*electronics*

*Article*

# Experimental Approach for Reliability Analysis of Medium-Power Zener Diodes under DC Switching Surge Degradation

**Daniel van Niekerk and Johan Venter ***

Department of Electrical and Electronic Engineering Technology, University of Johannesburg, Johannesburg 2028, South Africa; dvanniekerk@uj.ac.za
* Correspondence: johanv@uj.ac.za

**Abstract:** This study investigated the reliability of Zener diodes subjected to a gradually increasing DC switching surge amplitude with delay internals between surges to avoid thermal degradation from different manufacturers with similar specifications. The analysis involved applying occasional 3 ms direct current (DC) switching surges with a gradual increasing surge voltage, followed by a constant current test to verify device functionality for three different selected manufacturer 5.1 V Zener diodes. This experimental approach was used to identify the maximum surge current that each Zener diode could handle before failing to clamp the surge voltage at the specified Zener reference voltage. Statistical analysis revealed significant differences in the maximum average surge current between different manufacturers. The maximum average surge current findings just before failure were 1.98 A, 3.18 A, and 3.33 A, respectively, and associated 95% confidence interval ranges can be used as a reliable metric to compare Zener diode population reliability against occasional DC switching surges. The findings revealed variations in the DC switching surge current handling capabilities between Zener diodes from different manufacturers with similar electrical specifications. The statistically measured maximum average surge current just before device failure can be considered an effective metric to compare the reliability of Zener diodes against DC switching surge degradation.

**Keywords:** Zener diode; Zener reference voltage; DC switching surge; pn-junction

check for updates

**Citation:** van Niekerk, D.; Venter, J. Experimental Approach for Reliability Analysis of Medium-Power Zener Diodes under DC Switching Surge Degradation. *Electronics* **2024**, *13*, 1976. https://doi.org/10.3390/electronics13101976

Academic Editor: Ahmed Abu-Siada

Received: 22 April 2024
Revised: 12 May 2024
Accepted: 16 May 2024
Published: 18 May 2024



## 1. Introduction

Zener diodes have been used extensively in a wide variety of voltage reference and protection applications since they were first introduced in 1934 by Clarence Zener. Typically, a Zener diode contains an extra doped region that is varied to change the Zener reference voltage clamp level [1]. The Zener quantum tunneling effect demonstrates the unique operating function distinguishing it from other types of diodes. Zener diodes are also used to clamp surges to an acceptable voltage level, therefore, some form of degradation will occur. This degradation can change the performance of the Zener diode due to the channeling of surge energy away from the protected circuit and dissipation in the form of heat. Previous studies have attempted to characterize Zener diodes in terms of reliability, focusing on 1/f noise [2,3], breakdown voltage mismatch [4], pulsed electrical overstress [5], functional data analysis [6], physical failure analysis [7], and technology computer aided design (TCAD) [8]. In some of these studies, non-destructive methods were used, and in other studies, computer aided designs were used. Although these methods provided great insight into how these diodes work, performance analyses of Zener diodes subjected to occasional DC switching surges with a gradually increasing surge voltage are still lacking, according to the authors. Experimental DC switching surge degradation analysis has been shown to be a reliable method to determine the durability performance of metal oxide varistors (MOV) [9]. The aim of this study was to find a novel experimental approach to determine the actual current–voltage characteristics of a Zener diode under this type of

DC switching surge degradation. The actual Zener diode reliability will be measured not only to compare with other published reliability performance methods. According to the authors, this study distinguishes itself from other studies because it is an experimental approach to characterizing the reliability of Zener diodes subjected to DC switching surge degradation. Zener diodes are commonly used to protect integrated circuit (IC) pins from occasional DC switching surges, as illustrated in Figure 1.

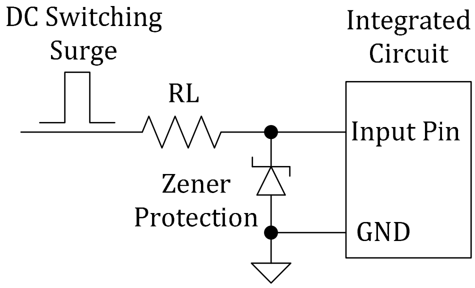


**Figure 1.** Zener diode DC switching surge protection for IC pins.

In this application, an external Zener diode is placed near the IC pin, often with a series resistor for heat dissipation. During a DC switching surge, the Zener conducts, clamping the voltage near its reference to a safe level for the IC pin. The series resistance is generally used to dissipate the surge current energy as heat, instead of the Zener diode device. However, what is the maximum average surge current a Zener diode can handle on its own, just before it fails to clamp the voltage effectively? It is this maximum average surge current that can serve as a Zener diode reliability metric for DC switching surges. Therefore, this study investigated this metric to determine how Zener diodes from three different manufacturers with similar electrical specifications fared under occasional DC switching surges with a gradually increasing amplitude. In addition, since DC switching surges typically occur randomly, the Zener diodes have time to dissipate absorbed energy as heat. Therefore, this study will include experimentally determined cool-down internals between surges to avoid thermal degradation. The novel aspect of this work is that only one single method is employed to characterize Zener diodes, where multiple factors are considered at the same time.

The rest of this paper is organized as follows. In the introduction, the problem is described, and the publications devoted to it are studied in Section 2, which presents the literature study. A description of the proposed novel experimental approach including block diagrams and the test stand setup is presented in Section 3., and the analysis of the recorded measurement results is presented in Section 4. The conclusions and reference list are provided at the end of the work.

## 2. Literature Study

Zener diodes have proven to be a valuable component in voltage reference, voltage regulation, and protection circuits for many years. Due to inadequate electricity infrastructure upgrades in many countries, the electricity supply has become problematic due to frequent power cuts, and in some countries, controlled power cuts. Therefore, it is essential to use reliable protection circuitry to protect sensitive appliances and equipment from DC switching surges that can significantly degrade components over time. Zener diodes are still robust components to use in protection, regulation, and reference circuits, however, since it is not possible to quickly upgrade electricity infrastructure, the reliability of Zener diodes needs to be determined.

Researchers have developed a number of methods to analyze the behavior of Zener diodes. A novel method to extract the breakdown voltage of a Zener diode is presented in [8], where automated iterative matrix calculations were used to find the breakdown voltage. Sentaurus Technology computer aided design (TCAD) was used to obtain the data, and data filling together with data smoothing was used to process the data, which together with the median absolute deviation (MAD) is used to detect the breakdown voltage. These are expensive ways to characterize Zener diodes, whereas the method proposed in this study makes use of random discrete samples and statistical analysis. The advantage is that real-world effects are considered, which need to be included in mathematical models that may still be somewhat lacking. Previously published work indicates that as the positive biasing voltage is increased, breakthrough occurs, showing a tunneling effect as a direct result of the Zener implant [1,6–8,10,11]. Self-heating in Zener diodes is a matter of concern and should be dealt with accordingly [12] where temperature drift is confirmed. This results in variations in reverse breakdown voltages, and [13] showed that drift is a problem in the medium- and long-term. Long-term stability stress testing revealed that there can be a shift in Zener voltage over time [1]. Appropriate methods of testing are required to ensure that this is significantly reduced. In this work, experimentally determined cool-down time intervals between surges were implemented to avoid Zener diode thermal runaway.

In [6], the authors used four methods to determine the Zener diode behavior, namely functional data analysis, amplitude and phase distances, functional principal component analysis, and functional regression. I–V data were obtained experimentally by sweeping biasing voltage and recording the current through the Zener diode. Trend graphs were obtained, which corresponded to other works and the results of this study. However, the study by [6] lacked an analysis of the DC type switching surge degradation. 1/f noise analysis is a beneficial non-destructive tool to analyze reliability, which is used by electromigration in VLSI interconnection [2]. For currents lower than 1 mA, the effect of 1/f noise and white noise is insignificant [2]. For currents above 1 mA, 1/f noise is proportional to the current flow, and white noise reduces as the current flow increases. Accelerated life tests have been performed using reverse bias and a constant current of 65 mA, which is contrary to the 45 mA and 1 mA tests results shown in the Zener diode manufacturer datasheets. Additionally, the total stress time was 3000 h, which is an extremely long duration test. Our proposed method takes a small fraction of that time, yielding suitable results under real-world conditions.

On the IC level, two types of Zener diodes exist, namely the *surface Zener diode* and *buried Zener diode* [1]. The difference is in the placement and location of the Zener implant, which touches the silicon-oxide layer in the case of a *surface Zener diode*, and the implant is placed away from the silicon-oxide layer in the case of a *buried Zener diode*. The reason for placing the implant away is to reduce the "walkout" effect. This will allow the junction to settle quicker between pulses, resulting in more stable functionality. The Zener implant doping also determines the Zener reference voltage level [1]. These two methods can result in vastly different characteristics. It can be difficult to determine the exact characteristics based on this, and therefore, an experimental method would provide the actual characteristics in real-world conditions. In the work by [14,15], a software switching technique was used to reduce switching surges. However, it will not always be possible to use software and accompanying hardware to reduce switching surges, since it may not always be economically feasible and practical to implement. In the work of [12], a methodology for using Zener reverse breakdown voltage to accurately establish junction heating curves was established, where special attention was paid to the pulse length and spacing. Punch-through diodes were used in [10], which are typically made up of $n^+$-p-$n^+$, $p^+$-n-$p^+$, $n^{++}$-p-n-$n^{++}$, and $n^{++}$-p-n-x, where x is the alternating regions of $n^{++}$ and $p^{++}$. This results in high differential resistance at high current densities. Therefore, as the biasing voltage is increased beyond a certain point, breakdown occurs due to the tunneling effect. However, this breakdown occurs at much higher voltages compared to single layer Zener diodes, although the effect is the same. These punch-through diodes are therefore a great alternative to protection circuits at a higher cost of production.

Electrical overstress (EOS), where over-current and over-voltage is applicable, remains a concern of designers because it is not well understood [16]. Here, the authors used a complicated system to test this using a PC, signal generator, power amplifier, and oscilloscope to perform a manual test. Since modern day systems try and incorporate 4IR type automated systems to obtain valid measurements, in our work, we used a custom built system where the data were recorded automatically through calibrated sensors. Additionally, it is noted that the voltage spikes or surge duration can be 4.5 ms long, but typically, it is commonly accepted that a surge lasts around 3 ms [17].

In the work of [7], a novel method was introduced to locate the defects of a Zener diode in circuit. This can be beneficial for existing circuits, but it does not assist developers when they are designing new circuits. A statistical analysis is a good way to alleviate the problems that designers would have using PFA. The work of [4] can be used to determine breakdown voltage mismatches, which can be used in conjunction with the work described in this study, with some acceptable modifications. Again, a proper statistical analysis is required to ensure reliable specifications. This specific aspect, however, was not the focus of this work, although it can be seen in the literature that studies on statistical analysis are somewhat lacking. An application where Zener diodes were used where they should be characterized correctly is in the work of [5], where a reverse biased Zener diode was used for the open circuit voltage measurement of a solar panel. In another application, NMOS devices were used to emulate Zener diodes [18], where one would need accurate I–V curves.

Switching surges is a problem in bi-directional dual active bridge DC–DC converters [14], where they are reduced using a digital operation method. Although the surge was reduced in this application, the authors of this work noted that switching surges were a problem. Surge arresters are one method used to reduce switching surges [15] by channeling the excess energy away from the application, which is typically used at higher voltage applications. Zener diodes can serve as a promising candidate for lower voltage applications, especially at lower currents. The work presented in this paper attempts to show a controlled way to characterize the I–V curves of Zener diodes subjected to occasional DC switching surges.

## 3. Methodology

The same proposed experimental setup was used to comparatively analyze the reliability of all three manufacturer selected Zener diodes against DC switching surges and therefore, the measurement consistency in this study was more important than the absolute accuracy. The algorithmic flowchart for the proposed experimental approach is illustrated in Figure 2. This flowchart outlines the steps to determine the maximum average surge current level that a Zener diode can withstand when subjected to a gradually increasing DC switching surge voltage amplitude.

The surge voltage level applied to the Zener diode was set by a digital potentiometer that controlled the output voltage of the DC–DC converter supplied by a 30 V supply. At startup, the surge voltage level was initially set close to the rated Zener reference voltage of 5.1 V. A dedicated Zener reference voltage measurement circuit was then used to measure, at room temperature, the developed voltage across the Zener diode under test when a (manufacturer specified) constant current of 45 mA flowed through the device, expressed as $V_{45\ mA}$. The Zener diode was then transferred by a relay to the Zener DC switching surge current measurement circuit. The actual set surge voltage level provided by the DC–DC converter was then measured and recorded. The IEEE standard C62.11 defines the DC switching surge current as a rectangular waveform that consists of an approximate constant current magnitude for its duration [17,19]. This long pulse more closely reflects the actual stress a Zener diode experiences during real-world DC switching surge events. Based on industrial knowledge regarding failure probability within a finite time frame, C62.11 specifies a valid energy rating window between 2 ms and 3.2 ms [17]. Therefore, a typical DC switching surge duration of 3 ms was applied to the Zener diode under test, while average surge current level through the device was measured and recorded. After measuring the surge current, the Zener diode underwent an experimentally determined 2-s cool-down period, allowing for any absorbed surge energy to dissipate as heat. The diode had sufficient time for thermal recovery before the next surge, which was verified by an infrared thermometer focused on the device throughout the 80 applied surges.

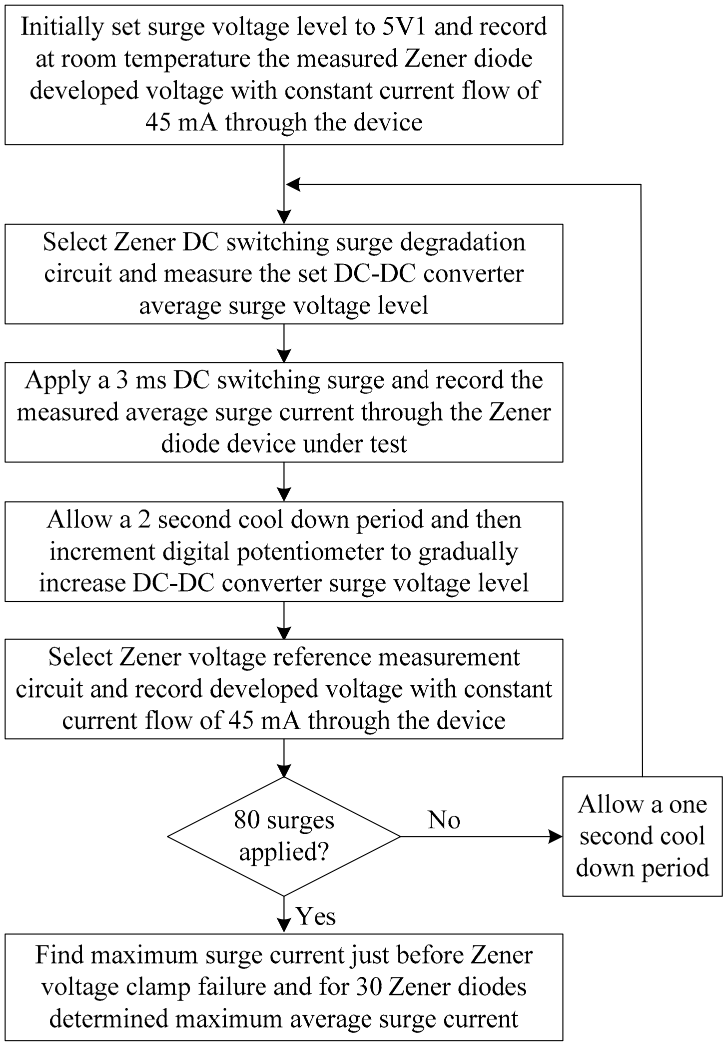


**Figure 2.** Algorithm flowchart to determine the maximum average surge current level.

Following the cool-down period, the digital potentiometer setting was incremented to gradually increase the DC–DC converter's output voltage surge level for the subsequent DC switching surge event. The Zener diode under test was then relayed back to the voltage reference measurement circuit. The developed voltage ($V_{45\ mA}$) across the Zener diode with the constant 45 mA current was measured and recorded again. Through experimentation, it was determined that all three selected manufacturer Zener diodes with similar specifications would typically fail within 80 applied 3 ms DC switching surge events with a gradual increase in surge voltage level starting at the rated 5.1 V. Therefore, if 80 applied surges had not been reached, an additional one second cool-down period would have been implemented before subjecting the Zener diode to another surge with a slightly higher surge voltage level. After applying 80 surges, the recorded data were investigated to find the maximum surge current level reached just before the device failed to clamp at the rated Zener reference voltage level. To achieve statistically significant results, at least 30 random Zener diodes from each of the selected manufacturers (excluding any outliers) underwent this testing process. This then allowed for the calculation of a maximum average surge current level before failure.

*3.1. Surge Voltage Level Measurement*

The surge voltage level of the DC–DC converter controlled by a digital potentiometer was scaled down using a voltage divider network for measurement by the microcontroller's analog-to-digital converter (ADC). Two 10 K resisters, each with a 1% tolerance, were used to divide a maximum 10 V voltage setting down to an acceptable microcontroller 5 V ADC input level. The ADC had a 10-bit resolution with a ±2 LSB absolute accuracy. Therefore, a 5 V input divided by 2 to the power of 10 is 4.88 mV per bit change, and a +2 LSB error would be 9.76 mV. The maximum surge voltage setting reached after 80 incremental digital potentiometer steps was 8.1 V. Therefore, the maximum potential error would be 9.76 mV divided by 8.1 V, which is 0.12%. With voltage divider resistors of 1% tolerance, the DC–DC surge voltage level measurement can be considered accurate because the error will not be more than 0.2%. In addition, to improve the measurement consistency, the ADC took five evenly spaced voltage samples 100 ms apart. The average surge voltage applied to the Zener diode was then calculated by averaging these five samples, as illustrated in Figure 3.

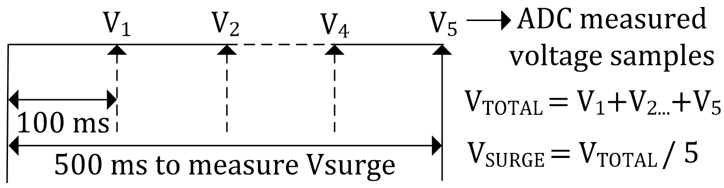


**Figure 3.** Average surge voltage level measurement.

*3.2. Zener Reference Voltage Measurement*

A dedicated Zener reference voltage measurement circuit was employed in order to measure the developed reference voltage across the Zener diode under test by applying a 45 mA constant current flow through the device, as shown in Figure 4. Following each DC switching surge event, the Zener diode was transferred back by a relay to the voltage reference measurement circuit. Here, the voltage developed across the Zener diode ($V_{45\ mA}$) was measured again with the constant current flow of 45 mA. This measurement serves to assess whether the Zener diode can still regulate at the selected reference voltage level of 5.1 V. To ensure an accurate measurement of the Zener diode's post-surge voltage regulation capability, a constant 45 mA current was applied for 100 ms to allow for full conduction before measuring the reference voltage. This practice aligns with recommendation by IEEE standard C62.33, which suggests applying a constant current source (CCS) within 20 ms to 100 ms before measuring the reference voltage of a MOV [20].

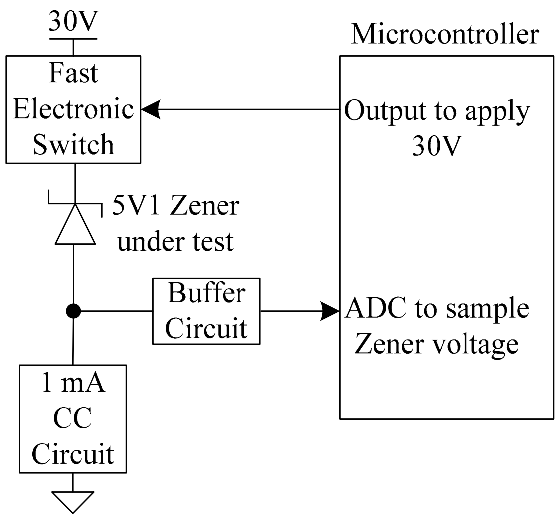


**Figure 4.** Zener voltage reference measurement circuit.

A precise 30 V linear DC power supply was switched across the Zener diode under test in series with a calibrated 45 mA CCS circuit by means of a fast solid-state electronic switch. Using an accurate 6 and 1/2-digit precision multimeter, a trim pot was used to calibrate a TLV431 device to ensure a 45 mA CCS. To prevent any circuit loading, a buffer circuit was employed to measure the average voltage developed across the CCS circuit. This average measured voltage was subtracted from the applied precise 30 V linear DC power supply to determine the actual voltage reference developed across the Zener diode under test. To improve the measurement consistency, after the 45 mA constant current flowed through the Zener diode for 100 ms, ten evenly spaced 10 ms interval ADC voltage samples were measured and used to calculate the average Zener voltage reference, as illustrated in Figure 5.

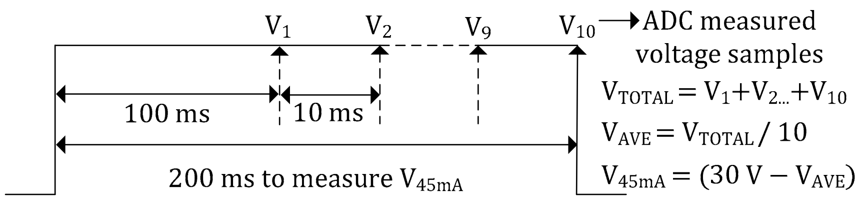


**Figure 5.** Average CCS voltage measurement and Zener reference voltage calculation.

### *3.3. DC Switching Surge Current Measurement*

To generate a DC switching surge, the Zener diode under test was connected for a set duration to the output voltage of a DC–DC converter. A digital potentiometer allows for incremental adjustment of the converter's output voltage, thereby gradually increasing the applied surge voltage level. A fast solid-state electronic switch connected the Zener diode to the selected DC voltage surge level for a programmed duration of 3 ms. A high accuracy Hall-effect current sensor (ACS723) was used to sample the current flowing through the Zener diode ten times during the 3 ms surge event. The ACS723 Hall-effect current sensor device was linear throughout the current measurement range of 10 mA up to 5 A and had a sensitivity of 400 mV/A with an error of $\pm 2\%$. The measured current samples were then used to calculate the average surge current level experienced by the Zener diode. A block diagram illustrating the DC switching surge current measurement circuit setup is shown in Figure 6.

To improve the measurement consistency of the average surge current, the Hall-effect current sensor sampled the current ten times during the 3 ms DC switching surge event at evenly spaced intervals of 300 µs. The average surge current was calculated by summing the ten samples and dividing by ten, as illustrated in Figure 7.

A photograph of the actual constructed experimental test stand setup to investigate the Zener diode reliability against DC switching surges is shown in Figure 8. The test stand setup photo clearly shows a connected 5.1 V Zener diode under test. A precise 30 V linear DC power supply was provided for the Zener voltage reference measurement circuit, and a relay was used to switch the Zener diode between this circuit and the DC switching surge current measurement circuit. An adjustable 5 V to 10 V digital potentiometer that controlled the DC–DC converter output was connected to the DC switching surge current measurement circuit. A high accuracy Hall-effect current sensor (ACS723) was used to measure the average current during the 3 ms DC switching surge events at different adjusted DC–DC converter output voltage levels. The test stand setup operation was automated by the microcontroller code for the measurements of the 80 applied surges. The measurement results were recorded on a secure digital (SD) card. A personal computer (PC) serial interface cable was used the start the automated measurements and to indicate when the test was completed via the PC serial monitor. The SD card was then removed, and the measurement data of the Zener diode under test were saved to the PC for later analysis. The Zener diode was then replaced with the next Zener diode to test, the data cleared, and SD card inserted again.

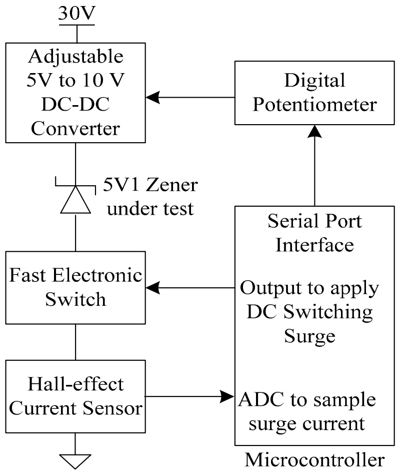


**Figure 6.** Zener DC switching surge current measurement circuit.

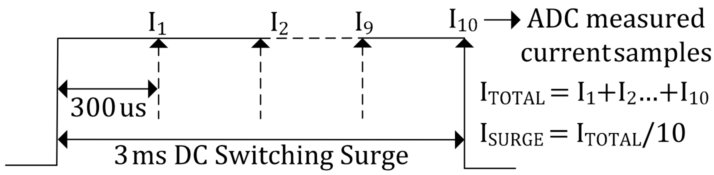


**Figure 7.** Average surge current level measurement and calculation.

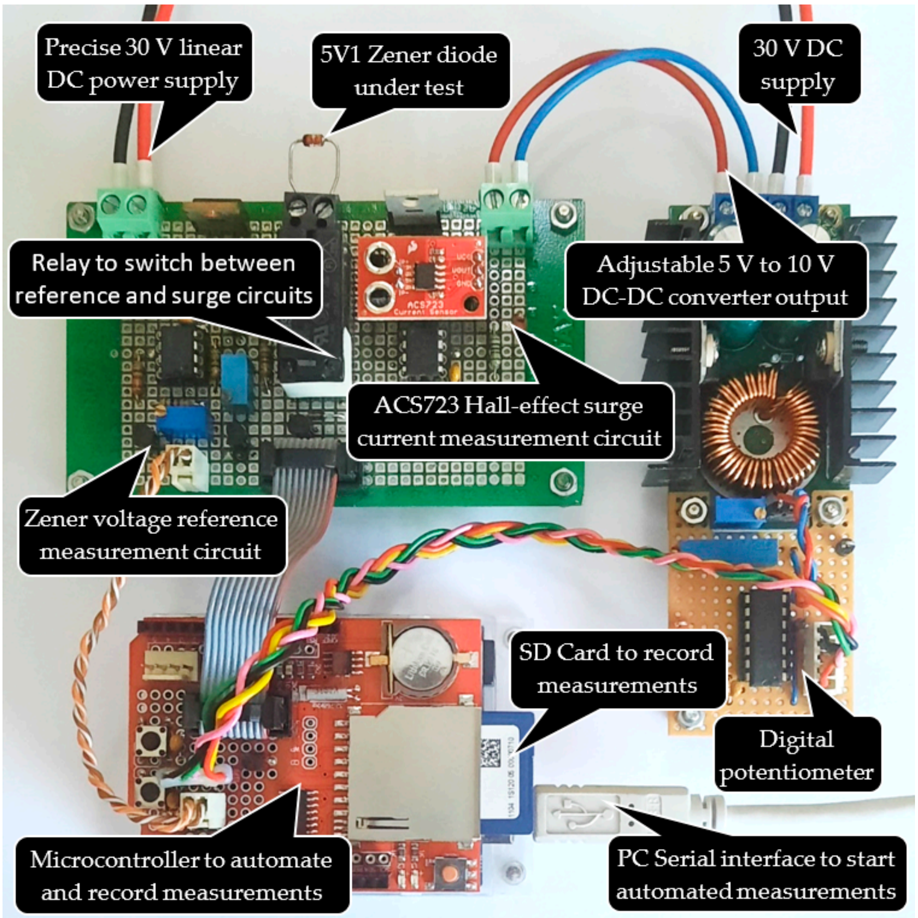


**Figure 8.** Actual constructed experimental test stand setup.

## 4. Results and Discussion

This experiment utilized three commercially available medium-power Zener diodes from different manufacturers that shared a similar physical size and electrical specifications. The Zener diodes were assigned to the following manufacturer group identification codes: UV, WX, and YZ. These Zener diodes belong to the standardized BZV85 series with a nominal voltage of 5.1 V and a typical tolerance range of ±5% (E24 series). To ensure statistically significant results, 30 random Zener diodes were obtained from each selected manufacturer. Table 1 summarizes the similar electrical specifications of all three selected manufacturer Zener diodes.

**Table 1.** Similar selected manufacturer Zener diode electrical specifications.

| Parameter | Specification |
|---|---|
| Power dissipation (Pz) | 1.3 W |
| Test current (Iz) | 45 mA |
| Reference voltage (Vz) | 5.1 V |

To identify the maximum surge current ($I_{Surge}$) level that the Zener diode could withstand before failing to regulate the voltage, a gradually increasing surge voltage ($V_{Surge}$) level was utilized during the 80 applied DC switching surges, as graphically shown in Figure 9. This approach allowed for a more precise detection of the $I_{Surge}$ just before the Zener diode could no longer maintain the 5.1 V reference voltage level.

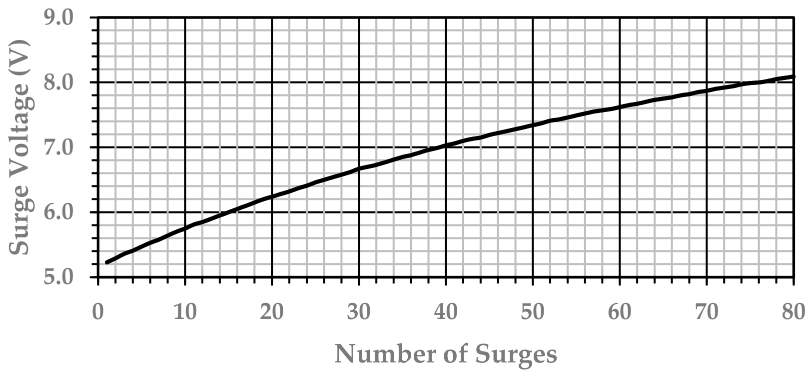


**Figure 9.** Gradual increasing surge voltage level vs. surge number.

A typical response of a Zener diode reference voltage ($V_{45\ mA}$) measured at a 45 mA constant current to the gradual increasing $V_{Surge}$ level applied during the 80 DC switching events is graphically shown in Figure 10.

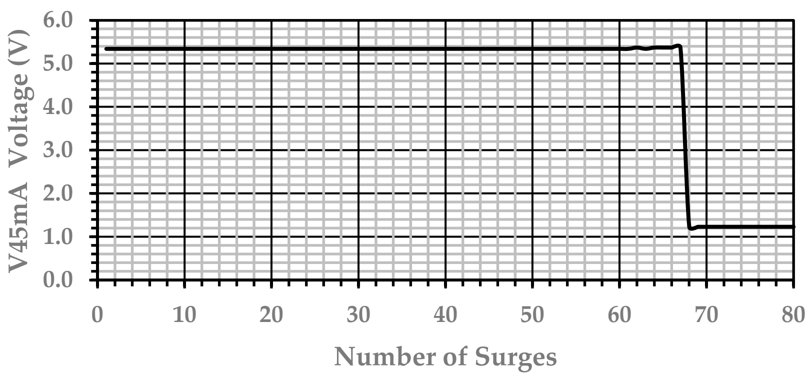


**Figure 10.** Zener reference voltage vs. surge number.

The corresponding surge current characteristic of a typical Zener diode in response to the gradual increasing $V_{Surge}$ level applied during the 80 DC switching surge events is graphically shown in Figure 11.

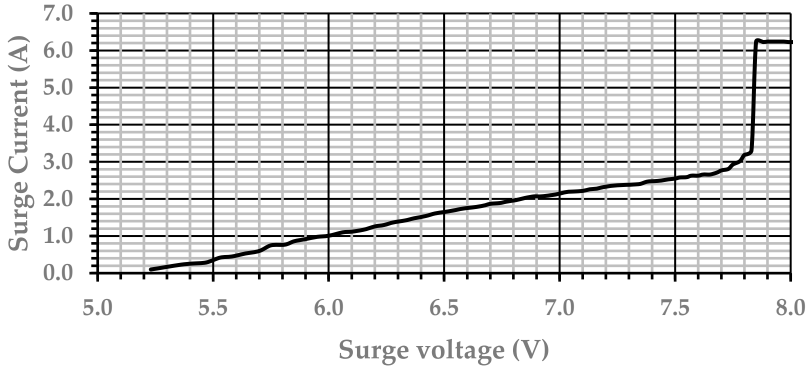


**Figure 11.** Zener surge current vs. surge voltage level.

Figures 10 and 11 depict the response of a typical Zener diode under test to the gradual increase in $V_{Surge}$ during the 80 DC switching surge events. As the applied $V_{Surge}$ level surpassed 7.8 V, the Zener reference voltage ($V_{45\ mA}$) measured at a constant current of 45 mA significantly dropped from an average of 5.37 V to 1.23 V. This indicates a decline in the Zener diode's ability to regulate voltage at higher applied $V_{Surge}$ levels. It can be observed that the $I_{Surge}$ through the Zener diode also increased from 3.19 A to a maximum of 6.24 A, which is the limit of the adjustable DC–DC converter's output current. For each manufacturer's random 30 Zener diode sample, $I_{Surge}$ data from the 80 recorded events were analyzed to find the critical $I_{Surge}$ level reached right before the device failed to maintain the 5.1 V voltage reference. The following equation was used to calculate the maximum average $I_{Surge}$ based on the identified critical $I_{Surge}$ levels:

$$\overline{I_{Surge}} = \frac{\sum I_{Surge}}{n} \tag{1}$$

where $\overline{I_{Surge}}$ is the maximum average surge current of a sample of n equal to 30 and $I_{Surge}$ is the maximum surge current level reached just before device failure excluding any outlier measurements. The population standard deviation (σ) can be estimated for each sample by using the following sample standard deviation (S) calculation:

$$S = \sqrt{\frac{\sum\left(I_{Surge} - \overline{I_{Surge}}\right)^2}{n - 1}} \tag{2}$$

where S measures how spread out the $I_{Surge}$ data points are from the calculated $\overline{I_{Surge}}$. A lower S value indicates that the $I_{Surge}$ data points are clustered closer to $\overline{I_{Surge}}$, while a higher S value suggests a wider spread. However, an outlier $I_{Surge}$ data point fell significantly outside the typical range of the other values and could have distorted the $\overline{I_{Surge}}$ and S calculations, making them less representative of the overall sample. Therefore, $\overline{I_{Surge}}$ and the associated S calculation are most reliable when the $I_{Surge}$ data distribution is not significantly skewed or has no outliers. Therefore, if $I_{Surge}$ outliers had been excluded from a sample, the $\overline{I_{Surge}}$ and associated S calculations can be used as valid estimates of the population mean and standard deviation. This approach ensures that the calculated values provide an accurate representation of the Zener diode population, allowing for reliable inferences to be drawn using statistical methods.

### 4.1. Five-Number Summary

A more informative approach to describe the $I_{Surge}$ data distribution is to utilize a five-number summary and its corresponding boxplot graph. A five-number summary divides the ordered $I_{Surge}$ data points into four equal-sized groups or quartiles of 25% each. The boxplot then visually represents this summary [21]. Boxplots can reveal skewness in the data, facilitate a comparison between the mean and median $I_{Surge}$ values, and help identify outliers situated far outside the plot's whiskers. Furthermore, boxplots are particularly useful when comparing $I_{Surge}$ data from different Zener diode manufacturers because they enable a quick visual comparison of their statistical characteristics such as spread, center, and the presence of outliers. One advantage of using quartiles is their resilience to outliers because quartiles divide the ordered data into equal groups where extreme values have a lesser impact on their calculation compared to the mean. The interquartile range (IQR) is another useful statistic derived from the five-number summary and is determined as follows:

$$\mathrm{IQR} = (\mathrm{Q3} - \mathrm{Q1}) \tag{3}$$

where IQR represents the spread of the middle 50% of the ordered $I_{Surge}$ data. Q1 denotes the first quartile separating the lowest 25% of $I_{Surge}$ data and Q3 represents the third quartile separating the highest 25% of $I_{Surge}$ data. While outliers may not always be visually obvious, their presence can be determined mathematically. A common practice involves calculating the upper and lower limits based on the calculated IQR. Data points that fall outside these limits are considered outliers because they deviate significantly from the majority of $I_{Surge}$ data. This approach provides a more objective way to identify outliers compared to solely relying on visual inspection. A sample of the $I_{Surge}$ data is not considered as outlier if it remains within the limits of the following equation [21]:

$$\mathrm{Q1} - (\mathrm{IQR} \times 1.5) \leq I_{Surge} \leq \mathrm{Q3} + (\mathrm{IQR} \times 1.5) \tag{4}$$

The five-number summary, calculated IQR, outlier limits, $\overline{I_{Surge}}$, and associated S for the three selected manufacturer Zener diode samples of 30 each is shown in Table 2.

**Table 2.** Zener diode $I_{Surge}$ five-number summary, IQR, outlier limits, $\overline{I_{Surge}}$, and S.

| Statistics | UV (A) | WX (A) | YZ (A) |
|---|---|---|---|
| Minimum | 1.38 | 2.60 | 2.58 |
| Quartile Q1 | 1.80 | 2.95 | 3.15 |
| Median | 1.98 | 3.18 | 3.33 |
| Quartile Q3 | 2.12 | 3.34 | 3.56 |
| Maximum | 2.58 | 3.70 | 4.02 |
| IQR = (Q3 − Q1) | 0.31 | 0.40 | 0.40 |
| Q1 − (IQR × 1.5) | 1.33 | 2.36 | 2.55 |
| Q3 + (IQR × 1.5) | 2.58 | 3.94 | 4.16 |
| Mean ($\overline{I_{Surge}}$) | 1.97 | 3.16 | 3.32 |
| StDev (S) | 0.27 | 0.29 | 0.36 |

While quartiles (Q1, Q3, and IQR) offer a useful summary of the $I_{Surge}$ data distribution, they only consider specific points within the dataset. The associated S, on the other hand, incorporates all $I_{Surge}$ values, thereby providing a more representative statistic for the spread of $I_{Surge}$. In Table 2, it can be observed that the minimum and maximum $I_{Surge}$ values for each manufacturer's sample fell within the associated outlier limit calculations. This indicates an absence of extreme outliers that could significantly distort the $\overline{I_{Surge}}$ and S calculations. Therefore, the $\overline{I_{Surge}}$ and S calculations shown in Table 2 can be considered as reliable estimates of the $I_{Surge}$ distribution for the respective Zener diode populations of each selected manufacturer.

Side-by-side boxplots, as shown in Figure 12, offer a visual comparison of the $I_{Surge}$ data distribution across the three selected Zener manufacturer samples of UV, WX, and

YZ. On each boxplot, the circles represent all 30 average measured Zener diode $I_{Surge}$ data just before device failure to maintain the 5.1 V voltage reference. The IQR or the middle 50% of the ordered $I_{Surge}$ data distribution is represented by the box with the center line representing the median $I_{Surge}$ data value.

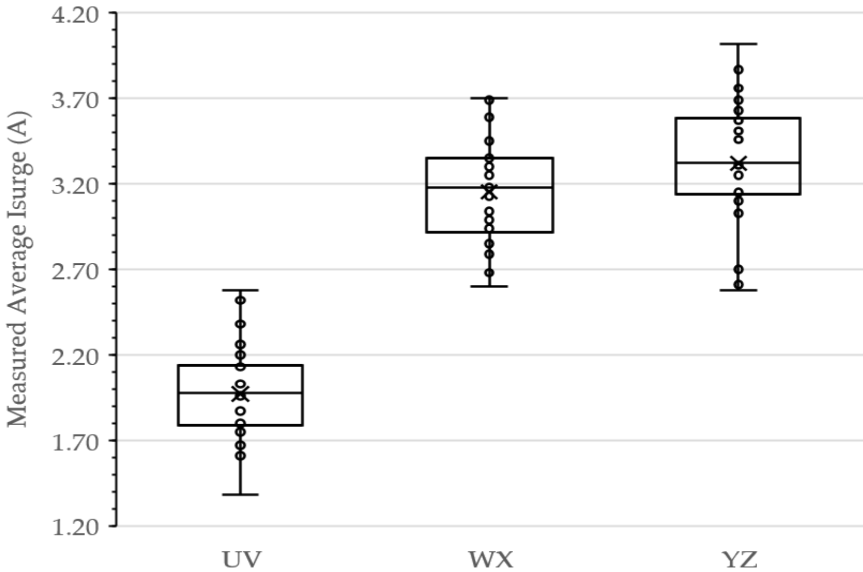


**Figure 12.** Side-by-side boxplot of the Zener diode samples: UV, WX, and YZ.

All $I_{Surge}$ data values of all three samples were within the expected outlier limits. The boxplots also showed relatively symmetrical distributions, indicating no significant skewness for each sample, since the mean and median were almost equivalent. The average $I_{Surge}$ values marked by "X" for WX and YZ were almost similar, suggesting comparable DC switching surge current handling capabilities for these diodes. However, the UV sample displayed a distinct $\overline{I_{Surge}}$ value, which highlights a potential significant variation in surge current handling capability compared to the other two manufacturers. This observation provides a valuable insight where WX and YZ likely offer a consistent performance due to their similar $\overline{I_{Surge}}$ and distribution values, while the UV sample's difference warrants further investigation.

### *4.2. Confidence Intervals*

The calculated $\overline{I_{Surge}}$ obtained from a large sample of 30 served as an estimate of the actual population mean (μ) for the entire Zener diode population. However, a sample is only a small subset of the population and may not perfectly reflect the entire population. Different samples drawn from the same population yielded slightly different $\overline{I_{Surge}}$ results due to random sampling variations. To account for this inherent variability and expressed uncertainty associated with the $\overline{I_{Surge}}$ estimate, the confidence interval concept can be used. A range of plausible values likely to contain the true population mean parameter can be represented by a confidence interval. Typically, a confidence interval range is selected to cover the 95% confidence level (LOC) of all possible means that can be obtained from multiple samples of the same Zener diode population. The remaining 5% is the level of significance (LOS), or the chance that the calculated confidence interval may exclude the true mean due to random sampling variation. The confidence interval width depends on the population variation, sample size, and selected LOS. However, large sample sizes of 30 or more are similar to each other because the effects of a few unusual data values are evened out by the other sample data values. By using a single large sample and the central limit theorem, the population mean and standard deviation can be estimated and used to then calculate the confidence interval range limits for the population mean [22]. The sampling distribution of the mean statistic ($\bar{X}$) is the distribution of all possible calculated sample means that can be obtained from multiple samples of the population. According to the central limit theorem, the sampling distribution parameter mean ($\mu_{\bar{X}}$) is equal to the true population mean (μ), and its standard deviation ($\sigma_{\bar{X}}$) is equal to the population standard deviation (σ) divided by the square root of the sample size. However, rarely enough is known about the population to determine its actual parameter values. Therefore, the central limit theorem ensures that with a large sample of 30 Zener diodes, the $\overline{I_{Surge}}$ and S calculation without any outlier data can be a reasonable estimation of the actual population mean (μ) and standard deviation (σ), respectively. The sampling distribution standard deviation ($S_{\bar{X}}$) can then be estimated by using the following equation:

$$S_{\bar{X}} = S/\sqrt{n} \tag{5}$$

where $S_{\bar{X}}$ is the standard error of the mean that can be used to find the confidence interval range limits by using the following equation underpinned by the central limit theorem:

$$C_I = \overline{I_{Surge}} \pm t\frac{S}{\sqrt{n}} \tag{6}$$

where $C_I$ is the confidence interval range within which the true population mean (μ) is likely to reside. To calculate this range, the t-distribution, rather than the normal distribution, should be used when the population variance is not known and has to be estimated from the sample data [22]. The specific "t" value used depends on the sample size (n) and the chosen LOC. If the sample size is large (n = 30), the t-distribution then more closely resembles a normal distribution, and the "t" value can be obtained from a t-distribution table using the sample size (n) and the desired LOC [22]. However, Microsoft Excel software in Microsoft Office 365 can be used to calculate the "t" value. Excel's T.INV function uses the sample size (n) and level of significance (LOS) as inputs and returns the corresponding "t" value as shown:

$$t = \text{T.INV}(\text{LOS}/2,\ n-1) = \text{T.INV}(0.05/2,\ 30-1) = -2.045 \tag{7}$$

The lower and upper range limits of the $C_I$ is determined by $t\frac{S}{\sqrt{n}}$, which represents the margin of error. Equation (6) can be used with $\overline{I_{Surge}}$ and the associated S to calculate the confidence interval range limits of all three selected manufacturer Zener diode samples, as shown in Table 3.

**Table 3.** Confidence interval limits for all three selected manufacturer average $I_{Surge}$.

| UV Average $Q_{TOT}$ for | $C_I$ Lower Limit | $C_I$ Upper Limit |
|---|---|---|
| UV | 1.87 A | 2.07 A |
| WX | 3.05 A | 3.27 A |
| YZ | 3.18 A | 3.45 A |

The forest plot shown in Figure 13 utilized the calculated $C_I$ to visually compare the $\overline{I_{Surge}}$ population estimate ranges for the Zener diode UV, WX, and YZ samples degraded by 3 ms DC switching surges. Each $C_I$ range represents the estimated range within which each manufacturer's true population $\overline{I_{Surge}}$ likely resides with a 95% LOC. This allows for a visual assessment of the potential differences in the population DC switching surge current handling capabilities between the three manufacturers.

When the 95% $C_I$ ranges of different samples do not overlap at all, it suggests a statistically significant difference in the population $\overline{I_{Surge}}$ values. In this case, the treatment of 3 ms DC switching surge degradation likely had a different effect on the population estimated $\overline{I_{Surge}}$ for the UV Zener diodes compared to WX and YZ. Conversely, the overlapping 95% $C_I$ ranges of WX and YZ indicated no statistically significant population difference due to the treatment. Therefore, since the 95% $C_I$ range for the UV manufacturer clearly fell outside the ranges of WX and YZ, there is a 95% chance of a significant potential variation in the reliability of Zener diodes due to DC switching surge degradation for different device manufacturers with similar electrical specifications.

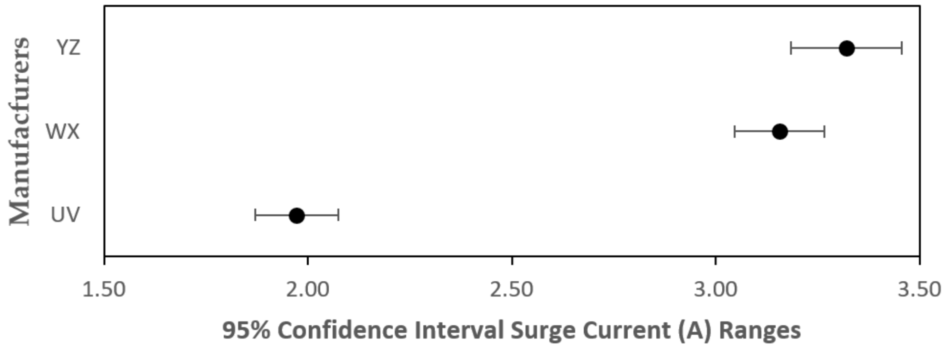


**Figure 13.** Forest plot of 95% $C_I$ ranges of $\overline{I_{Surge}}$ for the UV, WX, and YZ samples.

## 5. Conclusions

This study analyzed the 3 ms duration DC switching surge current handling capabilities of 5.1 V Zener diodes with a gradually increasing surge voltage for three different selected manufacturers with similar electrical specifications. The experiment used an automated calibrated measurement approach and statistically analyzed the maximum average surge current (excluding any outliers) tolerated by 30 random Zener diodes from each of the three selected manufacturers. The analysis of the three selected Zener diodes revealed an average surge current before failure of 1.98 A, 3.18 A, and 3.33 A, respectively. The key findings include a boxplot comparison showing that the maximum surge current sample data distributions for WX and YZ were similar, suggesting a comparable surge current handling capability. However, the UV maximum surge current sample data distribution was significantly different compared to WX and YZ. The UV sample exhibited a distinct maximum average surge current value compared to WX and YZ, which indicates a significant difference in surge current handling capability. The 95% confidence intervals were used to statistically compare the population maximum average surge current estimate ranges across the three selected manufacturers. The UV sample 95% confidence interval did not overlap with either WX or YZ, thereby revealing that there was a statistically significant population difference in the maximum average surge current handling capability. Therefore, the statistically measured maximum average surge current just before device failure has been proven to serve as an effective metric for comparing the reliability of Zener diodes to DC switching surge degradation. These findings reveal the potential variations in DC switching surge current handling capabilities between Zener diodes from different manufacturers that have similar electrical specifications. Therefore, further investigation into the reasons for the observed differences may be valuable.

**Author Contributions:** Conceptualization, D.v.N. and J.V.; Methodology, D.v.N.; Software, D.v.N.; Validation, D.v.N. and J.V.; Formal analysis, D.v.N.; Investigation, J.V.; Resources, D.v.N. and J.V.; Data curation, D.v.N.; Writing—original draft preparation, D.v.N.; Writing—review and editing, J.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References


1. Liew, M.; Bolhan, N.I.; Lim, L.; Sim, P.C.; Yang, H.; Holke, A. Integrated Zener Diodes for Smart Power IC. In Proceedings of the 2019 IEEE 9th International Nanoelectronics Conferences (INEC), Kuching, Malaysia, 3–5 July 2019.
2. Zhuang, Y.; Du, L. 1/f noise as a reliability indicator for subsurface Zener diodes. *Microelectron. Reliab.* **2002**, *42*, 355–360. [CrossRef]
3. Graffeuil, J.; Bary, L.; Rayssac, J.; Tartarin, J.-G.; Lopez, L. Assessing Zener-Diode-Structure Reliability From Zener Diodes' Low-Frequency Noise. *IEEE Trans. Devices Mater. Reliab.* **2007**, *7*, 468–472. [CrossRef]
4. Yang, M.; McAndrew, C.C.; Chao, L.; Xia, K. Characterization and Modeling of Zener Diode Breakdown Voltage Mismatch. In Proceedings of the 2019 IEEE 32nd International Conference on Microelectronic Test Structures (ICMTS), Kita-Kyushu, Japan, 18–21 March 2019.
5. Lim, V.C.H.; Leong, C.S.; Sopian, K.; Zaidi, S.H. Pulsed Solar Panel Light Current-Voltage Characterization Based on Zener Diode. In Proceedings of the 2016 IEEE Conference on Systems, Process and Control (ICSPC), Melaka, Malaysia, 16–18 December 2016.
6. Champon, X.; Angeles, D.; Buchheit, T.; Canfield, D.; Tucker, J.D.; Adams, J. A Statistical Assessment of Zener Diode Behavior Using Functional Data Analysis. In Proceedings of the 2023 7th IEEE Electron Devices Technology & Manufacturing Conference (EDTM), Seoul, Republic of Korea, 7–10 March 2023.
7. Qian, X.; Tian, L.; Wen, G.; Zhang, H.; Li, X. Advanced Method to Locate The Defect on Zener Diode to Avoid Cutting The Circuit in Failure Analysis. In Proceedings of the 2019 IEEE 26th International Symposium on Physical and Failure Analysis of Integrated Circuits (IPFA), Hangzhou, China, 2–5 July 2019.
8. Liang, Y.; Zhang, D.; Chen, Y.; Zhao, D.; Shao, Y.; Wang, K. A Novel Method for Automatically Extracting Breakdown Voltage of Zener Diodes from I-V Characteristics Curves. In Proceedings of the 2023 International Symposium of Electronics Design Automation (ISEDA), Nanjing, China, 8–11 May 2023.
9. van Niekerk, D.; Bokoro, P. A Durability Model for Analysis of Switching Direct Current Surge Degradation of Metal Oxide Varistors. *Electronics* **2022**, *11*, 1329. [CrossRef]
10. van Dalen, R.; Koops, G.E.J.; Pfennigstorf, O. Punch-through diodes as replacement for low-voltage Zener diodes in ESD protection circuits. *J. Electrost.* **2004**, *61*, 149–169. [CrossRef]
11. Biswas, J.C.; Mitra, V. Negative Resistance in Zener Diodes. *Solid-State Electron.* **1978**, *21*, 1053–1055. [CrossRef]
12. McAfee, R.; Fish, M.; Gess, J. Zener Diode Reverse Breakdown Voltage as a Simultaneous Heating and Temperature Sensing Element. In Proceedings of the 2022 21st IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTherm), San Diego, CA, USA, 31 May–3 June 2022.
13. Power, O.; Walsh, J.E. Investigation of the Long and Medium-Term Drift of Zener Diode-Based Voltage Standards. *IEEE Trans. Instrum. Meas.* **2005**, *54*, 330–336. [CrossRef]
14. Takasaki, M.; Ishizuka, Y.; Ninomiya, T.; Furukawa, Y.; Hirose, T. Switching Surge Reduction of A Bi-Directional Dual Active Bridge DC-DC Converter With Digital Operation. In Proceedings of the 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2–6 September 2013.
15. Sen, S.; Mehraeen, S.; Moghbeli, M. Application of Surge Arrester in Limiting Voltage Stress and DC Breaker. In Proceedings of the 2023 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, 13–14 February 2023.
16. Zhu, F.; Fouquet, F.; Ravelo, B.; Alaeddine, A.; Kadi, M. Experimental investigation of Zener diode reliability under pulsed Electrical Overstress (EOS). *Microelectron. Reliab.* **2013**, *53*, 1228–1292. [CrossRef]
17. *C62.11-2012*; IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (>1 kV). Revision of IEEE Std C62.11-2005; IEEE: New York, NY, USA, 2012. [CrossRef]
18. Finco, S.; Casimiro, A.P.; Santos, P.M.; Tavares, P.; Castro Simas, M.I. High Performance NMOS Active Zener and Rectifier Diodes. In Proceedings of the Conference Record of the 2001 IEEE Industry Applications Conference, 36th IAS Annual Meeting, Chicago, IL, USA, 30 September–4 October 2001.
19. Woodworth, J.J.; Comber, M.G. Improvements in IEEE C62.11 test standards. In Proceedings of the PES T&D 2012, Orlando, FL, USA, 7–10 May 2012; IEEE: New York, NY, USA, 2012; pp. 1–7. [CrossRef]
20. *C62.33-2016*; IEEE Standard for Test Methods and Performance Values for Metal-Oxide Varistor Surge Protective Components. IEEE: New York, NY, USA, 2018. [CrossRef]
21. Shayib, M.A. Applied Statistics 2013. 2013. Available online: https://www.win.tue.nl/~%7B%7Drmcastro/AppStat2013 (accessed on 10 January 2021).
22. Ross, S. *Introduction to Probability and Statistics for Engineers and Scientists*, 4th ed.; Elsevier Academic Press: Burlington, VT, USA, 2009; pp. 242–454.