

Electrical Safety in Academic Laboratories: A Risk Assessment of Ageing Portable Appliances

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ABSTRACT

Electrical safety risk assessment in academic laboratories is critical due to the high-frequency use of ageing equipment by students and staff. This paper presents a safety evaluation of 341 units using Portable Appliance Testing (PAT), specifically focusing on earth bond testing as the primary safety metric to detect protective conductor degradation. Appliances such as desktop computers, oscilloscopes, digital analogue training systems, and automatic voltage regulators (AVRs) were analyzed to determine the correlation between service years and earthing integrity. Statistical analysis via one-way ANOVA and the Chi-square test of independence revealed divergent safety trends across equipment categories. While IT equipment remained largely independent of age ($p = 0.483$, $X^2 = 3.942$), laboratory-specific instrumentation demonstrated significant safety risks over time. Notably, Digital Analogue Training Systems and AVRs showed a significant dependency on service years ($p < 0.001$), with Chi-square results of $X^2 = 26.742$ and $X^2 = 11.119$, respectively. Units in service for over 10 years frequently exceeded the 0.1Ω safety threshold defined by IEC 60335-1, indicating a deteriorated earthing path. These findings highlight a critical need for enhanced laboratory safety management and the implementation of a mandatory annual PAT schedule for equipment older than 10 years. Such proactive maintenance is essential to mitigate electric shock hazards and ensure a secure, compliant learning environment in higher education institutions.

Keywords: Portable Appliance Testing (PAT); Electrical Safety Academic Laboratories; Appliance Ageing Risk Assessment; Earth Bond Resistance Testing; Laboratory Equipment Maintenance Malaysia

INTRODUCTION

Safety risk assessment of electrical equipment is crucial because electricity can be hazardous to people and ultimately result in death (Doan 2015, 2017, 2025). The most common hazards of electricity are electrical shocks that occur when the user comes into contact with live conductors, damage caused by arcing of electrical appliances, burns from faulty electrical appliances, and explosions that occur when static electricity from the electrical equipment burst in a flammable or dusty environment (Esch & Joggerst 2023; Gordon, Cartelli & Graham 2018a; Gordon et al. 2022). The human body can

only resist 50 or 230 V of touch voltage for no more than 5 and 0.4 s, respectively. The human body can tolerate 100 and 30 mA of alternating current for less than 0.5 and 5 s, respectively (Esch & Joggerst 2023; Teo 2012). This indicates that the human body can only resist very low limits of voltage and current over a certain time period. Any sources or loads supplied from electrical equipment can simply surpass the limit of the human body. Thus, if the electrical equipment is not maintained regularly, this can cause serious electrical accidents to people and damage to the electrical equipment itself (Gordon, Cartelli & Graham 2018b). According to the Energy Commission of Malaysia (Suruhanjaya Tenaga 2024a), there are 69 and

58 cases of fatal and non-fatal accidents in 2021 and 2022, respectively. Electrical accidents constitute one out of 69 cases in 2021 and two out of 58 cases in 2022. Proper safety evaluation of protective conductors in academic institutions is necessary to maintain operational safety standards and effectively safeguard students against latent electrical hazards. The total number of electrical accidents caused by defective electrical equipment is shown in Figure 1. Based on Figure 1, the number of electrical accidents has increased over the years, which is indeed expected since there is an increase in the use of electrical equipment. Although portable appliances do not provide significant amounts of power compared with the supply power from the distribution system, if the portable appliance is faulty, then there is a high likelihood that the fault can be hazardous to the user (Gordon, Cartelli & Graham 2018b).

Defective electrical equipment contributes to the increase in the number of electrical accidents over the years, which is attributed to the lack of periodic maintenance (Araneo, Dehghanian & Mitolo 2019a, 2019b; Ayi & Hon 2018; Bai et al. 2022). Based on the authors' observations, most higher institutions of learning in Malaysia do not have standard guidelines on the periodic inspection and testing of portable appliances. In contrast, several international universities and safety organizations implement structured Portable Appliance Testing (PAT) schedules tailored to the environment and appliance risk level. For instance, in high-risk laboratory and workshop environments, both the (University of Essex 2013) and the (University of Nottingham 2015) mandate simple visual checks before use alongside compulsory annual combined inspection and testing for Class I and Class II equipment. The (Health and Safety Executive 2013) prescribes a risk-based matrix where earthed Class I equipment undergoes formal visual checks every 6 to 12 months and testing every 1 to 2 years, while information technology (IT) equipment can extend testing up to 5 years. Furthermore, the Institution of Engineering and Technology (IET 2020) outlines stringent school environment protocols, requiring weekly visual checks, formal inspections every 4 months, and complete testing every 12 months for Class I appliances, extending to 48 months for Class II appliances.

In Malaysia, portable appliances approved by the Energy Commission are classified into three distinct categories determining their electrical testing frameworks (Suruhanjaya Tenaga 2024b). Class I appliances rely on both basic insulation and protective earth grounding paths via a three-pin plug; hence, they strictly require a comprehensive testing suite comprising earth bond, insulation resistance, substitute leakage, and load tests (IEC 60335-1 2021). Class II appliances utilize double or reinforced insulation barriers with no ground conductor path, omitting the earth bond test but requiring insulation resistance, substitute leakage, and load validation (IEC 60335-1 2021). Class III appliances operate via separated extra-low voltage (SELV) sources below 24 V or 12 V and do not require PAT safety tests (IEC 60335-1 2021).

Among these procedures, the earth bond test serves as the primary evaluation for Class I equipment, measuring the resistance between the ground pin and exposed metalwork using injected currents - over 10 A according to (IEC 60335-1 2021), or a reduced 100–200 mA for IT equipment under (AS/NZS 3760 2022; BS 7671 2022). To satisfy safety thresholds, the maximum resistance reading must not exceed 0.1Ω for standard equipment, or $(0.1 + R) \Omega$ for appliances with an attached mains supply cord, where R represents the cord's protective conductor resistance (IEC 60335-1 2021; IET 2020). Complementing this, the insulation resistance test applies a high DC voltage (typically 500 VDC, scaled down to 250 VDC for sensitive IT equipment) to check insulation effectiveness, necessitating minimum boundaries ranging from $0.25 \text{ M}\Omega$ for Class III up to $2.0 \text{ M}\Omega$ for Class II appliances (IEC 60335-1 2021; IET 2020). To circumvent potential high-voltage testing damage, the substitute leakage test applies a low voltage ($\sim 35 \text{ VAC}$) to verify that leakage current limits remain safe, capping touch currents at 0.25 mA for Class II, 0.5 mA for Class III, and 0.75 mA to 3.5 mA for Class I configurations (IEC 60335-1 2021; IET 2020). Lastly, while not mandatory for regulatory safety compliance, a load test can be performed to document operational power consumption (kVA) and current metrics (A) for long-term equipment maintenance profiling (Fluke 2013).

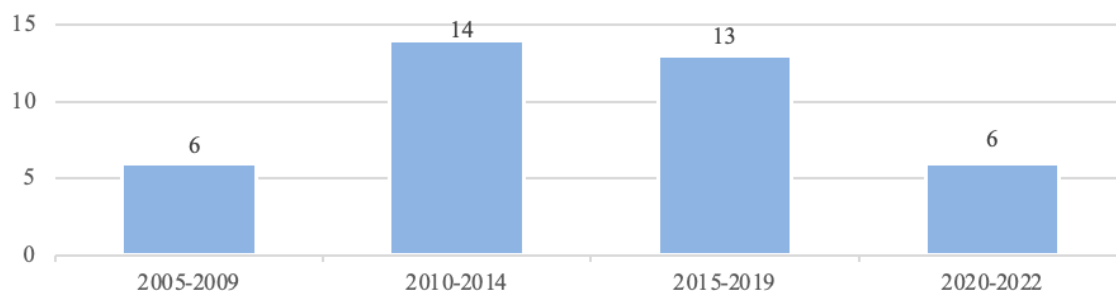


FIGURE 1. Number of electrical accidents caused by defective electrical equipment

METHODOLOGY

EXPERIMENT DESIGN & PROCEDURE

The research method consisted of two phases. In the first phase, earth bond tests were conducted using the Fluke 6200 portable appliance tester (Figure 2). The earth bond tests measure and check the resistance value between the earth pin of the mains supply plug of the tested appliance and the earthed body of the tested appliance. This test determines the resistance to ensure the suitability of the earth point for electrical appliances. Thus, this test is only applicable for Class I appliances, which have an earth pin in their plugs. There are two types of earth bond tests: (1) high current test (25 A) and (2) low current test (200 mA). The low current test is used for Class I information technology equipment whereas the high current test is used for other Class I appliances. The same connections are used for both tests, which involve attaching the clip to any exposed metal part of the tested appliance and plugging the test lead into the BOND 25 A/200 mA socket of the portable appliance tester. According to the (IEC 60335-1 2021), the maximum resistance should be 0.1Ω ('pass'), indicating that there is a good earth connection and the appliance is considered to be safe. If the resistance exceeds 0.1Ω , the appliance is rated as 'fail'.

A total of 341 portable appliances at selected teaching and learning laboratories in Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, were tested using the portable appliance tester. Four types of appliances were tested in this study: (1) desktop computers (138 units), (2) oscilloscopes (46 units), (3) digital analogue training systems (36 units), and (4) automatic voltage regulators (121 units). In the second phase, the results were analysed using one-way ANOVA and Chi-square test of independence. Prior to performing the one-way ANOVA, the fundamental statistical assumptions, specifically the normality of data distribution and homogeneity of variance, were verified using Shapiro-Wilk and Levene's tests, respectively. This ensures that the F-distribution results are valid and that the comparisons between appliance age groups are statistically robust (Ahmad et al. 2015; Nur Aiman Hanis Hasim et al. 2022).

The one-way ANOVA was used to determine whether the null hypothesis should be rejected based on the critical value of the F-distribution at a significance level α of 0.05. The null hypothesis H_o states that there are no significant differences between the means of the sample groups. In other words, the means of the sample groups are equal. The alternative hypothesis H_a states that there is a significant difference between the means of at least two sample groups. The null hypothesis is rejected in favour

of the alternative hypothesis if the F -value is higher than the critical F -value and the p -value is less than 0.05.

The Chi-square test of independence was used to determine whether the null hypothesis should be rejected based on the critical χ^2 test statistic at a significance level α of 0.05. The Chi-square test of independence is used to determine if there is a significant association between two categorical variables. The null hypothesis H_o states that there is no significant association between the resistance values obtained from the earth bond tests and the number of years the portable appliances are in service. In other words, these two categorical variables are independent of each other. The alternative hypothesis H_a states that there is a significant association between the resistance values obtained from the earth bond tests and the number of years the portable appliances are in service. Stated differently, the probability of the resistance having a certain value is dependent on the number of years the portable appliances are in service. The null hypothesis is rejected in favour of the alternative hypothesis if χ^2 exceeds the critical χ^2 and the p -value is less than 0.05.

STATISTICAL ANALYSIS FRAMEWORK

The mathematical framework governing the One-Way ANOVA and Chi-Square tests of independence was strictly adhered to for parametric and non-parametric evaluations, respectively. The One-Way ANOVA test statistic, F defined in Equation 1, is calculated as the ratio of mean square between groups (MS_B) to mean square within groups (MS_w):

$$F = \frac{MS_B}{MS_w} = \frac{\frac{SS_B}{k-1}}{\frac{SS_w}{N-k}} \quad (1)$$

where SS_B represents the sum of squares between groups, SS_w is the sum of squares within groups, k denotes the total number of sample age categories, and N represents the overall sample size ($N = 341$). Concurrently, the Chi-Square test statistic (χ^2) defined in Equation 2 evaluates the association between categorical variables:

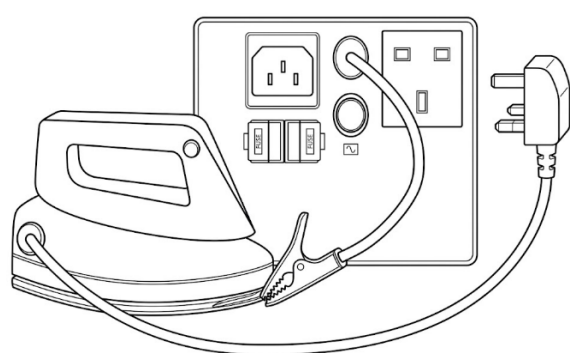
$$\chi^2 = \sum \frac{(f_o - f_e)^2}{f_e} \quad (2)$$

where f_o is the observed frequency of pass/fail status and f_e is the expected frequency under the null hypothesis of independence.

STUDY DESIGN & JUSTIFICATION

The laboratories in this study were selected using purposive sampling, focusing on educational environments with the highest student traffic volume to capture ‘worst-case’ operational safety scenarios. Appliance age categories (e.g., 2–5, 6–10, and 11–18 years) were defined based on typical equipment maintenance cycles and institutional lifecycle stages to enable meaningful parametric and non-parametric statistical comparisons. Earth bond testing was specifically prioritized over other testing parameters because protective conductor integrity serves as the mandatory primary defense against indirect contact shock in Class I appliances.

It is particularly effective at detecting mechanical wear, screw loosening, and conductor degradation in ageing protective earth (PE) pathways. Prior to running the One-Way ANOVA, all underlying statistical assumptions—specifically normality of data distribution and homogeneity of variance—were verified using Shapiro-Wilk and Levene’s tests, respectively, ensuring the mathematical validity of the resulting F-distribution calculations. In addition, the experimental setup ensured consistent ambient conditions during testing to prevent environmental humidity and temperature fluctuations from affecting the earth bond resistance measurements.



(a)



(b)

FIGURE 2. Connections for the PAT (Fluke 2013): (a) schematic illustration of the connections for the earth bond test and (b) photograph of the connections for the earth bond test of an oscilloscope

RESULTS AND DISCUSSION

OVERVIEW OF EARTH BOND TEST RESULTS

The safety status of 341 portable appliances was evaluated through earth bond testing to determine the integrity of the protective earthing path. As summarized in Table 1, the failure rates vary significantly across different equipment categories, with older instrumentation showing a marked increase in resistance values beyond the $0.1\ \Omega$ safety threshold.

STATISTICAL CORRELATION OF EQUIPMENT AGEING

To further understand the mathematical relationship between equipment age and electrical safety, One-Way ANOVA and Chi-square tests were conducted. The synthesized statistical results - including F-values, p-values, Chi-square statistics, and final dependency

conclusions—are consolidated in Table 2. The statistical outcomes in Table 2 indicate that while some equipment categories remain stable over time, others exhibit a statistically significant decline in safety compliance as service years accumulate.

DETAILED EVALUATION BY APPLIANCE TYPE

EARTH BOND TESTS FOR DESKTOP COMPUTERS

A sample of 138 desktop computers was tested using the low-current (200 mA) earth bond test and classified into four distinct service age groups: 2–5 years (41 units), 6–9 years (70 units), 10 years (18 units), and more than 10 years (9 units). As logged in Table 1, 106 units passed the earth bond test, while 32 units failed by exceeding the $0.1\ \Omega$ limit. The observed mean resistance values were $0.1108\ \Omega$ (2–5 years), $0.1426\ \Omega$ (6–9 years), $0.0883\ \Omega$ (10 years), and $0.0770\ \Omega$ (>10 years). As shown in Table 2, the One-

Way ANOVA yielded an F-value of 0.822, which was lower than the critical F-value of 2.672 ($p = 0.484$). Hence, the null hypothesis failed to be rejected. Furthermore, the Chi-square test of independence yielded a test statistic of $\chi^2 = 3.942$, which was below the critical value of 7.815 ($p > 0.05$). This confirms that the earth bond resistance values and pass/fail rates in desktop computers remain statistically independent of equipment service age.

EARTH BOND TESTS FOR OSCILLOSCOPES

A total of 46 oscilloscopes were evaluated across three age categories: 2–4 years (8 units), 5–7 years (14 units), and more than 7 years (24 units). Oscilloscopes demonstrated an exceptionally high safety compliance rate, with 45 units passing and only 1 unit failing (Table 1). The recorded mean resistance values were 0.0563Ω (2–4 years), 0.0614Ω (5–7 years), and 0.0761Ω (>7 years). As reported in Table 2 the One-Way ANOVA produced an F-value of 7.053, exceeding the critical F-value of 3.214 ($p = 0.0022$), indicating a statistically significant difference in mean resistance across age groups. However, the Chi-square test of independence yielded $\chi^2 = 0.937$, well below the critical threshold of 5.991 ($p > 0.05$). Thus, the overall safety pass/fail status of oscilloscopes remains independent of service age, benefiting from robust internal earthing connections and high manufacturing quality.

EARTH BOND TESTS FOR DIGITAL ANALOGUE TRAINING SYSTEMS

Testing conducted on 36 Digital Analogue Training Systems revealed severe protective earthing degradation over time. The equipment was categorized into three service groups: 2–4 years (10 units), 5–17 years (12 units), and more than 17 years (14 units). Across the sample, only 8 units passed while 28 units failed (Table 1). Mean resistance increased significantly from 0.1100Ω in 2–4 year units to 0.2378Ω (5–17 years) and 0.2393Ω (>17 years). As summarized in Table 2. One-Way ANOVA returned an F-value of 27.735, vastly exceeding the critical F-value of 3.285 ($p < 0.001$). The Chi-square test produced $\chi^2 = 26.742$, exceeding the critical threshold of 5.991 ($p < 0.001$). Both statistical tests strongly rejected the null hypothesis, establishing a significant dependency between service age and earth bond resistance failure.

EARTH BOND TESTS FOR AUTOMATIC VOLTAGE REGULATORS (AVRS)

A sample of 121 AVRs was assessed across four age brackets: 2–5 years (31 units), 6–10 years (72 units), 11–18

years (9 units), and more than 19 years (9 units). Overall, 80 units passed and 41 units failed (Table 1), representing a high overall failure rate of 33.9%. Mean resistance rose from 0.0730Ω in younger units to 0.2167Ω in the 11–18 year bracket. As presented in Table 2, ANOVA yielded an F-value of 15.545 ($p < 0.001$), while the Chi-square test yielded $\chi^2 = 11.118$ ($p < 0.05$). These results confirm a statistically significant dependency between service age and earthing path degradation in AVRs.

COMPARATIVE INTERPRETATION OF FINDINGS

Synthesizing the empirical data from Table 1 and Table 2 reveals a clear divergent trend between IT equipment and laboratory-specific training systems. While desktop computers and oscilloscopes maintain reliable earthing integrity regardless of age, training systems and AVRs suffer drastic safety compliance drop-offs after 10 years in service.

EQUIPMENT TYPE AND SAFETY STABILITY

The analysis reveals a divergent trend between IT equipment and laboratory-specific training systems. Desktop computers showed an independent relationship between age and safety ($p = 0.483$), likely due to their static placement and consistent indoor environment. Oscilloscopes, while showing a significant ANOVA result, maintained high pass rates, suggesting superior build quality and robust internal earthing connections compared to another lab equipment.

IMPACT OF AGEING ON LABORATORY TRAINING SYSTEMS AND AVRS

A significant dependency on service years was identified for Digital Analogue Training Systems and AVRs ($p < 0.001$). For the training systems, the failure rate increased drastically for units in service for more than 10 years, with the majority of failures occurring in units exceeding 17 years. The technical justification for this degradation involves several factors:

1. **Oxidation and Corrosion:** Over decades, the metal contact points at the earth pin and internal chassis connections undergo oxidation, which naturally increases contact resistance.
2. **Mechanical Wear:** These appliances are subject to frequent handling and terminal connections by students. Such mechanical stress can loosen internal earthing screws and strain the protective earth conductor.

3. Thermal Cycling: Repeated power cycles lead to internal heating and cooling, which can cause expansion and contraction of earthing terminals, eventually compromising the low-resistance path required for safety.

PRACTICAL IMPLICATIONS FOR LABORATORY MANAGEMENT

The findings highlight that relying on visual inspections is insufficient for older laboratory equipment. The high failure rate of AVRs (33.9%) and Training Systems (77.8%) suggests that current maintenance protocols are inadequate. Based on the statistical dependency observed, it is recommended that a mandatory annual earth bond testing schedule be implemented for any appliance exceeding 10 years of service to mitigate the risk of electric shock in the teaching environment.

TABLE 1. Consolidated Summary of Appliance Safety Status and Resistance Trends

Appliance type	Service Age (Years)	Sample Size (n)	Mean Resistance (Ω)	Pass Count	Fail Count
Desktop Computers	2 to 10+	138	0.111	106	32
Oscilloscopes	2 to >7	46	0.064	45	1
Digital Analogue Training Systems	2 to >17	36	0.195	8	28
AVRs	2 to 11+	121	0.11	80	41

TABLE 2. Consolidated Summary of Statistical Analysis

Appliance type	ANOVA (F-value)	p-value	Chi-square (χ^2)	Dependency result
Desktop Computers	0.822	0.483	3.942	Independent
Oscilloscopes	7.052	0.002	0.937	Independent
Digital Analogue Training Systems	27.734	< 0.001	26.742	Significant Dependency
AVRs	15.545	< 0.001	11.118	Significant Dependency

CONCLUSION

This study successfully assessed the electrical safety of 341 portable appliances across laboratory environments. The findings indicate that while modern IT equipment remains largely compliant, specialized laboratory instrumentation such as Digital Analogue Training Systems and Automatic Voltage Regulators (AVRs) exhibit a critical dependency between service age and earth bond resistance failure. Statistical analysis confirmed that appliances in service for over 10 to 17 years are significantly more likely to exceed the 0.1 Ω safety threshold, primarily due to internal oxidation, mechanical wear from student handling, and thermal cycling over extended lifecycles. This study was primarily limited to earth bond testing of Class I appliances within a specific faculty. To establish a comprehensive safety profile for higher learning institutions in Malaysia, future research should expand to include Class II appliances and incorporate insulation resistance and leakage current testing. Such data will be vital in developing a national standardized guideline for periodic portable appliance testing (PAT) in academic laboratories. To

enhance overall laboratory safety management, university administrators and safety officers are strongly advised to adopt a proactive, risk-based inspection framework. First, mandatory annual earth bond testing must be enforced for all Class I appliances operating beyond 10 years of service to detect protective conductor degradation before critical failures occur. Second, a biennial PAT inspection schedule is recommended for medium-risk equipment aged between 5 to 10 years. Third, structured laboratory orientation modules should be incorporated at the beginning of academic semesters to train undergraduate students on proper plug handling and cable strain relief, directly minimizing mechanical stress on internal earthing terminals. Furthermore, routinely monitoring protective earthing paths helps extend the operational longevity of critical laboratory assets while maintaining strict institutional regulatory compliance. Implementing these institutional policy changes will significantly reduce indirect contact electric shock hazards, prolong equipment operational lifespans, and ensure strict compliance with national safety guidelines within Malaysian higher learning institutions.

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DECLARATION OF COMPETING INTEREST

None.

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