Effects of ZnO varistor degradation on the overvoltage protection mechanism of electronic boards

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ABSTRACT: In this study, we investigate degradation of ZnO varistors and their effects on electronic boards. We propose a model showing how the varistor clamping voltage Vv changes by time for different stress levels. To evaluate the model, we exploit measured experimental test data as well as field return data with over 1000 board failures. Varistors in-use are usually subjected to a long-term AC or DC voltage stress and surge which may lead to degradation of the varistors with an increase of the Vv parameters. We show that degraded varistors cause dramatic failures of other components in the same power block of the electronic board. We perform experiments on varistor degradation and failing mechanisms by applying 8/20 us, 2ms and accelerated AC voltage test methodologies. We also simulate the relation of the varistor degradation with other components in time domain.

1 INTRODUCTION

ZnO varistors have been widely used in electrical and electronics systems against overvoltage surges for their high nonlinear electrical properties (non-Ohmic current-voltage characteristics) and excellent energy handling capabilities [Clarke &Cream.1999, Boggs &Kuang.2006, Gupta&Ceram.1990]. ZnO varistors are variable resistors with the function of limiting or diverting transient voltage.

Choosing an appropriate varistor plays an important role in system safety and reliability. If ZnO varistors are used within their well-defined specifications, degradation due to the environment is not likely [Brown&Kenneth.2004]. ZnO varistors in-use are usually subjected to a long-term AC or DC voltage stress and surge which may lead to degradation of the varistors with an increase of the varistor clamping voltage Vv. This is called ageing phenomenon and will eventually make the varistors degraded and even thermally broken down or destructed. Degraded varistors affect system reliability and safety. For example, the degradation of varistors results in new marginal values of the Vv parameter leading to a change in maximum designed voltage criteria for other components in the same power block of the boards, especially for those in the power supply block. Therefore, varistor degradation analysis is crucial both in device and system level. As opposed to the works in the literature that only focus on a single degradation test, we comprehensively analyze different degradation phenomena of ZnO varistors with different tests methodologies. Most of these studies perform a specific test on the varistor degradation without considering its relationship with the system where the varistor is placed.

The structure of this paper is as follows. In section 2, we survey the field return data for a case study. Investigating the causes of failures in the field return data, we see that more than %30 failures are related to overvoltage. The overload response can be classified in two group, respectively heavy overload and moderate overload. While the heavy overload directly destroys varistors, the moderate one makes it degraded. In our case study, we observe that the degradation of the varistor causes failures of other components in the same power block of the electronic board.

In section 3- Degradation Mechanism, we describe the process of degradation of varistors and perform experiments on varistor degradation and failing mechanisms by applying 8/20 us, 2ms and accelerated AC voltage test methods. By applying accelerated AC voltages, we see either an increasing or a decreasing trend in the Vv parameter of varistors that depends on the current levels passing through the varistors. The tests show us a continuous and fast decreasing trend in the Vv parameter for current levels above a certain threshold and a slow increasing trend for current levels below the threshold. When degradation is happening, it shifts the I-V characteristic of the varistor above. We can understand this phenomena by measuring the Vv parameter of the varistor which is increasing.

In Section 4, we talk about degradation of varistor and its effect on the overvoltage protection mechanism of electronic boards. In this section, we first talk about overvoltage types and how a varistor protects other critical components from overvoltage. Then we describe our varistor degradation model by defining a degradation factor. By changing the degradation factor we can see what type of overvoltage can be tolerated by the system. In this section, we examine different input voltage shapes for different degradation factors. Simulation results show us that degradation of the varistor can cause serious failures for other components in the same power block of the board.

Section 5 reports the conclusion of the work.

2 FIELD RETURN DATA ANALYSIS

To evaluate the model, we exploit well-maintained field data with over 1000 board failures.

By investigating the field return data for a board which have been collected from services, we observed that 30% of failure sources are related to line overvoltage. The most of these failures occur in the input block of the board which is the power supply block. The most of the overvoltage failures happen in the geographical regions that have poor electrical grid quality. For this reason we can see overvoltage surges in the line which affects the electronic systems reliability.

Data shows us that overvoltage failures which are 30% of all failures, consists of the varistor failures and the failures in the circuitry which is assumed to be protected from overvoltages by the help of the varistor. Therefore, the type of overvoltages and the parts and components in the system which are subjected to overvoltage are crucial for analysis.

If we examine overload response of the system, we will see two types corresponding to heavy and moderate overloads [EPCOS DataBook.2008]. These overloads in terms of surge currents and the varistor's responses are extensively investigated in the following sections.

2.1 *Heavy overload*

When the surge current is far beyond the specified rating criteria of the varistor, varistor will puncture and even in extreme cases it will burst. The overload can overheat the varistor ceramic that causes the varistor unsoldered from the electrodes. In field return data survey we see approximately 33% of overvoltage failures are related to the heavy overload that directly makes the varistor fail. In the field return data, thes type of failures are noted as open circuited and punctured varistors.

2.2 *Moderate overload*

When the surge current or continuous overload is up to approximately one or a half times above the specified rating, it can lead to a change in varistor voltage (Vv) [EPCOS DataBook.2008]. In most cases the varistor will not be destroyed, but there may be irreversible change in its electrical properties which we call degradation. In overvoltage field data analysis, we see more than 50% of failures are related to this kind of overload. In such a failure the actual system which is assumed to be protected is failing. There has been a lot of failures in the field return data for this type of moderate overload; the varistor has not been failed but it couldn't protect, so other components in the same block were failed. Therefore, studying the mechanism of degradation and its effect on other components become critical to us.

3 DEGRADATION MECHANISIM

It is well-known that the ZnO varistor experience degradation due to current impulses. Several studies have shown this phenomena [Tsukamato.2014, .Mardira & saha.2001]. The reliability studies for choosing an appropriate varistor for electronic boards made by Arcelik company, Istanbul, show that Vv parameter of varistors which is one of the key parameters related to measuring reliability of a varistor, can be changed during reliabilities tests. The change of Vv shall be measured and the end-of-life is commonly specified when the measured varistor voltage (Vv) has changed by ± 10 percent ($|\Delta V/V\ (1\ mA)| \leq 10\%$) [EPCOS DataBook.2008].

The most of the increment are less than 10% and they can be count as a degradation. In order to understand the mechanism of degradation, we performed accelerated AC voltage tests. For different current levels passing through the varistor, we see either an increasing or a decreasing trend in the Vv parameter. The tests show us a continuous decreasing trend in the voltage parameter for current levels above a certain threshold and an increasing trend for current levels below the threshold.

3.1 *8/20 us surge current derating test*

Several studies show the degradation of varistor during 8/20u tests [Tsukamato.2014]. Test methods and condition of this test are detailed as follows.

100 unipolar surge currents (8/20 µs) with 30s interval are applied to a varistor. The amplitude of applied signals is determined by the corresponding derating curve for 100 impulses at 20 µs and the Vv should be |ΔV/V (1 mA)| ≤10%. ;[EPCOS Data-Book.2008]. Surge current has been applied on varistor by an impulse generator instrument (EMC Partner Moduler) at 85 C. Table 1 shows amplitude of applied signals for varistors.

Table 1. Amplitude of applied signals (8/20 us)

Series	V peak (v)
10mm/275v	1350
10mm/300v	1400
10mm/320v	1500
10mm/350v	1600
14mm/300v	1900
14mm/320v	2000
20mm/275v	3450

In total 276 varistor were tested. According to the Table 2, the Vv parameter for the applied signals has increased for all of the samples. Results show that large number of changes are between 2% and 6%.

Table 2. Changes in Vv parameter in 8/20 us test

Count	Vv changes Percentage
94	0%-2%
168	2%-6%
14	6%-10%

3.2 *2 ms surge current test*

100 unipolar surge currents (2 ms), with 120s interval are applied to a varistor, The amplitude of applied signals is determined by the corresponding derating curve for 100 impulses at 2 ms and the Vv should be |ΔV/V (1 mA)|≤10%. Table 3 shows amplitude of applied signals for varistors.

Table 3. Amplitude of applied signals (2ms)

Series	V peak (v)
10mm/275v	630
10mm/300v	690
10mm/320v	765
10mm/350v	825
14mm/300v	685
14mm/320v	740
20mm/275v	630

In total 230 varistor were tested. According to Table 4, the Vv parameter for the applied signals has increased for all of the samples. Results show hat large number of changes are between 2% and 10%.

Table 4. Changes in Vv parameter in 2ms test

Count	Vv changes Percentage
43	0%-
45	0%-2%
100	2%-10%
42	10%

3.3 *Accelerated Ac voltages (AC ageing)*

Many literatures had explained the aging characteristics and mechanisims of ZnO varistors, but the changing trend in Vv parameter of the ZnO varistor and its behavior for different voltage stress levels to find threshold value of varistors has not been clearly analyzed [He& Liu & Hu& Long.2011. Liu & He & Hu & Luo .2011. He& Liu & Hu& Zeng & Long. 2011].

The proposed test method and experimental procedure are given below.

The different accelerated ac voltage levels are applied on tested samples having diameter of 12mm and height of 15mm. We periodically measure the varistor voltage for a specific current passing through it. As an evaluation criteria, we use the change ratio of nominal varistor voltage (Vv at 1mA). According to IEC standard (IEC-60099-4) the accelerated AC voltage stress is applied at 1mA. But, in order to find threshold value we increase the assumed current level.

3.3.1 *Finding threshold*

In order to find threshold value we started current level from 10 mA. But, the varistor voltage plunged dramatically and after seconds varistor started to burn up. We decreased this value to 5mA but still there was a dramatic decline in varistor voltage. Figure 1 shows 2mA current level test for two samples. Trend shows considerable decreasing in varistor voltage during 130 minute test duration.

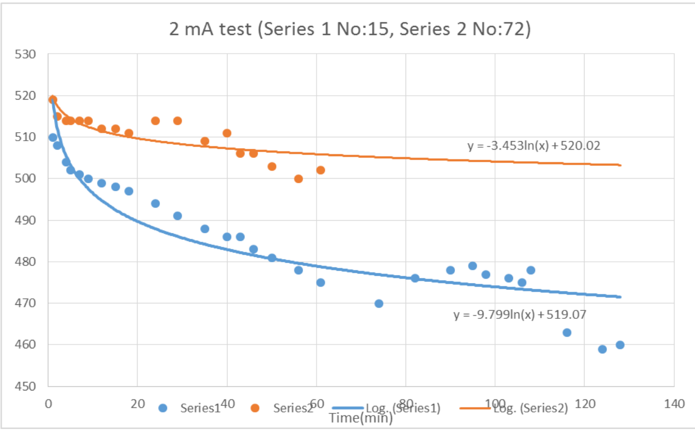

Figure 1. The results for 2 mA test in the time domain

According to Figure 2, varistor Vv voltage sees a slight decrease for 1.5mA test. It means that we are very close to the threshold and the threshold value is slightly under 1.5mA. We repeated the test for 0.7 mA and 1 mA and the results show an increasing trend in Vv. They are shown in Figure 3, and Figure 4.

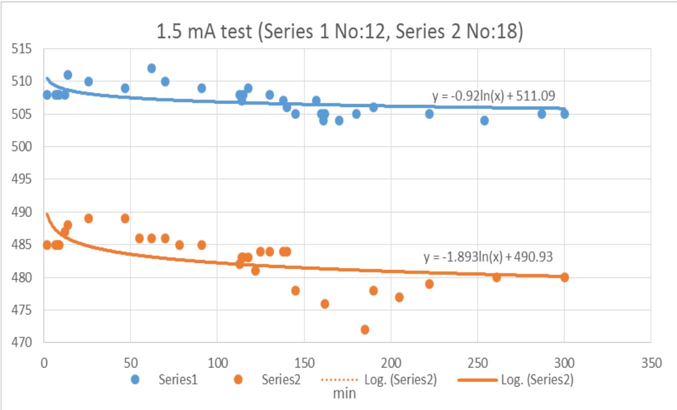

Figure 2. The results for 1.5mA test in the time domain

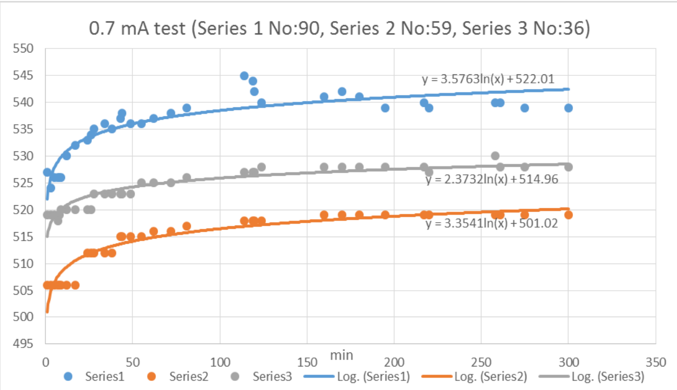

Figure 3. 0.7mA test

In conclusion, for current levels above 1.5 mA which is threshold value for this family of varistor samples, varistor voltage drops dramatically until it burns. We can classify this phenomena as a heavy overload which we described in the section "Field Return Data Analysis". This kind of heavy overload makes a varistor fail. On the other hand, for current levels less than the threshold value which is 1.5 mA, we will see increasing trend in varistor voltage (Vv). We classify this phenomena as a moderate overload which causes degradation in varistor.

3.3.2 *1mA test*

In order to understand mechanism and trend of degradation we repeated the tests for 1mA for several samples. According to IEC standard [IEC-60099-4] the accelerated AC voltage stress is applied at 1mA. Experimental procedures:

1. All samples were short circuited to ground for 24 hours in order eliminate any impacts from previous tests.
2. Reference voltage at 1 mA AC current were measured and periodically we measure the change of varistor voltage.
3. We record change for all samples in 300 minute time periods.

The results of 1mA test are shown in Figure 4.

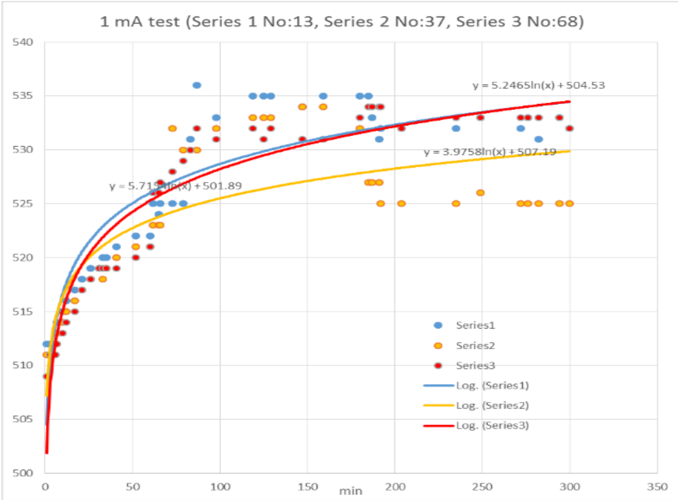

Figure 4. The results for 1mA test in the time domain

Noticeable feature of 1mA test results is rapid changes in Vv parameters during first minutes. It means the degradation speed in the first moments which stress are applied is fast.

4 DEGRADATION AND SYSTEM RELIABILITY

The environment that appliance electronic boards are used in is not homogeneous [Brown&Kenneth.2004]. Overvoltages are distinguished according to where they originate [EPCOS DataBook.2008]. In general, there are two type of overvoltages; internal overvoltages and external overvoltages. Internal overvoltages such as inductive load switching, arcing electrostatic, and ESD, originate in the actual system. On the other hand, external overvoltages like line interference, strong electromagnetic fields, and lightning can affect the system [EPCOS DataBook.2008]. Figure 5 illustrates a general power block protected by a varistor. According to Figure 5, when a transient occurs, current flows across Zsoruce. Zsoruce can be the ohmic resistance of a cable or the inductive reactance of a coil or the complex characteristic impedance of a transmission line. But, for calculation purposes this impedance is normally taken as being 50Ω [EPCOS DataBook.2008]. According to I-V characteristics of a ZnO varistor, when overvoltage is occurring, resistance of the varistor drops from high ohmic values to small ohmic values. The voltage division ratio is shifted, so the overvoltage drops almost across Zsource and the circuit parallel to the varistor is protected.

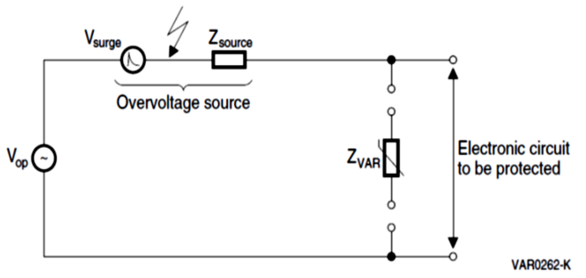

Figure 5. Equivalent circuit when overvoltage is occurring [EPCOS DataBook.2008]

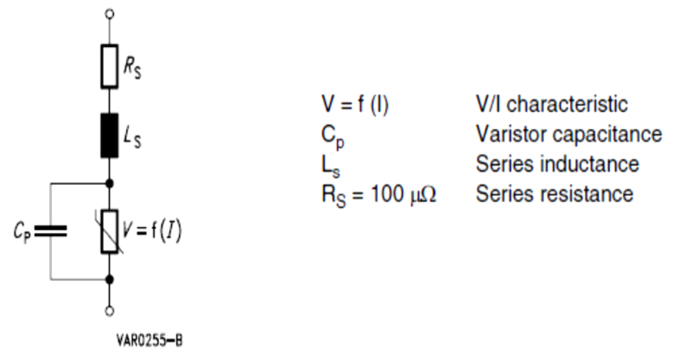

Figure 6. Varistor model, basic structure[EPCOS DataBook.2008]

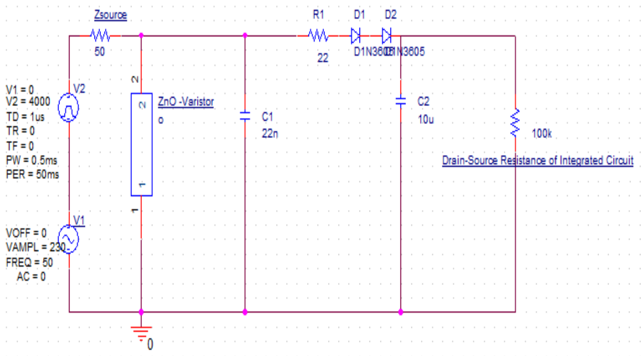

Figure 7. SPICE simulation of board circuit

In circuit design procedure, designers should know the worst-case design criteria for the protected circuit and select a proper ZnO varistor. Let us assume that a proper ZnO varistor has been selected according to the worst-case design criteria. As we discuss in this work, when degradation happens, the I-V characteristic of the ZnO varistor is shifting above. We can justify this phenomena by measuring the varistor voltage (Vv) parameter. Degradation of varistors results in new marginal values of the Vv parameter leading to a change in maximum designed voltage criteria for the other part of the boards.

In our case study, the part of the board to be protected has a maximum design criteria of 730V; clamping voltage of this part is 730V. A proper ZnO varistor has been selected according to this maximum criteria. Since it is hard to predict exact harmful conditions in the environment, we use worst case and best case conditions as limits. Amplitude up to 6 kV and pulse duration of 0.1us to 1ms are considered [EPCOS DataBook.2008].

4.1 *Simulation of Varistor Model and Degradation Factor*

In order to simulate the response of electronic board in case of overvoltage, we use a circuit simulation tool SPICE. We just simulate the related circuit which is subjected to overvoltage. We use a SPICE varistor model represented by its I-V characteristic curve, a parallel capacitance and series inductance as shown in Figure 6.

Figure 7 shows a part of SPICE simulated circuit subjected to overvoltage. We use an equivalent resistance of 100k as an approximation for the rest of the circuitry. This resistance has considerably large ohmic value. We know from datasheet information for the integrated circuit maximum clamping voltage is 730. In terms of overvoltage in kV ranges, the varistor protects this part and don't let it to experience voltages above this value. But what happens when the varistor is degraded. To see effects of degradation, we should apply some changes in the varistor SPICE model. For this purpose, we define a new parameter as a degradation factor in the mathematical approximation description of the varistor SPICE model. We call this parameter "Deg".

The following approximation is used for the mathematical description of the tested ZnO:

$$logV = b1 + b2.\log(I) + b3.e^{-\log(I)} + b4.e^{\log(I)} \quad I > 0 \quad (1)$$

We added degradation factor "Deg" to this formula according to below equation:

$$logV - LogDeg = b1 + b2.\log(I) + b3.e^{-\log(I)} + b4.e^{\log(I)} \quad (2)$$

We know that Vv parameter of ZnO varistor is measured voltage in 1mA. Therefore, for currents equal to 1mA, we can calculate different Vv values according to degradation factor. According to Table 4, the increasing trend of the Vv parameter is seen by change of the degradation factor considering that Vv of our tested varistor model is ideally 503v

Table 4. Vv values for different 'Deg' values

Degradation Factor (Deg)	Vv
1	503v
1.01	505.2v
1.02	508.1v
1.03	511.84v
1.04	516.6v
1.05	522.6v
1.06	530.1v
1.07	539.2v
1.08	550.5v
1.09	551.68v
1.1	553.7v

By using our degradation model, we can simulate different overvoltage types and different degraded varistors and see if it passes the maximum design criteria or not.

4.2 *Results of simulations*

We did several analysis by SPICE simulation software to understand the effect of degradation. We applied different overvoltage shapes to the input and then looked at a voltage which drops to the resistance of the circuitry. The maximum clamping voltage for our system was 730v. So, we based our analysis on this value. Our main interest is to see the maximum possible applied overvoltage or input voltage satisfying that the circuitry does not have a voltage drop above 730V. We gradually degraded the varistor and noted that the maximum passible applied voltage down dramatically.

4.2.1 *DC Stress Analysis*

Figure 8 shows the maximum tolerable applied DC voltage to the board by considering varistor degradation. According to Figure 8, maximum applied DC voltage for a varistor with Vv equal to 503 V is 1230 V. If we gradually degrade the varistor which results in increasing in Vv parameter, we will see that the maximum tolerable applied voltage is decreasing. This downward trend is continuing till the varistor has no contribution for protection.

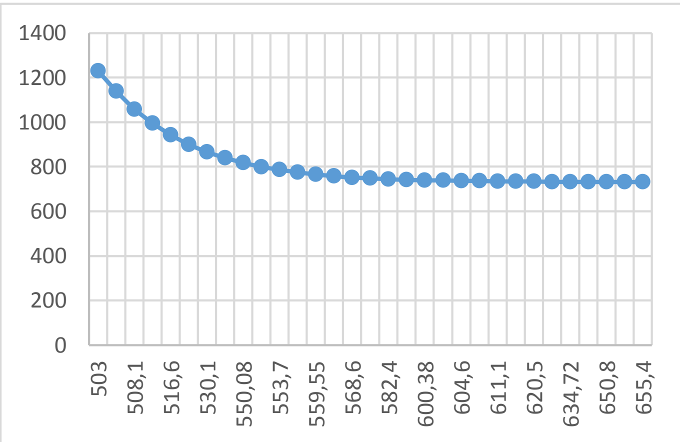

Figure 8. Maximum input voltage according to degradation of ZnO varistor

4.2.2 *Surged Pulse Voltage Analysis*

In figure 8, we observed the effect of degradation on protection limit of for DC input voltages. But as we see in Figure 7, our circuit has capacitive and inductive features too. Therefore, the DC analysis can neglect the effect of these features. For this purpose we perform pulse voltage and time domain analysis to apply more realistic dynamic overvoltages such as sinusoidal and surge pulses. Figure 9, shows the effect of degradation on maximum tolerable applied pulse voltage amplitude for different pulse durations. We can see DC like results for pulse durations over 1ms. It is obvious that if we decrease the pulse duration we can increase pulse amplitude, because varistor handles a specific amount of pulse energy. We didn't repeat the simulation for a pulse duration below 0.5 ms because the amplitude of the maximum tolerable input voltage exceeds 6kv which is not realistic overvoltage value.

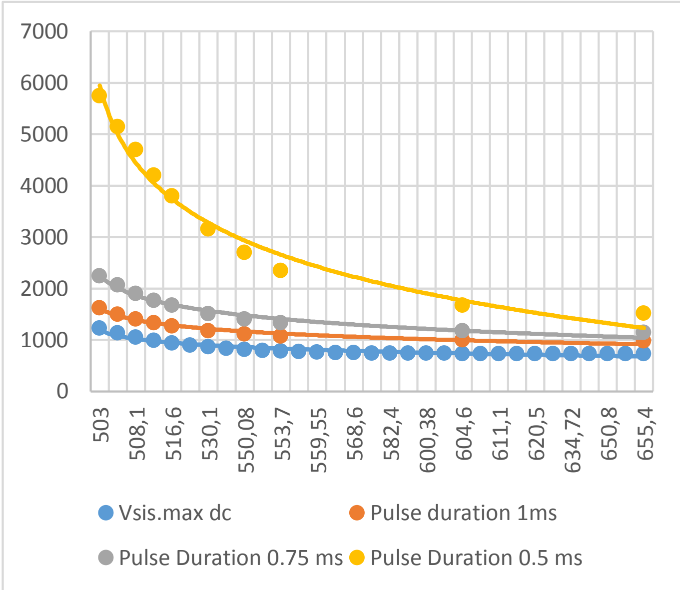

Figure 9. Different pulse voltage duration Vs Vv

4.2.3 *Time Domain*

Figure 10, shows the results of simulations for the circuit shown in Figure 7. A voltage of 230 volts and a frequency of 50 cycles per second is used for the alternating-current (AC) electric power supply. For none-degraded varistor, we have selected surged pulse voltage duration 0.5ms and we applied it in maximum value of sinusoidal wave to simulate the worst-case. Again our interest is to find the maximum tolerable applied pulse amplitude. According to Figure 10, the intersection of green curve which represents surged overvoltage pulse, and the red one which represents the dropping voltage on protected circuit is the maximum voltage value for the protected part of the system which the value should not pass the 730 v. In this case the maximum amplitude of overvoltage is 1570v (peak value of the green curve).

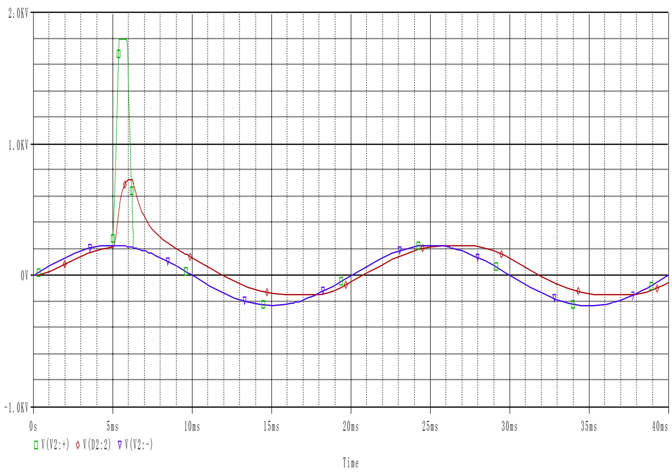

Figure 10. None-degraded time domain analysis with 0.5ms surged pulse voltage

Again, to understand the effect of ZnO varistor-degradation on the system in time domain we should look at the possible overvoltage pulse types for different degraded varistors. Figure 11 shows the effect of degradation on maximum tolerable applied amplitude of overvoltage for different pulse durations.

According Figure 11, as the Vv parameter is increasing, in other words the ZnO varistor is degrading, the capability of system to tolerate overvoltages is decreasing for all pulse durations. Other important feature of this figure is that at primary values of degradation for ZnO varistor, the capability of the system to handle the specified overvoltage type drops dramatically. It means that even in a small amount of degradation, the system might fail.

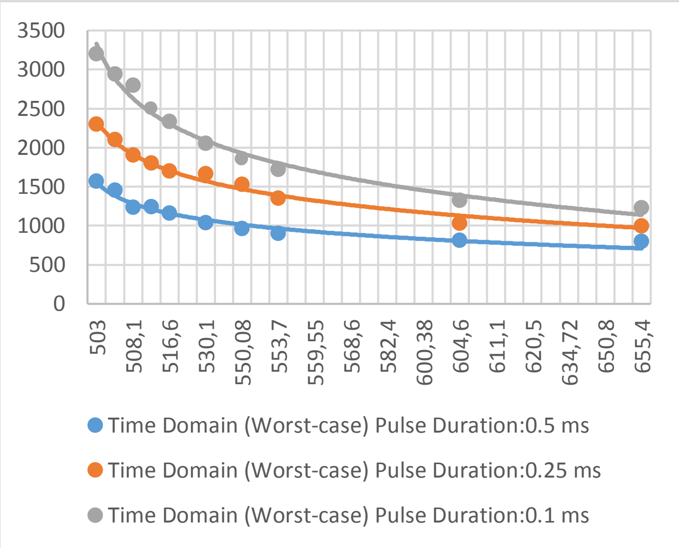

Figure 14-1. Different pulse overvoltages in time domain VS Vv

5 CONCLUSION

In this study, we focus on the degradation characteristics of ZnO varistor and its effects on the overvoltage protection mechanism of electronic boards. It is shown that moderate overload can degrade the ZnO varistor characteristic which causes in increasing of the varistor voltage parameter (Vv). To show the degradation phenomena in Zno varistors we performed several reliability and AC aging tests. Results of these tests prove the increasing of Vv parameter for moderate overvoltages. Furthermore, we find a threshold value to determine the border of moderate and heavy overvoltages. To evaluate the degradation mechanism, we first study the field return data of a product. Data showed us a relation between degradation and failing of the circuitry connected to a ZnO varistor. To verify this, we simulated the related circuit in SPICE software for different analysis and different overvoltage types. As a conclusion from simulation results, we observed that as a ZnO varistor degrading (Vv parameter increasing), the related system capability to handle the overvoltage is decreasing. It means that, if we consider a typical overvoltage type for a specific environment, the designed circuit maybe stand against this overvoltage, but in case of the degradation the failing is possible.

REFERENCES

Boggs S, Kuang J, Andoh H, Nishiwaki S.2006. Nanostructure of ZnO Fabricated via French Process and its Correlation to Electrical Properties of Semiconducting Varistors. *IEEE Trans Power Delivery 2000*;15(2):562–8.

Epcos AG. Data Book 2008. *SIOV Metal Oxide Varistors*.www.epcos.com

J. Brown Kenneth. 2004. Metal OxideVaristor Degradation. *IAEINEWS*:http://iaeimagazine.org/magazine 2004/03/16/metal-oxide-varistor-degradation.

Jinliang He∗, Jun Liu, Jun Hu, Rong Zeng(eds).2011. Non-uniform ageing behavior of individual grain boundaries in ZnO-varistor ceramics. *ScienceDirect*(J Journal of the European Ceramic Society 31 (2011) 1451–1456)

Jinliang He, Jun Liu, Jun Hu, Wangcheng Long.2011. AC ageing characteristics of Y2O3-doped ZnO varistors with high voltage gradient. *Materials Letters* 65 (2011) 2595–2597

Jun Liu, Jinliang He∗, Jun Hu, Wangcheng Long, Fengchao Luo.2011. Statistics on the AC ageing characteristics of single grain boundaries of ZnO Varistor. *Materials Chemistry and Physics* 125 (2011) 9–11

R David. Clarke.1999, Varistor Ceramics. *Journal of the American Ceramic Society*. Volume 82, Issue 3, pages 485–502, March 1999

Saha,T.K. Sutton,R.A.2001.The effects of electrical degradation on the microstructure of metal oxide varistor. *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*: 329 - 334 vol.1

Tapan K. Gupta. 1990. Application of Zinc Oxide Varistors. *Journal of the American Ceramic Society*. Volume 73, Issue 7, pages 1817–1840

Tsukamoto Naoyuki.2014. Study of degradation by impulse having 4/10llS and 8/20llS waveform for MOVs (metal oxide varistors). *Lightning Protection (ICLP), 2014 International Conference o:* 620 - 623

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