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Analysis of current harmonic on power system fuses using ANSYS

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Abstract

One of the most important protective devices in power systems are fuses which have been used for ages. Passing short circuit current from fuse causes to warm fuse element that it will open this path. Fuse temperature can directly affect fuse operation and its melting as well. Therefore, fuse should be designed in a way that it does not operate at nominal current and instantaneous over currents whereas it should operate at error case. In this paper, firstly, fuse element is investigated and its behavior is studied. Then, a sample fuse with its different sections is simulated under sinusoidal and non- sinusoidal currents. After that, different parameters such as thermal distribution, thermal flux, and electrical potential in all fuse parts are obtained for sinusoidal and non-sinusoidal currents. Also, Fuse temperature for various THD values is determined. Finally, an equation to determine fuse nominal current due to harmonics is presented.

Keywords: Thermal Flux, Current Harmonics, Power System Fuses, Finite Element Analysis, ANSYS.

Introduction

One of the earliest and simple protective devices in power systems are fuses which are classified into four categories (Torres, Fernandez *et al.*, 2005): High-voltage (HV): (132 kV); Medium-voltage (MV): (1 kV to 132 kV); Low-voltage (LV): (until 1 kV); Miniature: associated with physical dimensions.

In recent research, several models of fuses were developed (Dolegowski, 1976; Gnanalingam & Wilkins 1980; Narancic & Fecteau 1984; Petit, St-Jean *et al.*, 1989; Bottauscio, 1991; Douglas, 1993; Lee, 2010), most of them are based on a mathematical representation of the arc physics. These models include transient heating and fusion of notched strip elements in sand, arc ignition, and subsequent burn-back, radial expansion of the arc channels due to fusion of the sand, merging of adjacent arcs, and many other second-order effects (Memiaghe, Bussière *et al.*, 2007; Rochette, Bussière *et al.*, 2007).

Plesca (2007), developed a 3D thermal model in order to study the temperature distribution at a fast fuse. In this model, the thermal behavior of fast fuse depends on design of fuse link elements, material parameters and ambient conditions. Lindmayer (1999), has developed a Windows based program code for modeling complete fuses, including M-Effect, using the Finite Volume Method.

Beaujean, Newbery *et al.* (1995) has used a commercial FEM package to model heating of relatively simple fuse geometries without notches and with one single notch, respectively. Other FEM work has been reported in (Cañas, Fernández *et al.*, 1999;

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Jakubiuk & W, 2003; Pleşca, 2003).

Wilkins (1991) described the temperature distribution and the thermal and electrical resistances of basic elements of the fuses by exact or semi-empirical analytical equations, and combined with iterative solution procedures. The fuse link is represented by an equivalent R-C network (Gelet, Tournier et al., 1999; Pleşca, 2001; Hoffmann & Kaltenborn, 2003), Other simulations have also been done for fuse analysis among them finite element (Fernández, Cañas *et al.*, 1995; Kürschner, Ehrhardt *et al.*, 1995; Wilniewczyc, McEwan *et al.*, 1999), or Finite Difference schemes (Garrido & Cidrás, 1999) can be mentioned.

John (2006) presented thermal analysis of a medium voltage fuse by means of the finite element method. The thermal problem in electric fuses has been studied by different authors (Agarwal, Stokes et al., 1987; Sasu, 1995; Baraboi, Ciutea *et al.*, 1999; Lijun, Zhiying *et al.*,

1999; Kawase & Miyatake, 2000; Hoffmann & Kaltenborn, 2003), who have focused their analysis on the fuse element (Agarwal, Stokes et al., 1987; Sasu, 1995), the fuse contacts (Baraboi, Ciutea *et al.*, 1999), or larger parts of the fuse (Lijun, Zhiying *et al.*, 1999; Kawase & Miyatake, 2000; Hoffmann & Kaltenborn, 2003). In this paper, by modeling a 2D thermal model of fuse in ANSYS, the effect of harmonic on fuse thermal operation is investigated. The temperature distribution and thermal flux through all fuse link elements are obtained by ANSYS simulation.

Analysis of fuse operation for sinusoidal case

In this part, simulation is carried out for sinusoidal current. For this purpose, a fuse with following electrical Indian Journal of Science and Technology

Fig. 2. Temperature distribution along the fuse element



Fig. 3. Temperature distribution along the fuse length in sinusoidal condition



characteristics is simulated:

 $I = 100 \ A, \ \Delta V = 22 \ mV, \ R = 0.22 \ m\Omega, \ T_{melting} = 230 \ ^{\circ}C$

When fuse temperature reaches over 230 °C, fuse will be melted. The sample fuse with approximate length of 40 cm is modeled in ANSYS which is shown in Fig. 1.

In this case, static analysis is used. Thermal distribution in fuse is shown in Fig. 2. According to this figure, the maximum temperature belongs to center of fuse element. The minimum temperature is in external edges of fuse element which its value is 186.449 °C and the center of fuse element has maximum temperature about 211.305 °C. Temperature distribution versus fuse length is plotted in Fig. 3. In this figure, the maximum

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Fig. 4. Voltage distribution along the fuse link



value is in fuse element centre as it is going far from center, temperature value is decreasing (Table 1).

Fig. 4 shows voltage distribution in fuse link. In this case, for each fuse contact, voltages of 0 V and 22 mV are applied respectively. Voltage distribution through fuse element length is shown in Fig. 5. Considering this figure, the maximum and minimum fuse voltage values are respectively equal to 0.936 mV and 21.069 mV. One of the other important parameters in fuse thermal analysis is thermal flux which for fuse element is plotted in Fig. 6. It can be viewed from this figure that the maximum thermal flux value is in flux element edges which is equal to 1.27×10⁻⁷ W/m².

Fuse thermal behavior analysis using finite element for non-sinusoidal current

Here, it is assumed that fuse current waveform is nonsinusoidal. In other words, it contains harmonics. These harmonics affect fuse temperature rising which will be investigated in this part. First, the effects are discussed. Then, for different cases (current with different THD values), fuse will be simulated with ANSYS.

Losses in fuse element

In harmonic conditions, current contains different harmonics which each component can cause to create losses in fuse element. These losses lead to heat generation. If this heat is increased exceedingly, fuse element will be melted. Loss power can be written as:

$$P_{Loss} = R(I_1^2 + I_2^2 + \dots + I_h^2) = RI_1^2 \left(1 + \sum_{h=2}^n \frac{I_h^2}{I_1^2}\right) \quad (1)$$
$$\implies RI_1^2 \left(1 + THD^2\right)$$

Parameter	Material						
	Ceramic	Copper	Iron FE40	granular	Silver	Insulation material	Air
	body (5)	(1, 2)	(3)	quartz (7)	(6)	/pressed carton (4)	
Density, ρ [kg/m ³]	2400	8900	7190	1500	8210	1400	1.09
Specific heat,	1088	387	420.27	795	377	0.099	1006
c [J/kg⁰C]							
Thermal conductivity, λ [W/m ² C]	1	385	52.028	0.325	121.22	0.063	0.027

Table 1. Electrical and thermal characteristic of different parts of fuse

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Fig. 6. Thermal flux along the fuse element



Fig. 7. Normalized power losses in fuse length versus frequency





Fig. 9. Voltage distribution along the fuse element in harmonic condition



Fig. 10. Temperature distribution along the fuse link in harmonic condition (THD=40%)





(3)

fuse can be written as:

$$P_r = RI_r^2 \tag{2}$$

To have $\mathsf{P}_{\mathsf{loss}}$ = P_{r} , using (1) and (2) can be conclude that:

$$I^* = \frac{I_r}{\sqrt{1 + THD^2}}$$

Where I^* is the new nominal fuse current in harmonic condition. Fuse loss power is calculated for different harmonics with I = 100 A which its results are listed in Table.2. From this table data, normalized loss power in fuse element versus frequency is shown in Fig. 7.

|--|

f	h	P(W/m)	P_h/P_{50}
50	1	0.721	1
100	2	2.88	3.99
150	3	6.49	9
200	4	11.53	15.99
250	5	18.02	24.99
300	6	25.94	35.97
350	7	35.3	48.95

This figure indicates that this function is approximately quadratic which can be written as;

$$\frac{P_h}{P_1} = 0.0004 \times f^2 + 0.0002 \times f - 0.013 \tag{4}$$

According to results from Table.2, an estimated equation can be expressed for normalized loss power in different harmonics versus harmonic orders:

$$\frac{P_h}{P_1} = h^2 \tag{5}$$

Hence, harmonic of h^{th} order creates $P_h = h^2 P_1$ loss in fuse. If current amplitude of h^{th} harmonic is considered h^2 times of fundamental component, following equation can be written:

$$P_{Loss} = R \left(I_1^2 + \sum_{h=2}^{\infty} h^2 I_h^2 \right) = R I_1^2 \left(1 + \sum_{h=2}^{\infty} h^2 \frac{I_h^2}{I_1^2} \right)$$
(6)

Regarding that harmonics cause to rise the fuse temperature, therefore, amplitude of current fundamental component should be decreased. In other words, it should be de-rated or its capacity should be decreased. If current fundamental component is equal to I_r , de-rated current value will be obtained from:

$$I^* = \frac{I_r}{\sqrt{1 + \sum_{h=2}^{\infty} h^2 \frac{I_h^2}{I_1^2}}}$$
(7)

For instance, fundamental component and its harmonics are considered as follow:

 $I_1 = 100A, I_3 = 10A, I_5 = 5A$

Then, power loss can be calculated in two cases:

- without considering skin effect
- considering skin effect

Not considering skin effect (ignoring skin effect)

By ignoring skin effect, power loss can be calculated from (1). RMS fuse current should be de-rated about 0.62%. For

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example, if fuse nominal current is 100 A, current value of more than 99.38 A should not be flown through fuse:

$$I^{*} = \frac{100}{\sqrt{1 + \left(\frac{10}{100}\right)^{2} + \left(\frac{5}{100}\right)^{2}}} = 99.38 A$$
(8)
$$DR\% = \frac{99.38 - 100}{100} \times 100 = -0.62\%$$
(9)

Considering skin effect

If frequency effect or skin effect is considered, power loss should be determined from (6). In this case, DR is about 6.85% which is 10 times greater than DR in previous case:

$$I^{*} = \frac{100}{\sqrt{1 + 9\left(\frac{10}{100}\right)^{2} + 25\left(\frac{5}{100}\right)^{2}}} = 93.15 \ A \tag{10}$$
$$DR\% = \frac{93.15 - 100}{100} \times 100 \approx -6.85\%$$

Fuse simulation results when THD=10%

In this case, current THD through fuse is approximately equal to 10%. In continue thermal behavior of fuse different parts are evaluated using obtained simulation results. Temperature distribution in fuse element is shown in Fig. 8.

Clearly in this figure, the hottest point of fuse is in center of this element. The least temperature is located in external edges which its value is 188.215 °C. Voltage distribution along fuse element length is plotted in Fig. 9. According to this figure, the minimum and maximum potential of fuse element are respectively equal to 0.941 mV and 21.179 mV. In this condition, voltage values of fuse contacts are considered 0 V and 22.12 mV.

Fuse simulation results when THD=40%

Thermal distribution when THD=40% is shown in Fig. 10 that minimum and maximum temperatures are respectively 25.00 °C and 241.027 °C which in comparison with previous case, they are significantly increased.

THD effects on fuse temperature increasing

To investigate THD effects on fuse temperature, the hottest point temperature values for different THD values are obtained which are listed in Table 3.

Fuse temperature variation versus different THD values curve is specified in Fig. 11. This figure shows that by THD

Table 3. Fuse hot point temperature in different THD

Values							
THD	0	10	20	30	40		
T _{hot}	211	213.3	218.65	228	240.8		

Fig. 11. Fuse hot point temperature versus THD



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increasing, fuse temperature will be increased as well. This relationship can be estimated by following quadratic equation:

$$T_{hot} = 0.01 \times THD^2 + 0.029 \times THD + 210$$
(12)
Conclusion

Conclusion

In this paper, firstly, fuse operation has been analyzed. For this purpose, a sample fuse has been modeled in ANSYS software. Besides, regarding that fuse temperature has direct effect on fuse operation and its melting, therefore, fuse thermal analysis has been modeled and simulated in ANSYS. Moreover, fuse has been simulated under sinusoidal current and different parameters such as temperature distribution, thermal flux, voltage and so on relating to various parts of fuse have been obtained and investigated. Furthermore, an equation between fuse and harmonics has been presented. Also, fuse temperature increasing due to harmonic existing in fuse current has been evaluated. Fuse nominal current for different THD has been determined as well. Finally, a sample fuse under different harmonic currents has been simulated and the hottest point curve versus various THD values has been presented using simulation results by which fuse temperature at different THDs can be obtained.

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