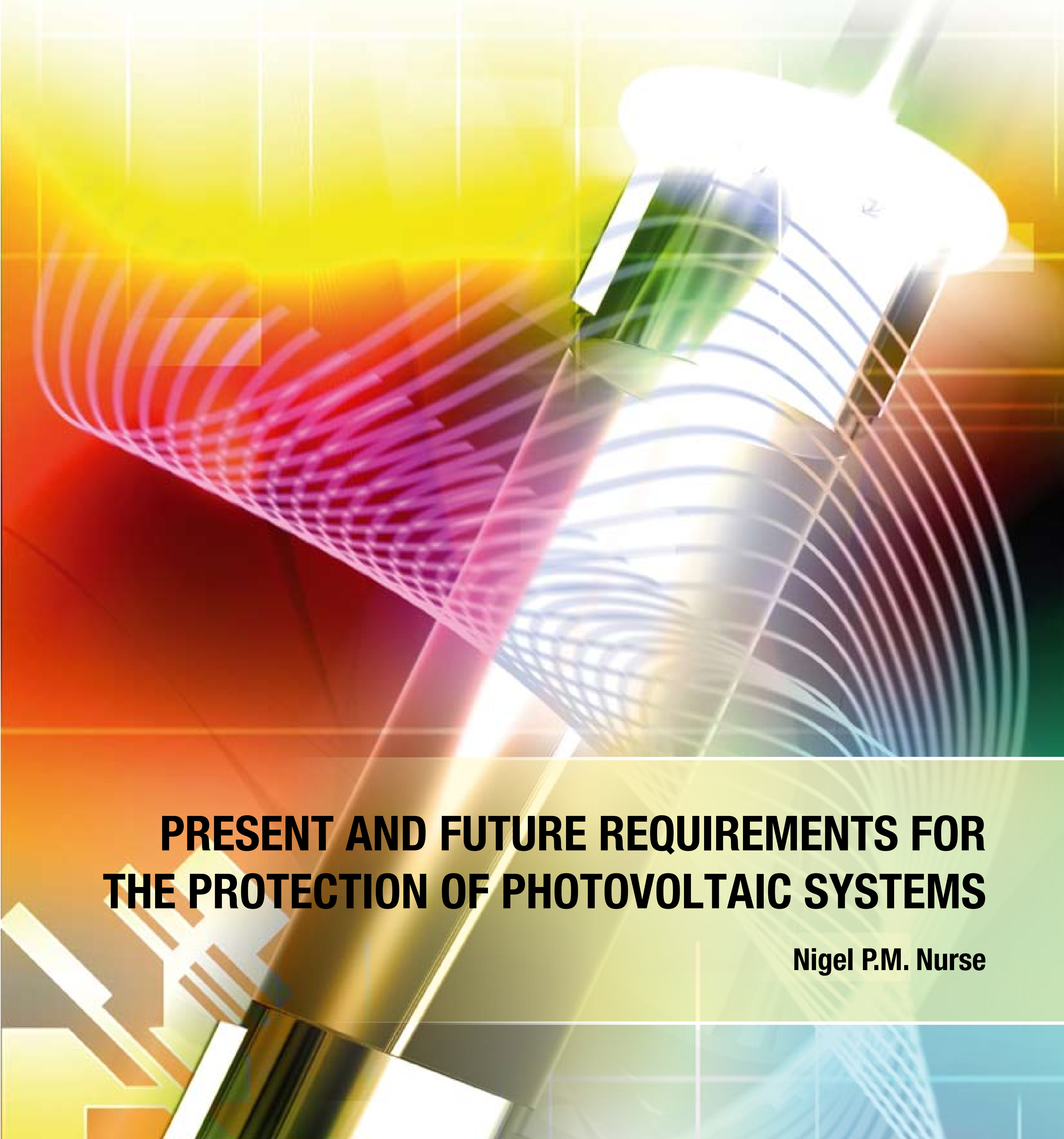

PRESENT AND FUTURE REQUIREMENTS FOR THE PROTECTION OF PHOTOVOLTAIC SYSTEMS

Nigel P.M. Nurse