Identification of short-circuits in electronic boards using electrical impedance spectroscopy

Yves Santos Borges[1]*, Pedro Bertemes Filho[2]

[1] yvessb@hotmail.com, [2] pedro.bertemes@udesc.br. Departamento de Engenharia Elétrica, Universidade do Estado de Santa Catarina (UDESC), Joinville, Santa Catarina, Brasil
* Corresponding author

Abstract

The increasing dependence on electronics in both industrial and public sectors highlights the critical importance of high-quality printed circuit boards (PCBs) to ensure reliability and user confidence. Traditional fault detection methods include visual inspections, automated optical inspection (AOI), in-circuit testing (ICT), and functional testing. However, these methods may not effectively detect subtle faults, such as early-stage corrosion or tiny unintended conductive paths, which could later lead to failures. Electrical Impedance Spectroscopy (EIS) emerges as a powerful tool in this context due to its non-destructive nature and its ability to provide detailed insights into the electrical properties of materials and structures within a PCB. This study aims to investigate the types of faults in printed circuits using Electrical Impedance Spectroscopy (EIS). A printed circuit board was developed using phenolic material with varying track thicknesses to simulate short-circuits and different levels of corrosion. Measurements of the electrical impedance spectrum between the track and the ground plane were conducted over a range of 1 to 500 kHz. The distances between tracks were measured using high-resolution microscope images. The key finding from this study is that the phase of the electrical impedance increases with the severity of the short-circuit, particularly in thinner tracks. This demonstrates the potential of EIS to detect and quantify faults that other methods may misidentify, offering a quantitative approach to assessing and potentially predicting PCB failures before they lead to device malfunctions.

Key-words: corrosion; electrical impedance spectroscopy; printed circuit board; short-circuit.

Identificação de curtos-circuitos em placas electrónicas usando espetroscopia de impedância elétrica

Resumo

A crescente dependência de eletrônicos nos setores industrial e público destaca a importância crítica de placas de circuito impresso (PCBs) de alta qualidade para garantir confiabilidade e confiança do usuário. Os métodos tradicionais de detecção de falhas incluem inspeções visuais, inspeção óptica automatizada (AOI), testes em circuito (ICT) e testes funcionais. No entanto, esses métodos podem não detectar efetivamente falhas sutis, como corrosão em estágio inicial ou pequenos caminhos condutores não intencionais, o que pode levar a falhas posteriormente. A espectroscopia de impedância elétrica (EIS) surge como uma ferramenta poderosa neste contexto devido à sua natureza não destrutiva e sua capacidade de fornecer insights detalhados sobre as propriedades elétricas de materiais e estruturas dentro de um PCB. Este estudo tem como objetivo investigar os tipos de falhas em circuitos impressos usando espectroscopia de impedância elétrica (EIS). Uma placa de circuito impresso foi desenvolvida usando material fenólico com espessuras de trilha variadas para simular curtos-circuitos e diferentes níveis de corrosão. Medições do espectro de impedância elétrica entre a trilha e o plano de aterramento foram conduzidas em uma faixa de 1 a 500 kHz. As distâncias entre as trilhas foram medidas usando imagens de microscópio de alta resolução. A principal descoberta deste estudo é que a fase da impedância elétrica aumenta com a gravidade do curto-circuito, particularmente em trilhas mais finas. Isso demonstra o potencial do EIS para detectar e quantificar falhas que outros métodos podem identificar erroneamente, oferecendo uma abordagem quantitativa para avaliar e potencialmente prever falhas de PCB antes que elas levem a mau funcionamento do dispositivo.

Palavras-chaves: *curto-circuito; corrosão; espectroscopia de impedância elétrica; placa de circuito impresso.*

1 Introduction

Technological advancements have significantly increased the reliance on electronic equipment across various sectors of civil society and industry. This article highlights the importance of these advancements and the critical need for reliability in electronic devices, which are directly influenced by the materials and technologies employed in printed circuit board (PCB) development. The evolution of PCB technologies, along with innovative manufacturing techniques, supports the growth of numerous industrial sectors dependent on electronic equipment, including telecommunications, automotive, aerospace, medical, and other industries.

A comprehensive understanding of PCBs, including their degradation processes, is essential for designing effective solutions and improvements. To maintain high standards in production processes, it is crucial to implement methodologies that analyze various production stages. These stages include the development of circuits through computational methods (Piumatti, 2021), the analysis of the actual printed circuit fabrication (Lee; Yao; Lee, 2020), and assessments of the board and electronic components at the final product stage (Raj; Sajeena, 2018). Quality inspection of PCBs requires processes and methodologies tailored to each specific project.

Currently, different processes are available for PCB manufacturing, involving subtractive methods such as chemical etching and milling, or additive methods (Florêncio; Correa; Amorim, 2014). Consequently, new technologies and emerging demands have shifted the focus of electronics and PCBs to new topics, such as the miniaturization of components, the development of systems that require high-frequency signal processors, the creation and application of more efficient and less polluting materials, electronics with greater energy and processing efficiency, and improvements in production processes and product quality, which include eliminating faults and defects in the manufacture of finished products (Dreslinski et al., 2010; Rigo, 2019). In response to these demands, certifications, and organizations have emerged globally to promote these improvements.

Methodological standardizations, such as PCOLA/SOQ/FAM, endorsed by the International Electronics Manufacturing Initiative (iNEMI), are employed to ensure product quality. PCOLA effectively evaluates the presence, correlation, orientation, functionality, and alignment of components within an electronic circuit (Parker, 2003). However, it is crucial to apply these methodologies and quality assessments throughout all stages of electronic production, particularly before the final stages. This proactive approach facilitates the early detection of potential errors or failures in the manufacturing process, preventing their propagation to subsequent stages.

In response to the need for early fault detection in manufacturing processes, this paper aims to elucidate various methods that assist in identifying and classifying faults in PCBs, emphasizing the nuances of several established methods. This discussion includes a detailed analysis of common PCB defects and faults, with special emphasis on electrical impedance spectroscopy (EIS) as an innovative alternative for fault detection. Furthermore, this paper presents a case study utilizing the EIS technique to investigate potential short-circuits in PCB tracks, detailing the methodology employed and discussing the results obtained. This illustrates the practical applications and effectiveness of this method in ensuring the integrity and reliability of PCBs. Early identification at the PCB design stage enables potential corrections and the elimination of faults, thereby avoiding wasted resources, time, and rework.

2 Defects and failures in PCBs

Electronic devices are manufactured through complex processes, each presenting opportunities for defects and failures. Defects are defined as deviations from accepted standards, necessitating corrective actions such as repair, disposal, or process adjustment. Failures, distinct from defects, refer to conditions that cause device malfunction or breakdown and may occur independently of detectable defects.

The environment in which electronic devices are manufactured and operated significantly influences their reliability. Contaminants such as dust, chemicals used during manufacturing, byproducts from production cycles, and residues from device operation can adversely affect performance. To mitigate these influences on Printed Circuit Boards (PCBs), several strategies are essential: (i) maintaining controlled conditions in manufacturing and operational environments; (ii) incorporating protective measures in designs to prevent corrosion; (iii) conducting regular preventive maintenance, including residue cleaning; and (iv) ensuring that physical stress on components does not exceed design specifications.

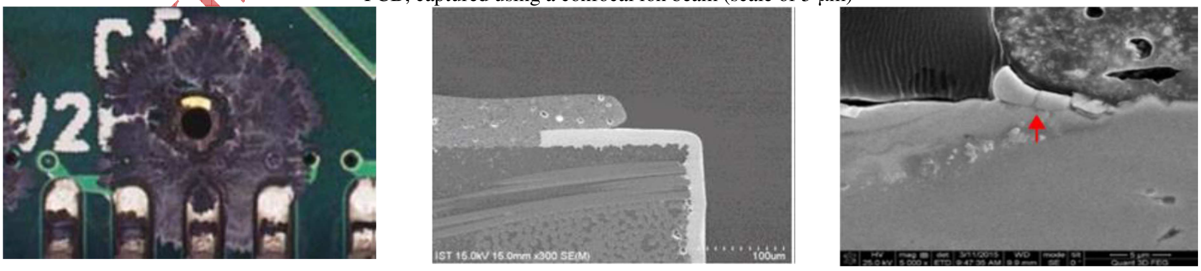
Uncontrolled contaminants can lead to significant PCB issues, such as corrosion and short-circuits between tracks. These problems often stem from the accumulation of conductive materials and pollutants, which facilitate anodic corrosion and electrolytic metal migration. This type of corrosion, akin to leakage current corrosion commonly observed in devices under high electromagnetic fields, occurs when there is a potential gradient across conductors separated by a thin aqueous solution of pollutants.

Quality assurance in PCB assembly begins with the evaluation of component placement and functionality on the board, which can be assessed through established methodologies (Parker, 2003). Prior to assembly, the integrity of track printing and hole drilling on PCBs is also critical, often evaluated using methodologies for detecting short-circuits and open circuits (Raj; Sajeena, 2018). Moreover, the inspection of highly complex PCBs, which incorporate electronic components such as resistors, capacitors, inductors, and integrated circuits of varying sizes—from millimeters to micrometers—requires non-destructive testing methods that preserve the integrity of the analyzed materials (Jellesen et al., 2010).

2.1 Image inspections

Analytical imaging methods play a pivotal role in identifying defects in PCBs, especially when combined with advanced computerized image processing techniques (Lee et al., 2017). Commonly employed modalities include optical microscopy (Fu et al., 2015; Lee et al., 2016a, 2017), scanning electron microscopy (Fu et al., 2015; Lee et al., 2016a; Lee et al., 2017; Salahinejad; Eslami-Farsani; Tayebi, 2017), and focused ion beam imaging (Chen et al., 2016; Fu et al., 2015). Scanning electron microscopy is renowned for its superior resolution over optical microscopy, a comparison detailed in studies by Lee et al. (2017). Additionally, focused ion beam imaging has gained prominence in industrial applications for its efficacy in corrosion analysis through high-resolution imaging, offering advantages over SEM. Notably, focused ion beam imaging facilitates the imaging of non-conductive materials without the prerequisite for chemical etching—a requirement often associated with both optical and scanning electron microscopy (Volkert et al., 2007). Comparative analyses of these imaging techniques are presented in Figure 1. The analysis reveals that SEM and focused ion beam imaging distinctly outline the contour edges of objects. Conversely, optical microscopy is more adept at capturing clearer images across larger surface areas, demonstrating its utility in broader evaluative contexts.

Figure 1 – (a) Image of a corroded area on a PCB, captured using optical microscopy (Lee; Yao; Lee, 2020). (b) Image of the track outline on a PCB with a solder mask, captured using scanning electron microscopy (Lee; Yao; Lee, 2020). (c) Image of a defective solder area on a PCB, captured using a confocal ion beam (scale of 5 µm)



(a) (b) (c)

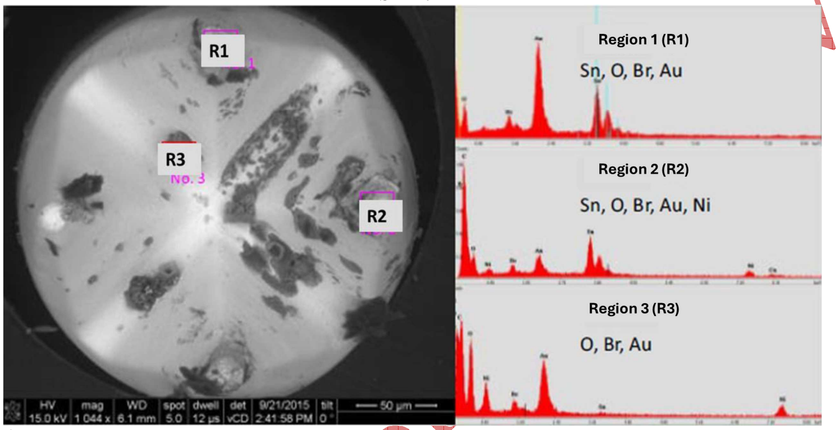
Source: Fu *et al*. (2015)

Production processes that necessitate rapid and frequent inspections increasingly rely on automation to meet efficiency demands. In a study conducted by Raj and Sajeena (2018), automated image comparison techniques were utilized to analyze the precision in drilling and track segmentation on PCBs. Furthermore, Kim et al. (2021) advanced this domain by implementing machine learning algorithms in conjunction with image processing to automate the identification of faults in PCBs.

2.2 Morphological analysis of material

In certain specialized scenarios, identifying the material composition of PCBs or the presence of contaminants necessitates the use of x-ray spectrometry techniques, specifically dispersive and photoelectric methods. These techniques leverage x-rays to conduct a comprehensive morphological analysis of various material constituents, including pollutants, corrosion, and soldering residues (Lee et al., 2016b; Salahinejad; Eslami-Farsani; Tayebi, 2017). Figure 2, for instance, illustrates three distinct regions of corrosion on a PCB as delineated by x-ray photoelectron spectroscopy. This method is particularly effective in distinguishing between different materials due to the unique spectral responses produced by each material under x-ray analysis.

Figure 2 – Regions of a PCB analyzed using x-ray photoelectron spectroscopy, where Au = gold, Br = bromine, Ni = nickel, O = oxygen, and Sn = tin

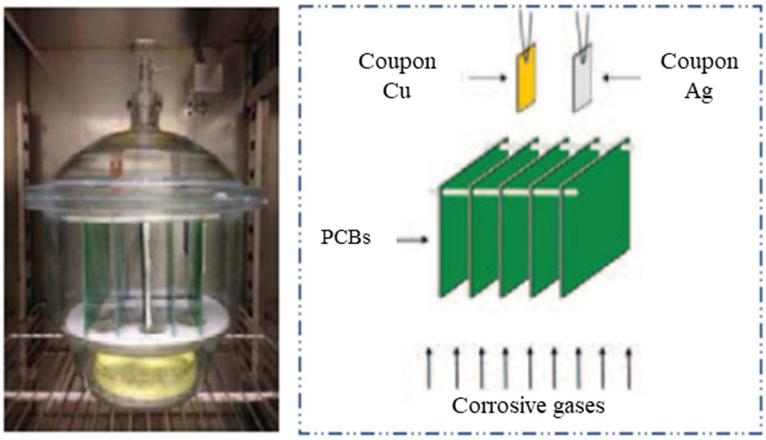


Source: Lee et al. (2016a)

2.3 Corrosion identification techniques

Coulometric reduction (Lee et al., 2016a; Lee et al., 2017) and mass loss/gain (Lee et al., 2017; Li et al., 2018) are quantitative methods commonly used for analyzing corrosion in printed circuit boards (PCBs) by employing corrosive gases. In coulometric reduction, the evaluation of coupons is based on the amount of corrosion that accumulates due to exposure to corrosive gases and the forced passage of current at electrical contact points on their surface (ASTM, 2013). Conversely, in the mass loss/gain technique, the difference in mass before and after exposure to a corrosive environment is recorded using high-precision balances. These methods typically employ silver (Ag) and copper (Cu) coupons, as these materials are common conductors in PCBs, and their corrosive behaviors are well understood within the context of these methods (ASTM, 2019). Figure 3 illustrates a gas chamber used for corrosion testing, applicable to both coulometric reduction and mass loss/gain tests, along with the basic elements necessary for these tests: corrosive gases, printed circuit boards, and copper or silver coupons.

Figure 3 – Chamber for applying corrosive gases on PCBs and coupons, where Au = cooper and Ag = silver



Source: Lee et al., 2016b

2.4 Electrical Impedance Spectroscopy (EIS)

Electrical Impedance Spectroscopy (EIS) is an analytical method used to examine the spectral response of a sample when subjected to an electric field. The sample may be biological (Olarte-Echeverri et al., 2010), conductive, semiconductive (Mansfeld, 2003; Tait, 1994; Xia et al., 2020), or even a chemical reaction (Narayanan et al., 1993). EIS is classified as a non-destructive electrochemical measurement technique, applicable in both alkaline and acidic solutions. The method involves exciting a low-intensity alternating electric current or voltage across a frequency range, typically between 10 mHz and 100 kHz. The response to this excitation is measured for each discrete frequency, allowing for the calculation of impedance, including both its magnitude and phase. From these measurements, both the impedance resistance (resistive component) and the impedance reactance (reactive component) can be determined and modeled using an equivalent electrical circuit that best represents the properties of the material under investigation, as demonstrated in studies on metal alloys (Łosiewicz et al., 2015).

Given that corrosion is an electrochemical process measurable by sensors (electrochemical probes), the EIS technique is applicable for investigating electrochemical changes in various material types (Somphotch et al., 2018). Due to its high sensitivity (up to 1 nV) and robustness, EIS can be employed for measuring isolated substrates; however, it is less suitable for measuring the reactance of residues (Jadhav; Gelling, 2019). Numerous EIS applications utilize small impedance probes (Abreu et al., 2017), which may display inductive behaviors at high frequencies due to the parasitic capacitances of the measuring cables. Furthermore, studies by Xia et al. (2020) have shown that factors such as the size, material, and distribution of electrodes on the impedance probe directly impact the accuracy and reliability of EIS measurements.

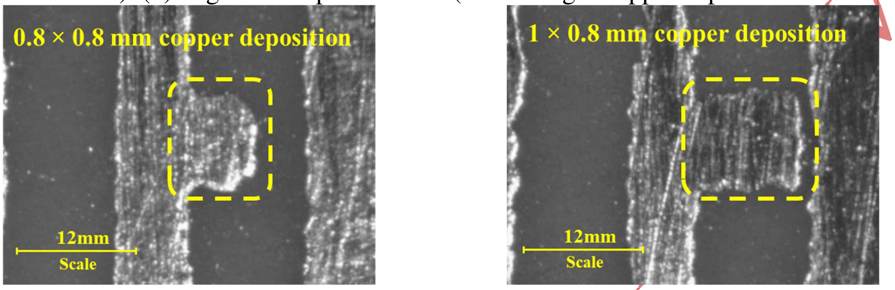
When studying the characterization of short-circuits in PCB tracks, it should be noted that the fault can be identified using electrical conductivity tests in direct current (DC). The prevention of a short-circuit, on the other hand, requires a more complex assessment in alternating current (AC) - the electrical impedance spectroscopy (EIS) technique is one of the AC techniques and can be adapted for this application, since the constructive characteristics of PCB tracks, such as the presence or absence of short-circuits, corrosion and track shapes, for example, influence the electromagnetic compatibility (EMC) of a PCB (Paul, 2005), and influence the impedance response in an eventual EIS measurement. A direct example of the impact that potential short-circuits have on electronics in use is the generation of PCB crosstalk due to the alteration of the insulation area between tracks (Paul, 2005) and the generation of accelerated micro corrosion due to current leakage (Ambat, 2006).

However, there is currently no technical formalization for the application of EIS to this characterization of faults in PCBs, opening space for a new area of study. However, there are studies on faults and the characterization of conductive materials using EIS, which are close to the objective of this work. Such as the study of corrosion (Tait, 1994) and the study of faults in electrical distribution network cables (Das; Reddy, 2022; Gong et al., 2022).

3 Methodology

To improve the detection of short-circuits using EIS, a phenolic PCB was specifically designed with features facilitating this investigation. The PCB layout includes the following: i) circuit tracks isolated by a minimum distance of 1.2 mm from the ground plane to ensure the absence of intrinsic short-circuits; ii) tracks where short-circuits were simulated through strategic copper deposition. The experimental setup involved four circuit tracks, each with different thicknesses: 0.65 mm (group T1), 1.25 mm (group T2), 2.25 mm (group T3), and 3.25 mm (group T4). To simulate varying short-circuit conditions, copper depositions were methodically applied between the tracks at different levels: none (representing no short-circuit), medium (with a copper deposition measuring 0.8 × 0.8 mm, as shown in Figure 4), and high (featuring a larger copper deposition of 1 × 0.8 mm). The region and measurements of the copper deposition used to simulate faults were designed to accommodate technical limitations in the track manufacturing process, particularly in terms of precision and scale, with a thickening between tracks of approximately 0.8 mm, as observed in laboratory tests.

Figure 4 – Simulation of short-circuit conditions. (a) Medium fault representation (with a copper deposition of 0.8 × 0.8 mm). (b) High fault representation (with a larger copper deposition of 1 × 0.8 mm)



(a) (b)

Source: research data

Detailed specifications for each track, including their respective thicknesses and the extent of simulated short-circuit conditions, are systematically presented in Table 1.

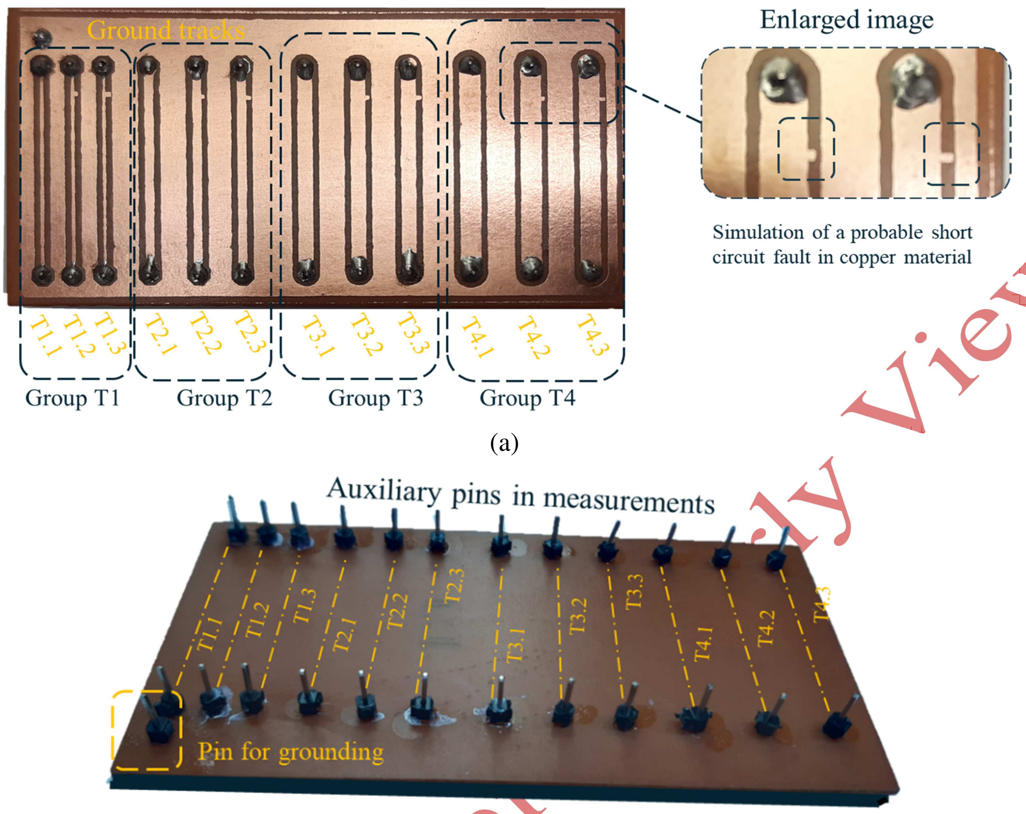
Table 1 – Technical specifications of the printed circuit board tested. Composed of groups of tracks with the same thickness, but different fault levels, simulating probably short-circuit conditions

Track	Short-circuit scenario	Thickness (mm)
T1.1	None	0.65 (group T1)
T1.2	Low	
T1.3	High	
T2.1	None	1.25 (group T2)
T2.2	Low	
T2.3	High	
T3.1	None	2.25 (group T3)
T3.2	Low	
T3.3	High	
T4.1	None	3.25 (group T4)
T4.2	Low	
T4.3	High	

Source: research data

The printed circuit board was manufactured manually in two stages. Initially, the circuit layout was transferred onto a phenolic board using a corrosion-inhibiting material to protect the underlying structure. This was followed by an etching process using ferric perchloride to precisely define the circuit paths. Throughout the fabrication process, potential discrepancies, such as imperfections in the layout transfer onto the phenolic substrate and variations in the etching degree, were carefully monitored. The result of the board, including the tracks used for the study, can be seen in Figure 5, which shows the upper and lower regions of the board, including auxiliary pins to facilitate measurements.

Figure 5 – (a) The upper part of the board, composed of copper tracks, where tracks with potential short-circuit faults are located. (b)The lower part of the board features soldered pins used to assist in measurements between the tracks and the ground plane



(a)

(b)

Source: research data

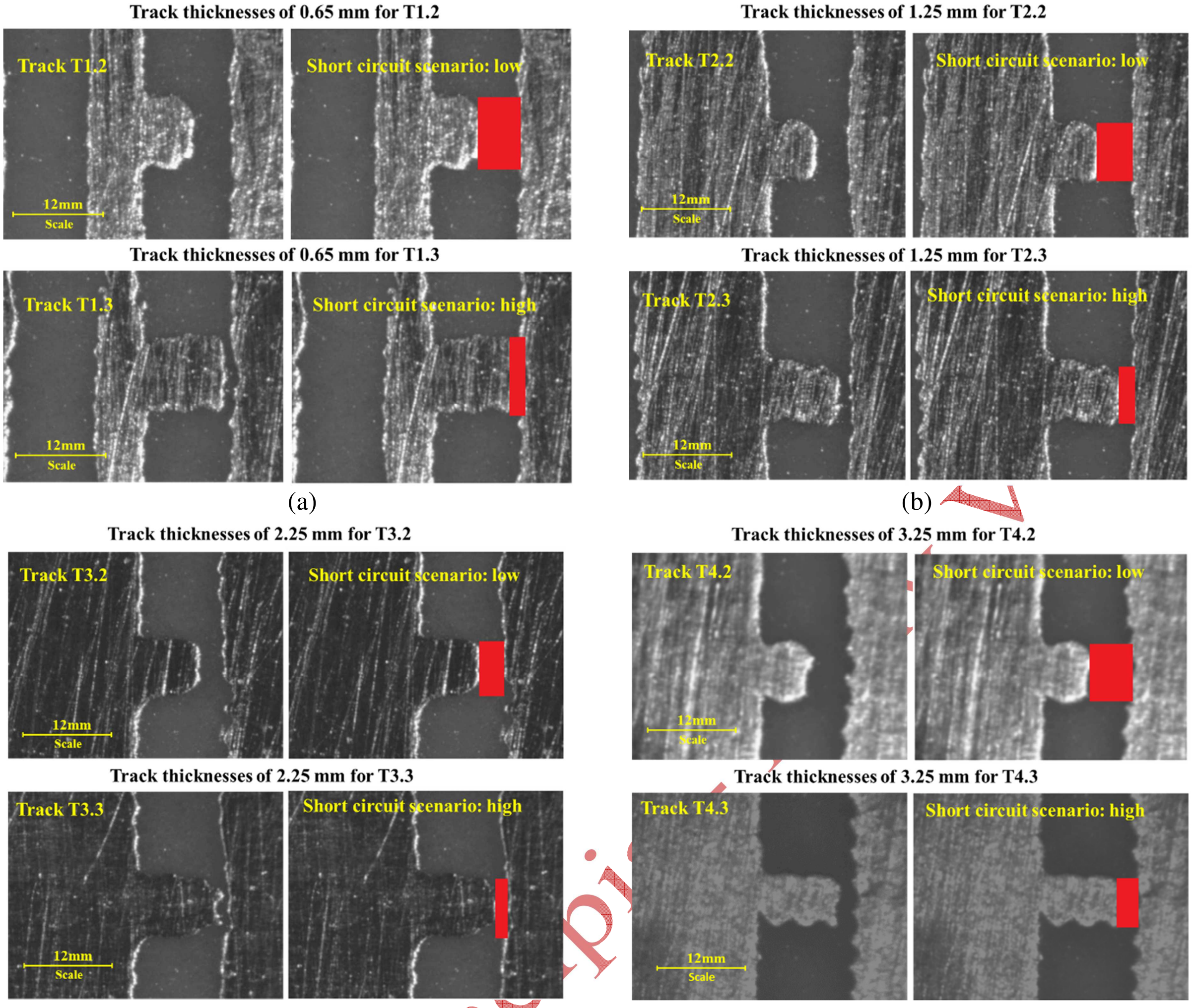
Impedance measurements for the EIS analysis were conducted using a high-frequency impedance spectrometer, specifically the HF2IS model from Zurich Instruments. The experimental setup employed a two-wire measurement configuration. One wire was systematically connected to various pins across the circuit tracks to assess their impedance properties, while the second wire was consistently attached to the ground pin to establish a reference point. A comprehensive dataset of 500 discrete measurements was collected, covering a frequency range from 1 kHz to 500 kHz. Five measurements were taken on each track, which were then filtered and averaged to produce the most accurate set of responses for the study.

4 Results

Analytical evaluations of the circuit tracks were conducted using both imaging techniques and EIS. High-resolution images were captured to closely examine the areas between the circuit tracks and the ground plane, focusing on regions simulating short-circuits. A Leica stereo binocular microscope, model MZ9.5, was utilized to ensure detailed visual inspection.

Figure 6 shows the images of the circuit tracks according to their respective thicknesses, organized into four distinct groups: (a) tracks with a thickness of 0.65 mm; (b) tracks with a thickness of 1.25 mm; (c) tracks with a thickness of 2.25 mm; and (d) tracks with a thickness of 3.25 mm. A set of four images represents each group. The images on the left side of each group depict the tracks in their unmodified state, while the pictures on the right highlight specific areas. These highlighted areas are marked in red to indicate regions that would be free of short-circuits if they were composed of conductive material.

Figure 6 – Microscopic images of the tracks, showing the insulation length, highlighted by red rectangles



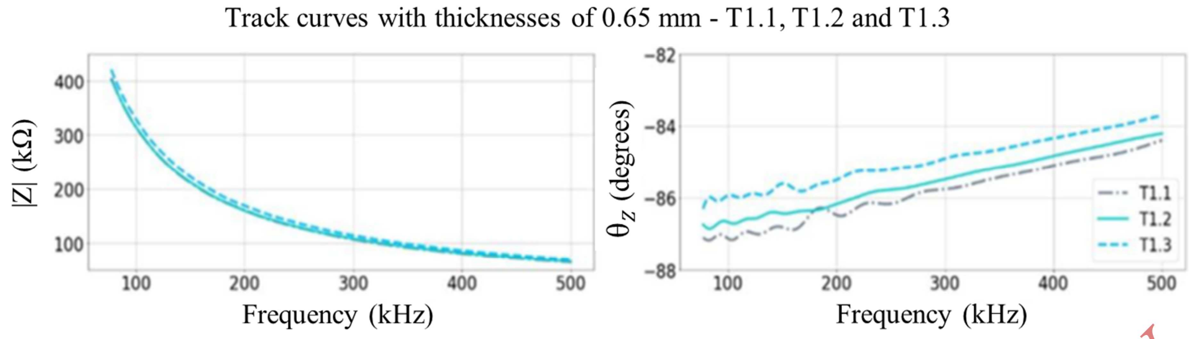
(a) (b)

(c) (d)

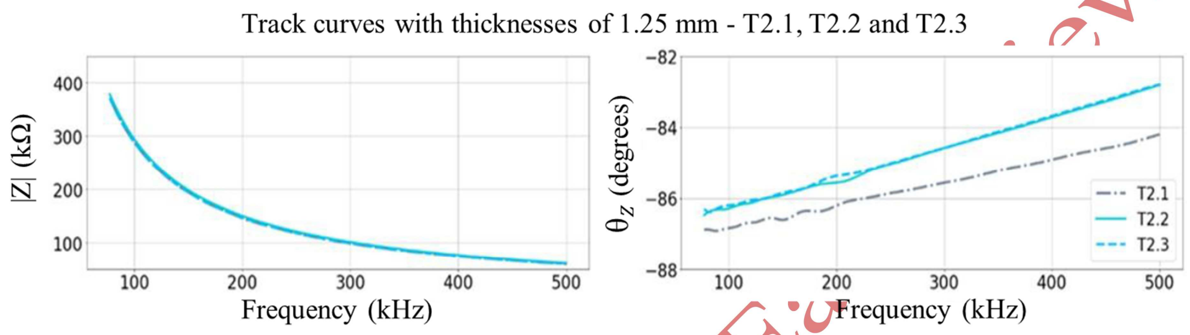
Source: research data

The analysis of EIS data, specifically between the pins and the ground point of the PCB, was conducted using graphs generated through Python programming. These analyses indicated that the impedance modulus between a track and the grounding zone is significantly high, generally exceeding 100 kΩ. This high impedance is primarily attributed to the spatial separation between the insulation of the tracks and the ground plane, which affects the measurement capabilities of the instrument. The instrument provided reliable readings predominantly at higher frequencies. Consequently, based on the graphical analysis, data collected below 50 kHz were found to exhibit considerable noise and were therefore excluded from further analysis to ensure the accuracy and reliability of the results. Figure 7 illustrates both phase and impedance modulus as a function of frequency.

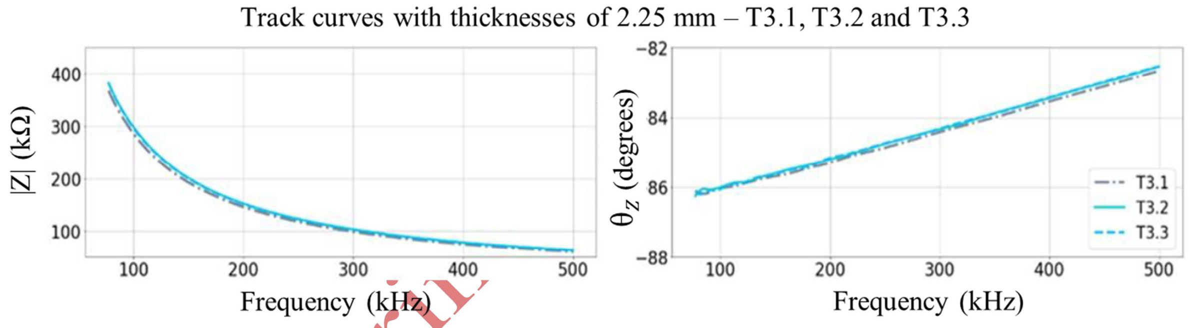
Figure 7 – Bode diagrams displaying the results of impedance measurements for tracks with identical thickness


Track curves with thicknesses of 0.65 mm - T1.1, T1.2 and T1.3

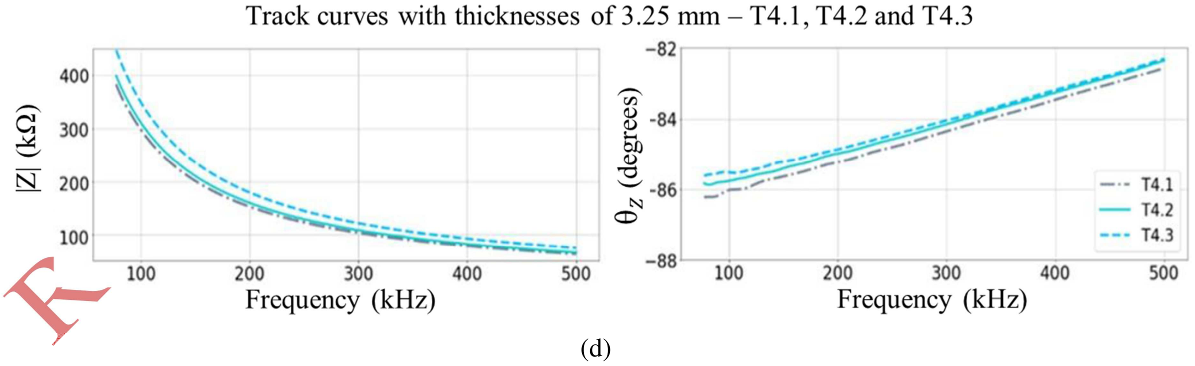
(a)


Track curves with thicknesses of 1.25 mm - T2.1, T2.2 and T2.3

(b)


Track curves with thicknesses of 2.25 mm – T3.1, T3.2 and T3.3

(c)


Track curves with thicknesses of 3.25 mm – T4.1, T4.2 and T4.3

(d)

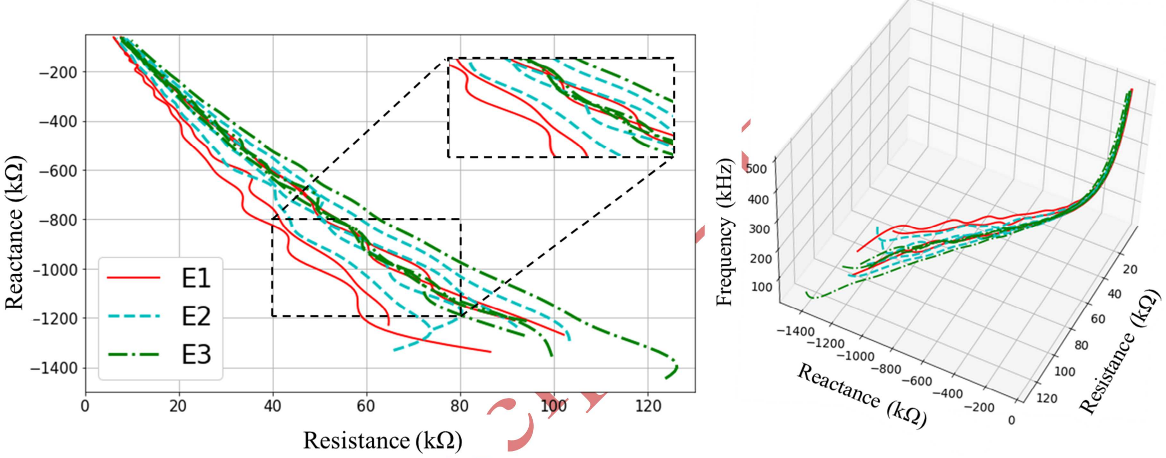
Source: research data

5 Discussions

The analysis of the impedance modulus as a function of frequency across various sets of curves reveals an exponential decay that is inversely correlated with frequency variations. Conversely, the impedance phase curves exhibit a linear relationship with frequency, indicating direct proportionality. A notable distinction between these types of curves is observed in their distribution; the phase curves demonstrate greater separation with minimal overlap compared to the modulus curves. This clear delineation in the phase curves particularly enhances the discernibility of potential short-circuits in tracks with smaller thicknesses due to their more dispersed distribution. Additionally, the phase curves show a tendency towards stabilization at higher frequencies, facilitating more reliable identification of underlying patterns and trends in the data.

To further explore the correlation between potential short-circuits and track thickness, an analytical examination was conducted using Figure 8. This analysis involved categorizing the impedance curves into three distinct groups based on their excitation states: (1) curves from tracks without short-circuit excitation, labeled as E1; (2) curves from tracks with partial short-circuit excitation, denoted as E2; and (3) curves from tracks under extreme short-circuit excitation, indicated as E3. These curves graphically represent the resistance and reactance components of impedance as functions of frequency variation. The analysis suggests no consistent correlation between the potential degree of short-circuit and track thickness across the tested frequency spectrum. No significant clustering of curves corresponding to similar short-circuit potentials was observed, indicating the absence of predictable patterns in impedance spectra under varying excitatory conditions.

Figure 8 – Curves illustrating the relationships between resistance and reactance values of impedance as a function of frequency variation. Tracks without short-circuit excitation are represented by E1, those with low short-circuits by E2, and those high short-circuits by E3, respectively



Source: research data.

While imaging techniques are critical for identifying surface-level defects, they often fail to detect subsurface issues such as corrosion and short-circuits. In this context, Electrical Impedance Spectroscopy (EIS) proves to be a superior technique, providing quantitative measurements of regions not accessible via surface imaging of printed circuit boards. EIS can be effectively integrated with other analytical or quantitative methods, enhancing its applicability in field operations and scenarios requiring low-complexity equipment. Additionally, EIS can be employed independently to identify and monitor defects like corrosion and short-circuits and to detect signs of material changes. This capability significantly improves the efficiency of quality inspection processes and predictive maintenance for PCBs. However, further research is needed to address the extensive variables associated with EIS, particularly those concerning electrode use, such as size, material, aqueous solution, and even the resistance characteristics of the cables connected to the probes. Patterns and differentiation were identified in tracks prone to short-circuits compared to healthy tracks within groups of tracks with the same thickness, especially in tracks of smaller thicknesses. However, it was not possible, using this method, to establish a correlation between tracks of different thicknesses grouped by potential short-circuit state. Moreover, differentiation of the short-circuit state is only observed in the analysis between tracks of the same thickness when considering the impedance phase value.

6 Conclusion

It can be concluded that Electrical Impedance Spectroscopy (EIS) is an effective technique for the early detection of PCB failures, providing a non-destructive and detailed approach to analyzing the electrical properties of materials. However, this study did not establish a viable mathematical correlation for measuring short-circuits in this particular type of printed circuit board (PCB). Further research is required to improve the characterization of potential short-circuits. The integration of new artificial intelligence (AI) methodologies could significantly enhance the characterization process, potentially advancing industrial quality systems based on PCB layouts.

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Conflict of interest
The authors declare that there are no conflicts of interest.

Ethical Committee Declaration
This manuscript does not involve human or animal subjects.

Contributions to the article
BORGES, Y. S.: conception or design of the study/research; data analysis and/or interpretation. **BERTEMES FILHO, P.:** data analysis and/or interpretation; final review with critical and intellectual contributions to the manuscript. All authors contributed to the writing, discussion, reading, and approval of the final version of the article.

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