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APPLICATION OF INFRARED THERMOGRAPHY TO NON-CONTACT TESTING OF VARISTORS

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Abstract

Testing of varistors using thermography was carried out in order to assess their protective properties against possible overvoltage phenomena in the form of high-level voltage surges. An advantage of the thermography technique is non-contact temperature measurement. It was proposed to assess the properties of varistors working in electronic devices as protective elements, on the basis of estimating temperature increments on varistor surfaces, registered by an infrared camera during surge resistance tests with standard voltage levels. To determine acceptable temperature increments on a tested varistor, preliminary testing was performed of P22Z1 (Littelfuse) and S07K14 (EPCOS) type varistors, working first at a constant load and presently during surge tests,. The thermographic test results were compared with measured varistor capacity values before and after tests. It was found that recording with thermography temperature increments greater than 6°C for both P22Z1 and S07K14 varistor types detects total or partial loss of varistor protective properties. The test results were confirmed by assessment of protective properties of varistors working in output circuits of low nominal voltage devices.

Keywords: thermography, testing, varistors

1. Introduction

Diagnostics of electronic devices is a significant element in their manufacturing. The basic tasks of device diagnostics are their testing and fault identification. Particularly significant are such testing and fault identification methods that enable diagnostics without interference with a tested object. Often the fault identification contains also finding elements being in a pre-fault state. It is necessary to select proper technology and methods enabling that kind of diagnostics.

The thermographic technology offers very advantageous conditions for assessing properties of single elements as well as whole devices [1-4]. Using an infrared camera allows for non-contact inspection of devices within the range of infrared radiation. Emission of the infrared radiation can be recorded without any interference with the inspected (diagnosed) device. Such method of assessing various materials quality is often more convenient because it does not require additional measurement setup and necessary wiring except of the camera when compared with other methods [5-7].

The data showing the device thermal emission levels can be converted into color thermograms; the colors and their intensity show the distribution of temperature on the device surface. It is also possible to record temperature increments, interpreted as the differences between maximum and minimum temperature at a given moment on the element (or device component) surface.

In the paper, application of thermography for assessing protective properties of varistors used in output circuits of low nominal voltage (ca. 12 V) devices, was proposed. A varistor is

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a protective element of the device, protecting the device against possible overvoltage phenomena in the form of high-level voltage surges. The proposed inspection procedure consists in assessing protective properties of varistors working in manufactured devices during testing performed according to the EN61000-4-5 standard, before launching the device into the market.

2. Thermographic inspection of varistors

A procedure of varistor inspection, applying a well-known thermographic technique, was proposed, allowing detection of varistors that are losing, or have just lost, their protective properties. It was assumed that varistor quality is determined on the basis of its capacity, and that a pre-defined change of its capacity shows loss of its protective properties. The latter practically eliminates the varistor from its application as a protective element, due to the change of its impedance and resulting changes in I-V characteristics. The issues were published in a conference paper [8].

The aim of research was finding dependences between varistor capacity values before and after load tests, and a parameter describing its thermal properties. The thermographic method enables a non-contact measurement of the inspected varistor temperature. However, the precise determination of the temperature value of every tested varistor is not possible. It results from difficulties in assessing the emission coefficients of varistors. Thus, in spite of using the same color palette for presentation of temperature values, it is difficult to compare temperature values of individual varistors. However, it is possible to apply, for assessing temperature properties of varistors, a temperature increment measurement method used during varistor operation, e.g. comparing temperature increments at the moment of test start $t = t_0$ and in successive moments $t = t_i$ where $i = 1, 2, \ldots, N$ and N is the number of observations
(measurements) with an infrared camera, till the end of testing, i.e. to $t = t_N$.

It was assumed that at the moment $t = t_0$ the temperature is constant on the surface of a inspected varistor, i.e. $T_{max0} - T_{min0} = \Delta T = 0$. It was also assumed that T_{maxi} and T_{mini} are, respectively, maximum and minimum temperature values appearing on the varistor surface at the moments t_i, where $i = 0, 1, 2, \ldots, N$. After switching the supply on, the temperature on the varistor surface begins to change and at successive moments $t = t_i$ a temperature increment occurs on the varistor surface; it is defined as: $T_{maxi} - T_{mini} = \Delta T_i$, where $i = 1, 2, \ldots, N$. The value of the temperature increment can be easily determined from thermograms and enables comparisons of varistor properties during testing independently their individual emission coefficients.

Considering the above assumptions, it was assumed that varistor capacity value changes are correlated with temperature increments appearing on the varistor surface during testing.

Determining temperature increments ΔT_i, where $i = 1, 2, \ldots, N$, corresponding with capacity changes, by a specified typical capacity value declared by the manufacturer in technical data of tested varistors, will enable to draw conclusions regarding protective properties of varistors mounted in devices. The varistor manufacturers show in the technical data that the varistor capacity tolerance in relation to its catalog value C_{cv} is ±10%. Thus, the capacity value changes exceeding +10% the nominal value for a given varistor type can be interpreted as losing protective properties of the varistor. In case of using the measurement of its capacity as an indicator of varistor protective properties, interference with the tested device would be necessary (soldering the varistor out from the device). On the other hand, testing with the thermographic method allows assessing the varistor in the operating circuit.

Testing was performed on two varistor types: P22Z1 (Littlefuse) and S07K14 (EPCOS); the technical data of the varistors are given in Table 1. They are protective low voltage varistors.

Table 1. Basic Series Rating & Specifications for: P22Z1 (Littlefuse) and S07K14 (EPCOS).

Varistor type	Maximal rating (85°C)			Specifications (25°C)		
	Continuous	Transient		Varistor voltage at 1mA DC Test Current		Typical capacity
P22Z1	V_{RMS} [V]	V_{DC} [V]	I_{TM} 8 x 20 µs [A]	V_{nommin} [V]	V_{nommax}[V]	f = 1 MHz [pF]
	14	18	250	18,7	26	2375
S07K14	V_{RMS} [V]	V_{DC} [V]	I 8 x 20 µs [A]	V_{nom} [V]	ΔV_{max} [%]	f = 1 kHz [pF]
	14	18	250	22	10	2300

To determine the relation between the values ΔT and ΔC, preliminary tests of varistors with the thermographic method were conducted:

- testing of varistor groups working in a period of 390 s at constant current, for a constant load,
- testing of varistor groups during application of surges with a specified frequency and for specified testing levels from a surge generator.

Varistors for all above tests were chosen from the same production set. The chosen varistors were preliminarily aged for 4 months in a climate chamber, at a constant supply voltage of 13.8 V at a temperature of 60°C. Therefore, it can be assumed that the elements were of very high quality.

During testing the varistors were operating at an ambient temperature of 22°C. Before testing and after its completion the varistor capacities were measured with a Good-Will LRC 810G bridge, at frequencies specified in Table 1.

Table 2. Relevant parameters of VigoCAM v50 camera.

Parameter	Value/Function description
Detector type	Non-cooled bolometric matrix (FPA)
Spectrum range	8÷14 µm
Thermal resolution	≤ 0.065°C (for a temperature of 30°C)

Thermograms were carried out with a VIGO System S.A. VigoCam v50 infrared camera equipped with a 35 mm lens, and tested varistors were situated at a distance of 0.75 m. During measurement the varistors were observed from above, i.e. like they are most often accessible in real circuits. The dimensions of the observed surface of a tested varistor were: 2.5 mm x 7 mm. The relevant parameters of the infrared camera are summarized in Table 2.

Fig. 1 presents the measurement circuit of varistors, during testing with a constant load (position 1 of the switch) and during testing with a surge generator (position 2 of the switch).

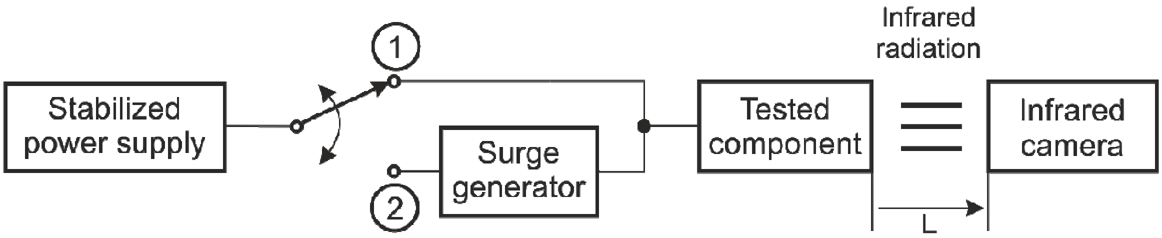

Fig. 1. Measurement circuit of varistors during testing, L = 0.75 m;
position 1 of switch – measurement with constant load,
position 2 of switch – measurement during surges.

The thermal inspections consisted in recording thermograms and temperature increments on the varistor surface.

3. Test results

3.1. Testing with a constant load

40 varistors (20 of both types) were chosen for testing. Each set of 20 pieces was divided into 4 groups, each of them containing 5 elements. Before starting the tests, the capacitance of each varistor was measured at f = 1 MHz and f = 1 kHz, for type P22Z1 and type S07K14 varistors, respectively. The measured capacitances were denoted $C(t_0)$, i.e. the capacitance at the moment $t = t_0$ (Table 3 and Table 4).

The varistors were submitted to load testing in the circuit with a stabilized supply unit (Fig. 1, position 1 of the switch), enabling to obtain the following current values (flowing through the varistors):

- 0.5 mA (group I, varistors Nos. 1, 2, 3, 4, 5),
- 1 mA (group II, varistors Nos. 6, 7, 8, 9, 10),
- 5 mA (group III, varistors Nos. 11, 12, 13, 14, 15),
- 10 mA (group IV, varistors Nos. 16, 17, 18, 19, 20).

In normal conditions varistors operate at currents in the µA range.

During load tests (with a duration of 390 s), varistor thermograms were obtained as a result of total twelve measurements. Due to the necessity of establishing varistor operating conditions for assessing temperature increment values, the recorded values of two first thermograms were excluded from consideration, so that the results of ten measurements (N = 10), recorded every 30 s, were used for assessment purposes. 24 hours after completion of testing the measurements of varistor capacitances were repeated, their results denoted as $C(t_N)$. The measurement results of capacitances and temperature increments ΔT are given in Table 3 (P22Z1 type varistors) and Table 4 (S07K14 type varistors).

It results from the data contained in Tables 3 and 4 that only group IV varistor capacitance values were changed by more than 10% of the manufacturer declared capacitance for both varistor types, i.e. exceeded 2612 pF for P22Z1 type varistors, and 2530 pF for S07K14 type varistors.

As it was noticed, the temperature increment values ΔT (Tables 3 and 4) were assessed on the basis of 10 recorded measurement results (with assumed loads). Taking into account that the temperature increments – and not the temperature values (in the 30°C or 40°C range) – are considered, even increments by ca. 1°C should be recognized as properly defined, and the obtained measurement results – at all current values – can be treated as credible.

The values presented in Tables 3 and 4 show a distinct increase of temperature increments on the varistor surfaces for the group IV of both varistor types. It corresponds with considerable capacitance changes for the same groups of varistors (by values greater than 10% of capacitance declared by the manufacturer). Thus, it can be assumed that temperature increments on the surfaces of P22Z1 type and S07K14 type varistors exceeding 6°C indicate a partial or the total loss of tested varistor protective properties. The assessed correlation coefficients between capacitance values $C(t_N)$ and temperature increments ΔT for P22Z1 type and S07K14 type varistors equal 0.84 and 0.86, respectively.

Table 3. Test results of P22Z1 type varistors; test with constant load.

I [mA]	Varistor No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	ΔT [°C]	Remarks
0.5	1	2268	2271	1.12	
	2	2259	2180	1.14	
	3	2250	2295	1.14	
	4	2218	2217	1.07	
	5	2199	2198	1.13	
1.0	6	2067	2088	1.37	
	7	2142	2172	1.59	
	8	2145	2158	1.39	
	9	2235	2238	1.81	
	10	2262	2278	1.46	
5.0	11	2207	2251	4.78	
	12	2225	2268	4.92	
	13	2045	2087	5.01	
	14	2271	2308	5.09	
	15	2292	2335	5.01	
10.0	16	2199	3075	10.38	$C(t_N) > 2612$ pF
	17	2071	4123	10.63	$C(t_N) > 2612$ pF
	18	2223	2805	10.31	$C(t_N) > 2612$ pF
	19	2221	3390	10.60	$C(t_N) > 2612$ pF
	20	2132	3192	10.72	$C(t_N) > 2612$ pF

Table 4. Test results of S07K14 type varistors; test with constant load.

I [mA]	Varistor No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	ΔT [°C]	Remarks
0.5	1	2494	2497	1.35	
	2	2176	2174	1.36	
	3	2156	2157	1.33	
	4	2353	2350	1.31	
	5	2276	2275	1.16	
1.0	6	2145	2156	1.78	
	7	2256	2255	1.56	
	8	2109	2112	1.57	
	9	2209	2310	1.80	
	10	2198	2250	1.79	
5.0	11	2411	2511	5.05	
	12	2321	2456	5.70	
	13	2121	2210	5.70	
	14	2298	2301	5.98	
	15	2194	2210	5.90	
10.0	16	2218	23144	10.79	$C(t_N) > 2530$ pF
	17	2416	3276	10.37	$C(t_N) > 2530$ pF
	18	2191	2934	10.76	$C(t_N) > 2530$ pF
	19	2318	3456	11.26	$C(t_N) > 2530$ pF
	20	2157	3003	11.43	$C(t_N) > 2530$ pF

It was assumed that detecting – by the measurement with the infrared camera – a temperature increment on the varistor surface exceeding 6°C for P22Z1 and S07K14 type varistors indicates loss of varistor protective properties defined in varistor operating conditions at a constant load.

Operating at a constant (with the range of several mA) load is not typical for varistors. Thus, the obtained results should be verified in conditions recommended by standards, i.e. during surges with defined voltage levels and durations.

3.2. Tests using the USC500N surge generator

20 varistors (10 of each type) were chosen for testing. The varistors were divided into two groups containing 5 pieces each. Before starting the tests, the capacitance of each varistor was measured. The measured capacitances were denoted $C(t_0)$, i.e. capacitance at the moment $t = t_0$. The capacitances were measured also after completion of the total test set; their values were denoted $C(t_{3N})$ for the first group of varistors and $C(t_N)$ for the second one.

Table 5. Test results of P22Z1 type varistors; surge tests.

Varistor No.	$C(t_0)$ [pF]	$C(t_{3N})$ [pF]	ΔT [°C] 500 V	ΔT [°C] 760 V	ΔT [°C] 1000 V	Remarks
1	2199	2322	1.69	2.44	3.62	
2	2071	2088	1.41	2.36	3.37	
3	2223	2219	1.53	2.52	3.45	
4	2221	2343	1.64	2.48	3.53	
5	2146	2290	1.72	2.57	3.61	
Varistor No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	ΔT [°C] 2000 V			
6	2268	2856	6.11			$C(t_N) > 2612$ pF
7	2259	2787	6.08			$C(t_N) > 2612$ pF
8	2250	2672	6.12			$C(t_N) > 2612$ pF
9	2218	2438	5.61			
10	2099	2558	5.58			

Table 6. Test results of S07K14 type varistors; surge tests.

Varistor No.	$C(t_0)$ [pF]	$C(t_{3N})$ [pF]	ΔT [°C] 500 V	ΔT [°C] 760 V	ΔT [°C] 1000 V	Remarks
1	2289	2287	1.54	2.35	2.91	
2	2270	2293	1.39	2.54	3.10	
3	2262	2343	1.52	2.37	2.89	
4	2223	2323	1.48	2.43	3.05	
5	2230	2361	1.51	2.46	2.97	
Varistor No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	ΔT [°C] 2000 V			
6	2327	3121	6.68			$C(t_N) > 2530$ pF
7	2270	2969	6.54			$C(t_N) > 2530$ pF
8	2289	3294	6.48			$C(t_N) > 2530$ pF
9	2270	2552	6.45			$C(t_N) > 2530$ pF
10	2262	2987	6.51			$C(t_N) > 2530$ pF

First, testing of 10 varistors (5 of each type) with a surge generator was performed (Fig. 1, position 2 of the switch). The varistor thermograms were obtained during application of surges (every 20 s.) for 3 voltage levels: 500 V, 760 V and 1000 V; for each voltage level and each varistor every 5 s. The testing procedure is in accordance with the EN61000-4-5 standard. $N = 41$ measurements (thermograms) were performed with the infrared camera. The varistors were submitted to surges at different voltage levels; the interval between applying successive levels was 24 hours. The test results are compiled in Table 5 (P22Z1 type varistors) and Table 6 (S07K14 type varistors).

On the basis of recorded temperature increments, average values (for tested varistors) were assessed. The values were not exceeding 2°C, 3°C and 4°C for P22Z1 and S07K14 type varistors, for voltage surge levels of 500 V, 760 V and 1000 V (Fig. 2 and Fig. 3), respectively.

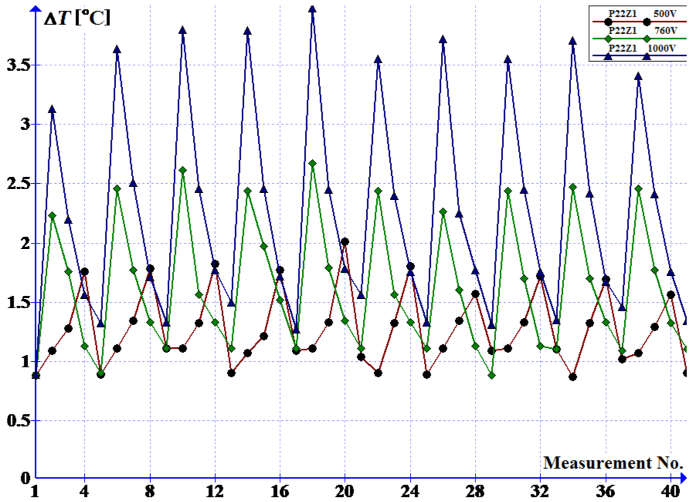

Fig. 2. Temperature increments Δ*T* recorded in successive measurements with an infrared camera during application of surges at 3 voltage levels: 500 V, 760 V and 1000 V for varistor No. 5 of P22Z1 type.

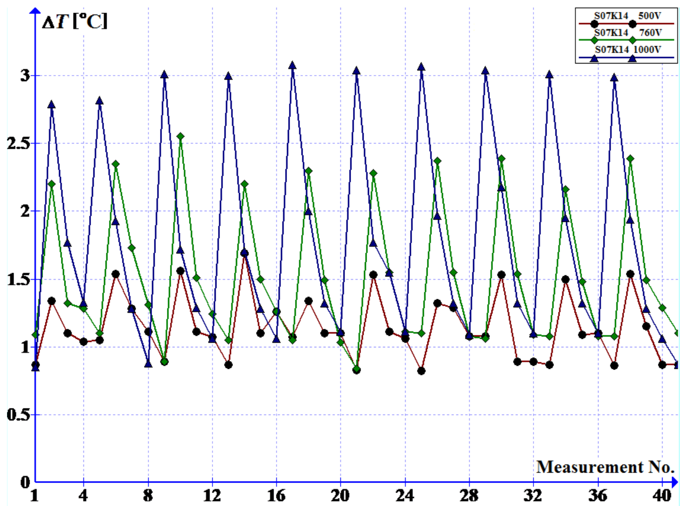

Fig. 3. Temperature increments Δ*T* recorded in successive measurements with infrared camera during application of surges at 3 voltage levels: 500 V, 760 V and 1000 V for varistor No. 5 of S07K14 type.

The varistor capacitance values measured after this test cycle have not changed to a significant degree, i.e. to a degree defined as corresponding with losing protective properties by varistors. Thus, it can be stated that all tested varistors preserved their protective properties. The temperature increment values on the varistor surfaces also have not indicated loss of protective properties (i.e. the values did not exceed 6°C) by P22Z1 and S07K14 type varistors.

The second test cycle performed for 5 successive varistors of each type consisted in applying every 20 s surges of 2000 V. This test is a destructive one, and it is not recommended by the EN61000-4-5 standard. For each varistor every 5 s a series of N = 41 measurements (thermograms) was performed with the infrared camera.

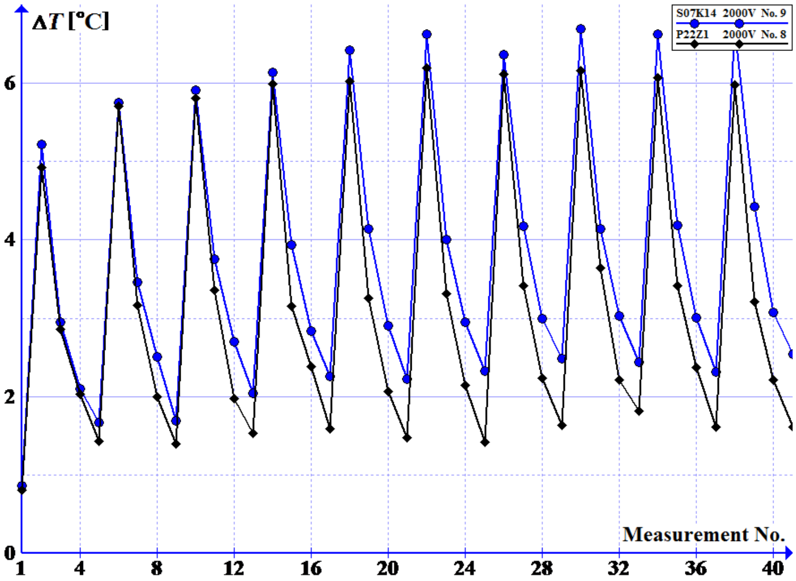

Fig. 4. Temperature increments ΔT recorded in successive measurements with infrared camera during application of surges of 2000 V voltage level for varistor No. 8 of P22Z1 type and varistor No. 9 of S07K14 type.

For P22Z1 type varistors average values of recorded temperature increments were calculated. They exceeded 6°C for varistors Nos. 6, 7 and 8, whereas for varistors No. 9 and No. 10 were smaller than 6°C. The capacitance values $C(t_N)$ for varistors Nos. 6, 7 and 8 exceeded 2612 pF, whereas for varistors No. 9 and No. 10 were smaller than the above value. Thus, the capacitance changes, as well as temperature increment values, indicate that varistors Nos. 6, 7 and 8 lose their protective properties.

For S07K14 type varistors average values of recorded temperature increments were calculated. For all varistors the values exceeded 6°C. The capacitance values $C(t_N)$ for all varistors exceeded 2530 pF. Thus, the capacitance changes, as well as temperature increment values, indicate that all S07K14 type varistors lost their protective properties.

Taking into account the promising test results obtained during surges, suggesting the capability to determine protective properties of varistors, testing of varistors operating as protective elements in devices was performed.

4. Testing of varistors operating in a device

A device containing low voltage protective varistors in the supply circuit was tested. The tests were performed for both varistor types, P22Z1 and S07K14, operating in Satel's GSM 4 communication module. The tested module was supplied with U_n = 12 V_{DC} voltage. The supply circuits were submitted to voltage surges with shapes corresponding to the EN61000-4-5 standard. The surge voltage level (2000 V) applied during tests was higher than indicated in standard requirements for this type of device. The tests were carried out for 3 varistors of each type. For each varistor values of its capacitance $C(t_0)$ i $C(t_N)$ were measured.

The inspection with the infrared camera consisted in recording temperature increments on tested varistors during tests for 3 voltage surge levels: 500 V (module No. 1), 1000 V (module No. 2) and 2000 V (module No. 3). For each voltage level and each device every 5 s N = 41 measurements (thermograms) were performed with the infrared camera. The results of GSM module measurements are contained in Table 7 (P22Z1) and Table 8 (S07K14).

Table 7. Test results of GSM modules with P22Z1 type varistors.

Module No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	Surge [V]	ΔT [°C]	Remarks
1	2215	2322	500	1.30	
2	2275	2285	1000	3.15	
3	2323	2781	2000	6.30	$C(t_N)$ > 2 612 pF

Table 8. Test results of GSM modules with S07K14 type varistors.

Module No.	$C(t_0)$ [pF]	$C(t_N)$ [pF]	Surge [V]	ΔT [°C]	Remarks
1	2250	2250	500	1.5	
2	2300	2305	1000	3.52	
3	2150	2820	2000	7.24	$C(t_N)$ > 2 530 pF

The recorded temperature increments for surges with 500 V, 1000 V and 2000 V levels were equal to 1.3°C, 3.15°C and 6.3°C for modules with P22Z1 type varistors, and 1.35°C, 3.52°C and 7.24°C for modules with S07K14 type varistors. The capacitance values of varistors submitted to surges with voltage levels of 500 V and 1000 V, measured 24 hours after completion of tests, have not changed significantly, i.e. to the point that corresponds with losing protective properties by varistors. Thus, it can be stated that the varistors have not changed their protective properties. The temperature increment values on the varistor surfaces have not also suggested loss of protective properties by varistors, i.e. they have not exceeded 6°C. However, the capacitance values of varistors operating in modules No. 3 submitted to surges with the 2000 V voltage level, measured 24 hours after completion of tests, have increased considerably. The temperature increment values on the varistor surfaces were higher – from the 20th measurement on – than the values suggesting loss of protective properties of varistors, i.e. exceeded 6°C (Fig. 5).

Fig. 5 illustrates that S07K14 type varistors showed a higher temperature increment (7.24°C) than the P22Z1 ones (6.3°C).

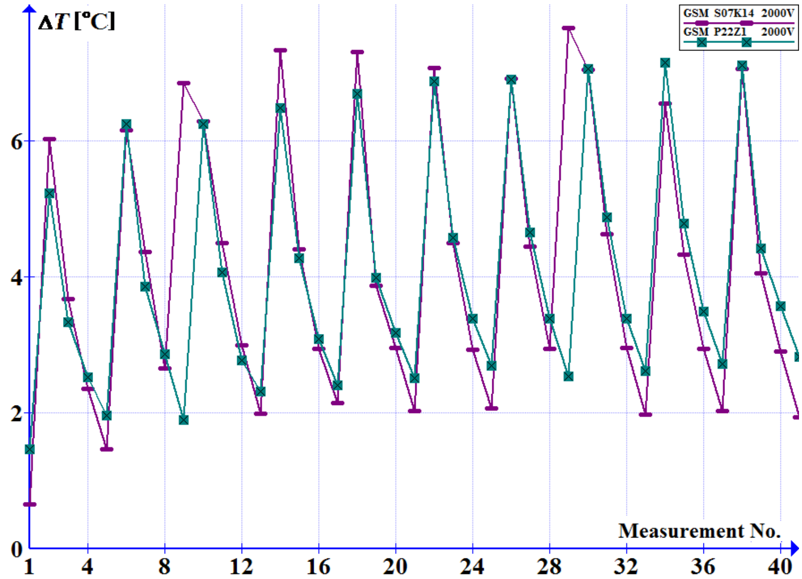

Fig. 5. Temperature increments ΔT recorded in successive measurements with infrared camera, during application of surges with 2000 V voltage level for P22Z1 and S07K14 type varistors operating in communication modules No. 3.

The level of changes in capacitance values and temperature increment values for varistors operating in modules No. 3 suggests recommending their replacement with other varistors before launching the GSM modules into the market.

5. Conclusions

The inspection of varistors performed using the thermographic technique indicates its usefulness to estimating protective properties of varistors, as well as diagnosing manufactured devices equipped with varistors before launching the devices into the market. The tests were performed for two types of varistors used as protective elements in low voltage circuits, namely P22Z1 and S07K14 types. For these types of varistors temperature increment values ΔT were defined, which – when obtained during tests performed in accordance with EN61000-4-5 standard – suggest losing protective properties of a tested varistor. It was found that for these varistors temperature increments exceeding 6^0C suggest total or partial loss of protective properties of a tested varistor. It should be stressed that the thermal technique allows assessing varistor properties without the necessity of isolating the varistors from the tested device. The temperature increment values for tested varistors operating in actual devices are close to the values assessed during operation with a supply circuit only. To sum up, for varistors type P22Z1 and type S07K14, there is a possibility of evaluating their protective properties during the test carried out for every GSM module, according to the EN61000-4-5 standard, before launching the module into the market. The results of performed tests indicate the necessity of carrying out preliminary tests in order to determine temperature increment values that would be considered as eliminating a given type of varistors from applying in the specific device.

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