Operational characteristics in thermal elements of low voltage automated fuses due to supraharmonics

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***Abstract*—The high penetration of small scale renewable Energy Sources (RES) and high power electronics in the low voltage network has led to significant increase of the inverters and power electronics operating in the said networks. This equipment induces current and voltage harmonic distortions in the electrical network of orders quite higher than the ones already regulated by international standards, which are known as supraharmonics (in the range of 2-150kHz). These harmonics, which are not easily filtered, pass through the distribution transformers to the final consumers' electrical installations such as homes, hospitals, schools and industries. These harmonics, and especially the harmonic distortion due to current, can influence the performance of a thermal element in automated fuses and Miniature Circuit Breakers (MCB). This paper examines the influence of such harmonic currents onto the thermal element of automated fuses and MCB, as their magnitude is not negligible and may alter the designed operational characteristics, while at this point there is absence of any specific regulation regarding their level. Simulation has been conducted by utilization of Matlab code analyses so as to define the impact of the supraharmonics on typical types of equipment. Simulation results are based on real measurements performed in a typical 8kWp small roof top PV installation.**

Keywords-- Fuses, Supraharmonics.

I. Introduction

This manuscript will describe the behavior of Miniature Circuit Breakers (MCBs) under the operation of electric current containing high frequency harmonics in the area of 2kHz to 20kHz. This frequency area is a band inside the supraharmonic frequency area beginning at 2kHz up to 150kHz [1]. This project is based on the electric current measurements, on an 8kWp small roof top photovoltaic (PV) installation, which were taken using an electric current probe and a Gwinstek GDS-2102A (100MHz- 2GS/s)digital oscilloscope. According to the measurements, the switching frequency for the inverter captured at 16kHz and the signal peak amplitude at this frequency was 0.15V when the amplitude at the base frequency (50Hz) was 18V peak. The power inverter of the PV is a SMA TRIPOWER 10000 which has as AC at 50Hz maximum operation electric current 14.5A [2]. This means, that for a peak current of 14.5A at 50Hz the corresponding current amplitude for 16 kHz will be 0.12A. As for the MCB, the composition for the head of the moveable contact is silver graphite Cag (5). The composition for the static contact is pure copper T2Y2 [3]. The bimetal plate's composition is 5J158 to TB180, depending on the current.

II. Technical dESCRIPTION of the problem

A. MCB Technical Description

An MCB includes a thermal and a magnetic element. The thermal element, usually referred as bimetallic strip, protects against the overload of an electric line. The magnetic element protects against a short circuit. Figure 1a illustrates the internal construction of an MCB.

This paper will examine the influence of the supraharmonics on the thermal element of the MCB. The bimetallic strip is a strip constructed by two different conducting strips, fused together, of identical dimensions but with difference in isotropic resistivityand isotropic elasticity. While the current carries through the bimetallic strip, the temperature rises which means that the length of each conducting element will change. Due to their difference in their isotropic resistivities and elasticities, one strip will demonstrate higher expansion than the other, resulting in bending of the bimetallic strip as Figure 1b illustrates.

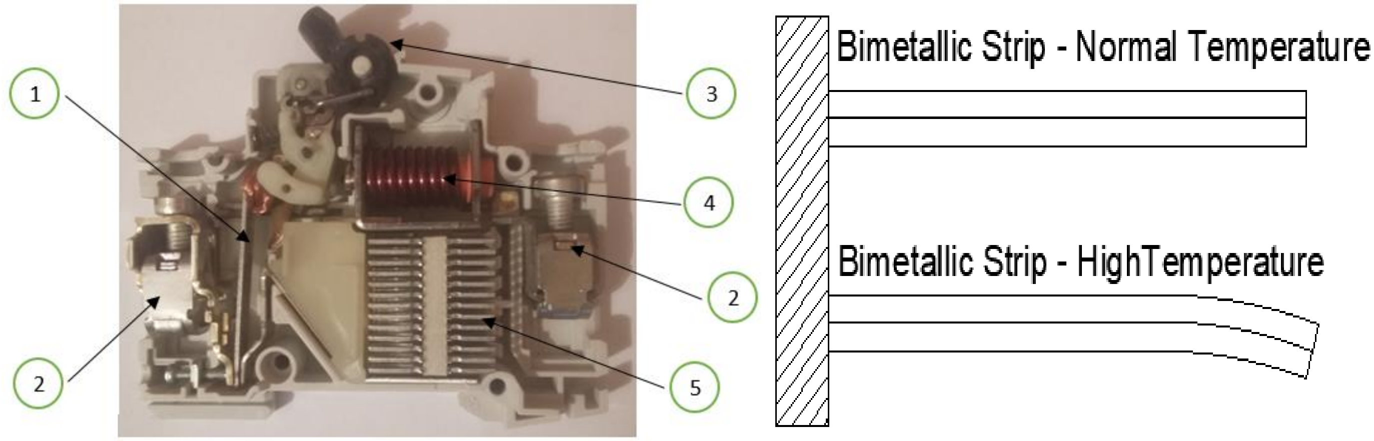
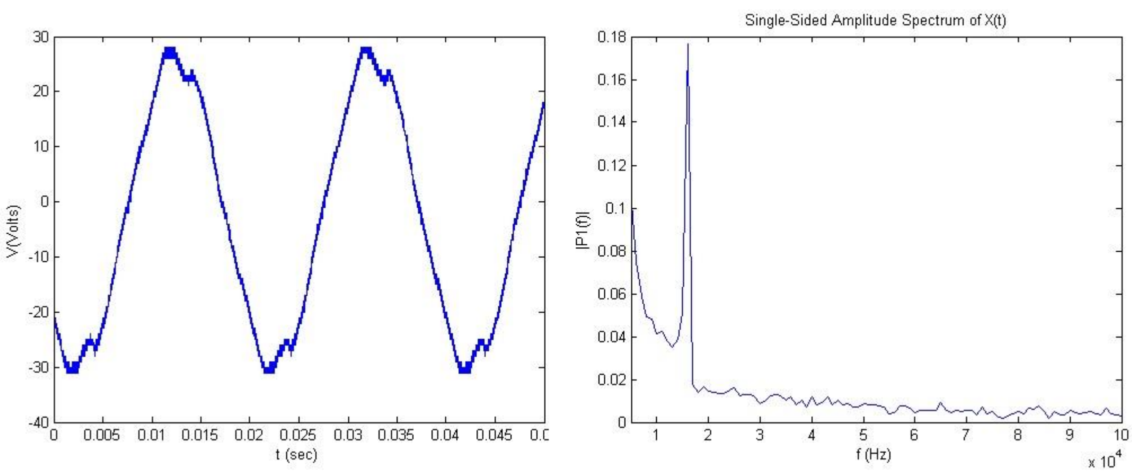


Figure 1. a) B16 MCB internal construction :**1**. Bimetallic Strip, **2**. Contact Terminal, **3**. Operating Handle, **4**. Coil Assembly, **5**. Arc Chamber
b) Operation of bimetallic strip

B. Inverter Technical Description

In order to proceed to the study of the supraharmonics on the thermal element of the MCBs a number of measurements must be done. The measurements were carried out on a 8kWp small roof top photovoltaic system, which uses an inverter type SMA TRIPOWER 10000. The electrical panel of the installation includes MCBs of 16A per phase and according to this type of MCB the following analysis has been done. After the measurements on the current of this PV system, the current probe sensor measured a 0.15V signal at 16kHz frequency when the peak value of the basic 50Hz frequency measured as 18V. Obviously the spike at the 16kHz sources from the inverter's switching frequency. Correspondingly, when the current per phase is 14A /50Hz the 16kHz electric current value will be 0,11A. Customizing these data on a large PV system producing 1,4kA per phase, the corresponding current value on 16kHz will be 11.67A, which is a value that can affect the electronics of a substation and pass on the medium voltage lines, after the PV's transformers. This supraharmonic value can affect the consumers if their protecting devices, and therefore the MCBs, fail to operate normally for electric currents at this frequency. Figure 2a illustrates the current probe output for a 40ms time interval, whereas Figure 2b illustrates the Fast Fourier Analysis over the signal in the band around of 16kHz.



(a) (b)

Figure 2. a) Current probe measurement for 40ms
b) Fast Fourier Analysis around the band of 16kHz

Table I illustrates the THD values for the SMA TRIPOWER 10000 inverter according to its manufacturer datasheet [4]. The 16kHz value, which was measured, is also included in this table.

TABLE I. SMA TRIPOWER 10000 CURRENT DISTORTION ACCORDING TO THE MANUFACTURER AND REAL MEASUREMENTS

Description	Harmonic Current % = I_n/I_1						
Hz(Order)	150(3rd)	250(5th)	350(7th)	450(9th)	550(11th)	650(13th)	~16kHz(320)
L1	0.10	0.47	0.76	0.02	0.08	0.36	
L2	0.14	0.62	0.66	0.06	0.11	0.34	
L3	0.16	0.47	0.74	0.03	0.07	0.35	
Mean Value	0.13	0.52	0.71	0.04	0.09	0.35	0.54

III. ANALYSIS OF MCB THERMAL ELEMENT'S BEHAVIOR

The behavior of an MCB's thermal element is described in this paragraph. AC MCBs are designed to operate under a normal frequency of 50 or 60Hz. However, the existence of harmonics and supraharmonics can affect the total thermal effect of the MCBs. This paper will examine the existence of an electric current of 50Hz frequency including a supraharmonic of 16kHz. Therefore, the influence of the skin effect on the thermal element must be considered in this analysis. According to the skin effect, a conductor presents different resistances at different frequencies. Each resistance multiplied with the square rms value of the electric current at each corresponding frequency, produces a specific thermal effect. By calling ΔT_{50} the temperature difference of a current carrying conductor for a current with frequency of 50Hz and ΔT_{16k} the corresponding temperature difference produced by a current at the frequency of 16kHz on the same conductor, the total temperature difference ΔT_{tot} can be calculated using the (1).

$$\Delta T_{tot} = \Delta T_{50} + \Delta T_{16k} \quad (1)$$

The resistance of a conductor, and therefore of a bimetallic strip, is proportional to the specific resistivity ρ [Ohm-m] and the length l[m] and is inversed proportional to the conducting cross section A[m^2] as (2) describes.

$$R = \rho \cdot l/A \quad (2)$$

The bimetallic strip can be analyzed as a rectangular conductor of width w and with a total thickness of t which means that the cross-section of the bimetallic strip is A = w·t. As the resistance of the conductor is depended from the electric current's frequency, the resistance at each frequency must be calculated. This calculation can be done using (3) [5].

$$R_{hf} = K_c\,[\rho \cdot l/(2 \cdot (w+t) \cdot \delta)] \quad (3)$$

Where ρ is the total specific resistivity of the bimetallic strip and is temperature dependent, l is the length, w is the width, t is the thickness of the bimetallic strip, δ is the skin depth and K_c is the increase in resistance due to the crowding phenomenon.

The skin depth is dependent on the frequency of the flowing electric current, and the (4) describes the calculation for this depth for a rectangular conductor [5].

$$\delta = [\rho/(\pi \cdot f \cdot \mu)]^{0.5} \quad (4)$$

Where μ [H/m] is the magnetic permeability of a rectangular conductor of a bimetallic strip.

The crowding effect is the phenomenon at which the electric current is concentrated at the edges and the corners of the rectangular conductors. The crowding factor can be calculated using the (5) and (6). Equation (5), calculates the K_c according to Cockroft [6], and it is valid only when the thickness is appreciably greater than twice the skin depth, ie in high frequencies [5].

$$K_c = 1.06 + 0.22 \cdot \ln(w/t) + 0.28 \cdot (t/w)^2 \quad (5)$$

$$K_c = 1 + F(f) \cdot [0.06 + 0.22 \cdot \ln(w/t) + 0.28 \cdot (t/w)^2] \quad (6)$$

The factor F(f) describes the variation with frequency, being unity at very high frequencies and zero at very low frequencies. The theoretical determination of F(f) is difficult and according to [5] it can be estimated using (7).

$$F(f) = (1 - e^{-0.048 \cdot p}) \quad (7)$$

Where p can be calculated using (8) [5].

$$p = A^{0.5}/(1.26 \cdot \delta) \quad (8)$$

Where A is the cross-sectional area in mm^2 and δ is the skin depth in mm.

As the resistances for each frequency have been calculated, the next step is the calculation of the temperature difference for the bimetallic strip. According to the bimetals' manufacturers [7, 8], the temperature difference can be calculated using (9).

$$\Delta T = I^2_{rms} \cdot R \cdot \Delta t / [c \cdot m] \tag{8}$$

Where I_{rms} is the rms value for the flowing AC electric current, R is the resistance of the bimetallic strip for a specific frequency, Δt is the time interval under which the flowing current is applied, c is the specific heat capacity of the bimetallic strip and m is the mass. The mass is calculated using (9).

$$m = d \cdot l \cdot w \cdot t \tag{9}$$

Where d is the density of the bimetallic strip. The bimetallic strip material's properties are illustrated in Table II [9].

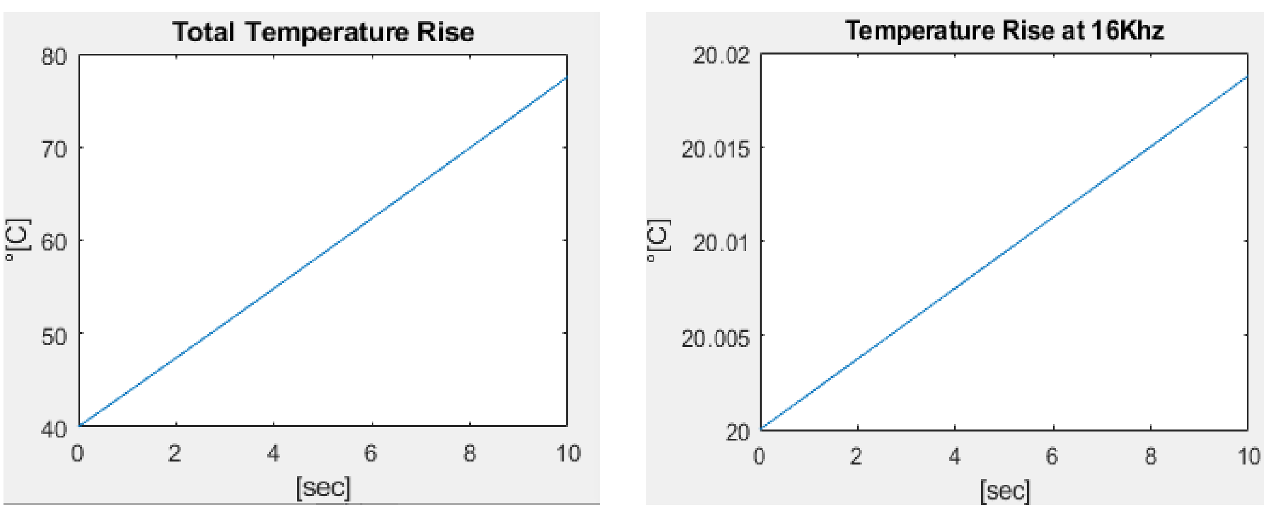
TABLE II. BIMETALLIC STRIP KANTHAL 100 PROPERTIES

Property	**Value**
Density	8.22 [gr/cm^3]
Specific Heat Capacity	0.460 [J/gr-°C]
Electrical Resistivity	0,0000620 [Ω-cm] at 0 °C
	0,0000860 [Ω-cm] at 200 °C
	0,000100 [Ω-cm] at 400 °C
Relative Magnetic Permeability	207 ± 10%

The magnetic permeability was difficult to be determined via availableliterature, and the bimetal manufacturers do not provide this parameter even thoughsome of them refer that the bimetal's material has ferromagnetic behavior. Ferromagnetic materials present a vast range of relative magnetic permeability values . For this reason, the relative magnetic permeability was experimentally measured following the procedure described in [10]. For the simulations, the magnetic permeability of the bimetal is assumed as a constant in contrast to the specific resistivity which is temperature dependent.

IV. SIMULATIONS AND RESULTS

Figure 3a illustrates the matlab results for the total temperature rise of the bimetallic strip of a B16 MCB due to a 16 peak electric current of 50Hz and the corresponding supraharmonic at 16kHz with peak value of 0.54% of 16 Amperes. Figure 3b illustrates the temperature rise due to the 0.54% of 16 Amperes at 16kHz electric current.



(a) (b)

Figure 3. a) Total Temperature rise for 50Hz and 16kHz electric currents
b) Temperature rise for 16kHz electric current

V. CONCLUSION

From the results it is observed that the tested value of supraharmonic at 16kHz does not significantly influence the bimetallic strip. As previously referred, for larger power electrical installations, where the fundamental's frequency current is larger, the corresponding electric current at 16kHz is also significantly elevated, in comparison with the corresponding at the 16A of fundamental electric current, and the thermal element of the MCB cannot react for the value at 16kHz. The above lead to the conclusion, that the high frequency currents which pass through the medium voltage transformer finally end up to the consumers, and the electrical installations are exposed on these high frequency currents with unknown until now results.

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