University of Southern Queensland

Faculty of Health, Engineering and Sciences

Safety of electrical equipment in water-based amusement rides from an engineering perspective

A dissertation submitted by

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Abstract

This thesis will research the risks of electrical equipment with water-based amusement rides from an engineering perspective. The project aims to provide recommendations and facilitate discussion around the application of electrical safety for water-based amusement rides. In October 2016, the amusement industry was changed forever by the deaths of four patrons on the Thunder River Rapids Ride circuit (Queensland Courts 2020b). The primary cause was the failure of the south pump due to an electrical fault in the circuit (Queensland Courts 2020b). Queensland Courts (2020b) state that, ultimately, the lack of an adequate safety system led to the deaths of four patrons. The findings highlight the importance of amusement ride research, particularly water-based research, as it is lacking in the industry. Research can identify risks associated with water-based amusement rides and identify areas to improve.

Firstly, the thesis included conducting background research on amusement ride incidents and accidents. The results indicate recurring areas that require improvement. Additionally, the thesis includes a review of the relevant legislative requirements, standards and codes of practice relating to amusement rides. The research into the amusement ride risks includes vibration, corrosion, power quality, insulation failure, maintenance (including records), inspection, identifying trends and an emergency shutdown system.

Next, the thesis includes developing a preventative maintenance program that extends water-based amusement ride research into power quality, partial discharge and thermal imaging. Testing information was collected and analysed. The thesis includes mitigation techniques and engineering recommendations to improve the safety of water-based amusement rides. The analysis discusses risks with water-based amusement rides to facilitate discussion. In addition, the thesis studies the application of electrical safety to water-based amusement rides. The thesis met the objectives; however, additional time would have permitted an investigation into a system to monitor and predict equipment failure. The initial testing results provide a benchmark of the expected values to compare to future test results.

The thesis is the first known research into water-based amusement rides. As such, there are areas of further work to develop. Further work includes investigating VSDs and downstream and upstream monitoring of VSDs to determine the possible harmonics generated and the safety implications. Similarly, further investigations could include the cathodic protection of amusement rides to determine if the theory could apply to amusement ride installations. The water-based amusement rides have large volumes of water that could benefit from preventative methods for corrosion. Likewise, future research into the integration of VLSI could lead to increased reliability and testability for safety shutdown systems.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Kendra Gurrin

Student Number: [redacted]

Signature

Date

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Abbreviations

AALARA	Australian amusement leisure and recreation association
AC	Alternating current
ASTM	American society of testing and materials
CEN	European Committee for Standardisation
CT	Current transformer
DC	Direct current
DRN	Design registration number
HV	High voltage
IEC	International Electrotechnical Commission
IGBT	Insulated gate bipolar transistors
ISO	International organisation for standardisation
LV	Low voltage
MV	Medium voltage
OEM	Original Equipment Manufacturer
OIR	Office of Industrial Relations
PD	Partial discharge
PDEV	Partial discharge extinction voltage
PDIV	Partial discharge inception voltage
PLC	Programmable logic controller
PRN	Plant registration number
PWM	Pulse width modulation
RMS	Root mean square
SAPOL	South Australia Police
SMS	Safety management system
THD	Total harmonic distortion
TRRR	Thunder river rapids ride
VRTP	Village Roadshow Theme Parks
VSD	Variable speed drive

Chapter 1. Introduction

Amusement rides in Australia are a popular tourist destination, with the Gold Coast featuring the largest theme park in Australia. The six largest theme parks had an average of 891,000 visits between 2000 and 2001 (Australian Bureau of Statistics 2002). Since 2001, visitor numbers to theme parks have been steadily increasing. Village Roadshow Theme Parks (VRTP) had 3.5 million visitors to Movie World, Sea World and Wet and Wild from 2022 to 2023 (Morris 2023). The increasing pressure to remain operational reached a critical point in 2016.

The amusement ride industry was changed forever by the deaths of four patrons on the Thunder River Rapids ride at Dreamworld (Queensland Courts 2020b). The incident resulted in legislation updates to improve amusement ride safety for patrons (Queensland Government 2022). Amusement ride safety relies heavily on understanding the associated hazards to reduce the risks. The thesis will research the risks of electrical equipment with water-based amusement rides. It will examine the ride requirements, the influence of industry organisations, and the knowledge gained from previous incidents. The thesis aims to facilitate discussion around the application of electrical safety for water-based amusement rides.

1.1 Justification for project

Theme parks contribute positively to the economy through employment, tourism, and commercial property developments. The Australian Small Business and Family Enterprise Ombudsman (2021) reported that Australia’s amusement, leisure, and recreation sector contributes $1.84 billion to the economy. The economic impact often expands beyond the theme park to local businesses and the development of the local area. Theme parks have been developing on the Gold Coast since the 1980s, with Dreamworld being Australia’s largest theme park.

Operation of Thunder River Rapids started in December 1986. Thunder River Rapids was a water-based ride designed to simulate white water rafting. The design included a raft that travelled through a water course. The ride design was approved in August 1987 and certified to Australian standards. In October 2016, the amusement industry was changed forever by the deaths of four patrons on the Thunder River Rapids ride. The primary cause was the failure of the south pump due to an electrical fault in the circuit (Queensland Courts 2020b). Queensland Courts (2020b) state that the fault could have been due to an Earth fault. Ultimately, the lack of an adequate safety system led to the deaths of four patrons.

The country was outraged at the utterly avoidable tragedy. The incident raised major safety concerns for amusement rides in Australia. The incidents at Dreamworld and an Eagle Farm construction site resulted in the review of the legislation by governments across Australia. The calamity was the catalyst for introducing industrial manslaughter charges in every Australian state and territory except Tasmania.

Following the incident, an investigation occurred to determine what happened. The Dreamworld inquest findings stated that ‘it was recognised that the level of risk to the public from amusement rides is comparable to that of facilities, which use, generate, handle or store hazardous materials (Queensland Courts 2020b, p. 201). This statement highlights the importance of understanding the risks involved. The legislative requirements include improvements to prevent similar incidents from occurring. Following the Dreamworld incident, the Queensland Government (2022) best practice review implements a risk-based approach to safety for theme parks. Implementing a risk-based approach highlights the importance of understanding amusement ride risks.

Moreover, amusement ride research is lacking in the industry, with water-based amusement ride research particularly scarce. Publishing data about the risks associated with water-based amusement rides, electrical equipment, and the compliance standards will benefit the industry. The thesis will examine the limitations and challenges of the Australian amusement ride standards for amusement rides built to international amusement ride standards.

1.2 Project aim

This thesis will research the risks of electrical equipment with water-based amusement rides from an engineering perspective. The project aims to provide recommendations and facilitate discussion around the application of electrical safety for water-based amusement rides.

1.3 Project objectives

The thesis objectives are achieved by performing the following:

1. Conduct background research on amusement ride incidents and accidents.
2. Research relevant legislation, standards and codes of practice relating to amusement rides in Australia.
3. Conduct a literature review of electrical safety of amusement rides, including vibration, corrosion, power quality, insulation failure, maintenance (including records) and inspection of amusement rides.
4. Design a field measurement program and collect relevant data for water-based amusement rides.
5. Process and evaluate the field data of the water-based amusement rides.
6. Investigate mitigation measures and techniques for the electrical safety of water-based amusement

rides.

7. Provide engineering recommendations.

If time and resources permit:

8. Investigate a system to monitor and predict equipment failure.
9. Provide recommendations for ongoing research.

1.4 Limitations

This thesis will discuss electrical equipment in fixed water-based amusement rides. The industry refers to amusement rides as amusement devices; the thesis will refer to them as amusement rides. The thesis considers fixed amusement rides, which are stationary. Therefore, the thesis does not consider the storage of amusement rides.

The thesis will not incorporate the specific requirements for different states and territories in Australia. Queensland has the largest number of theme parks with fixed rides, with Gold Coast known as the theme park capital of Australia. Thus, the legislation in this thesis will focus on the requirements in Queensland, Australia. Likewise, the thesis will only consider the Queensland codes of practice. The standards will focus on the Australian standards and requirements for amusement rides and compare the local standards to the international standards where relevant.

1.5 Ethical considerations

Ethical considerations are important when researching and completing field testing on water-based amusement rides. When applying their judgement, engineers make decisions based on a code of ethics. Those values and principles shape the decisions in engineering practice to ensure ethical engineering practice. The field measurement program needs to consider the methodology to uphold acceptable standards of conduct. Professional engineers strive to serve the community ahead of personal interests. The field measurement program considers the methodology to ensure the engineering practice's integrity, reputation and trustworthiness.

Furthermore, another ethical consideration in producing this thesis is the unintended consequences. The amusement ride industry has been under additional scrutiny since the Dreamworld incident; the sensitive nature of the subject matter could have unintended consequences. The parties involved will review the thesis to ensure responsible engagement with the community and stakeholders. The needs of the present will balance with the needs of future generations by considering the engineering task's economic, environmental, and social consequences.

The thesis considers the current use of the demonstrated technology outside the best practice applications. The thesis will review the research and discuss the existing technology's capabilities, limitations, and application. There is an ethical duty to understand and consider the implementation in alternative situations.

1.6 Thesis Outline

The introduction chapter examines the background information, project aim, objectives, limitations and considerations. Chapter 2 summarises the research into the requirements for amusement rides, the industry organisations, the coroner’s findings, the associated risks and review techniques to identify potential problems. Chapter 3 investigates preventative maintenance techniques to inform the field measurement program. Chapter 4 examines the research and justifies the methodology used. Chapter 5 presents the field testing results, followed by the conclusion and opportunities for further work in Chapter 6.

Chapter 2. Literature review

The literature review explores the safety of electrical equipment in amusement rides. The literature review consists of four sections. Section 2.1 assesses the relevant legislation, codes of practices, and standards. Section 2.2 discusses the amusement industry organisations. Section 2.3 summarises the coroner's findings, which provide recommendations for improvement. Section 2.4 examines the conditions amusement rides and equipment encounter. To contribute to the understanding of the risks for water-based amusement rides, section 2.5 summaries the research findings.

2.1 Legislation, codes of practice and standards

The legislation specifies the amusement ride requirements and codes of practice, while standards are best practice guidelines determined by experts. Research into the current legislation, codes of practice and standards will be conducted to understand the safety of amusement rides in Australia.

2.1.1 Legislation

The legislation is important in discussing theme park safety to understand theme park operators' obligations, requirements and duties for effective and safe amusement rides. Parliament makes and changes the laws, while the Government makes the rules to regulate those laws (Queensland Government 2021b). In Queensland, the Act and Work Health and Safety Regulation (2011) detail the legislative requirements for amusement rides (*Work Health and Safety Act* 2011). The Queensland Government (2022) publicised the best practice review of work health and safety following the Dreamworld incident. The updates include requirements for theme parks to prepare a safety case and the introduction of a licensing regime (Queensland Government 2022). The introduction of the legislation will benefit amusement ride safety.

Amusement rides are subject to a design registration process before operating in Australia to ensure the highest safety levels. Amusement rides are designed overseas and imported into Australia. The ride design must be registered in Australia to operate (Queensland Government 2021a). This process involves getting the ride design verified by a design verifier. The verifier must not be involved in the production of the design or engaged by the design company unless they use a quality system to undertake the design of the plant (Work Health and Safety Regulation 2011). The verification of the design ensures that the ride complies with Australian standards. The design verification is a valuable stage in ensuring publics safety.

Upon completion of the ride design registration, the Work Health and Safety Regulation (2011) states that the person with management or control has a duty of care regarding the operation, maintenance, inspection, and testing of amusement rides. The amusement ride maintenance, inspection and testing must follow the ride designer and manufacturer's recommendations. The thesis will consider the designer and manufacturer recommendations in the field measurement program.

In addition to design registration, the operator registers the plant item. To obtain registration, a competent person inspects the ride and deems the ride safe to operate. The Queensland Government (2022) best practice review includes the provision that once the ride is part of a major amusement park, it no longer requires plant registration (Work Health and Safety Regulation 2011). This is due to the duplication of requirements, as a major amusement park has specific requirements for ride inspection, testing and maintenance.

Furthermore, the legislative requirements include annual and major inspections by a competent person. The requirement for a major inspection by a competent person was added following the best practice review. The Work Health and Safety Regulation (2011) defines a competent person as a person determined by a regulator or a registered professional engineer. The Board of Professional Engineers of Queensland (2022) governs the *Professional Engineers Act* (2002). In Queensland, a registered professional engineer is referred to as a registered professional engineer of Queensland (RPEQ).

Ten years after commissioning or registering the amusement ride (whichever is earlier), there must be a major inspection. It must include examining critical components, including stripping down and removing paint, grease and corrosion, and checking the safe operation (Work Health and Safety Regulation 2011). The inspection responsibilities are important when reviewing the coroner’s findings in section 2.3.

Another addition is the licensing requirement for a major amusement park. A major amusement park incorporates at least four amusement rides in a workplace; this is in sections 608A to 608E of the Work Health and Safety Regulation (2011). The amusement rides must be stationary and used to conduct business. The operator (the person who manages the park and has the power to shut the entire park down) must apply for a major amusement park licence within two years of becoming a major amusement park.

The two-year period is to prepare a safety case (Work Health and Safety Regulation 2011). A safety case summarises the amusement ride hazards and the controls in place to minimise the risk of an amusement ride incident. How the theme park is managing safety must be demonstrated with a safety management system (SMS) (Workplace Health and Safety Queensland 2021a). Preparing a safety case ensures the operator understands and considers the hazards specific to the amusement ride.

An SMS is essential to demonstrate compliance. An SMS is a framework of the safety objectives, systems and procedures, performance criteria, and how to maintain adherence to the performance criteria (Electrical Safety Office 2022). Figure 2.1 illustrates an overview of the SMS elements.

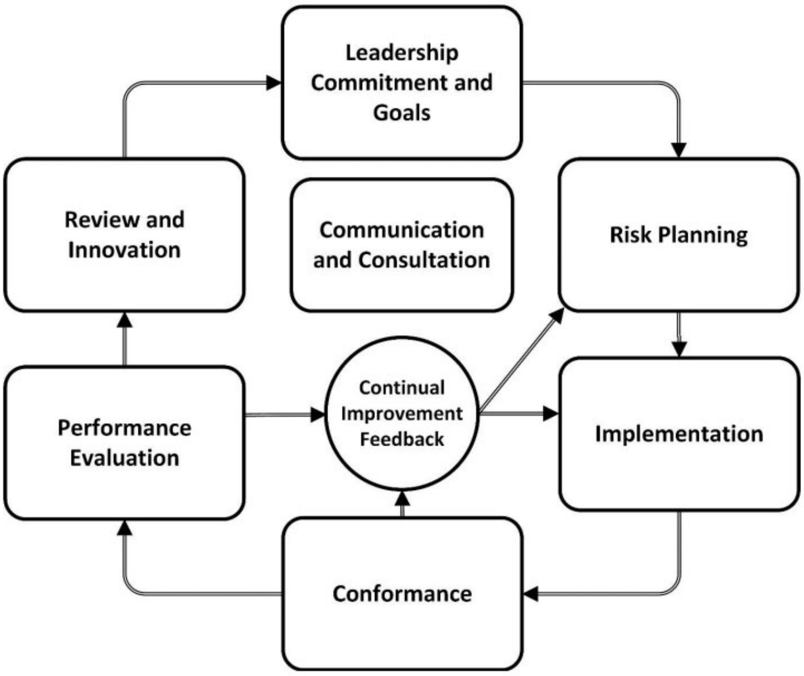

Figure 1 - SMS elements

Figure 2.1 SMS elements (Electrical Safety Office 2022, p. 10)

The SMS elements above are important as they show the overall life cycle of managing safety. The SMS life cycle ensures continual improvement of the systems and processes. Communication and consultation are essential to ensure the ride operators participate in safety discussions related to amusement rides. The SMS improves safety performance and legislation compliance and provides a systematic approach to managing safety.

2.1.2 Codes of practice

Codes of practice clarify the minimum legal standards in Queensland. Compliance with codes of practice is a legal requirement in Queensland (Safe Work Australia 2020). The codes of practice cover specific topics; therefore, they are not all-encompassing of the hazards and risks that may arise (Queensland Government 2023).

In addition, the Queensland Government has released the new amusement devices code of practice (Amusement devices code of practice 2023). The new code of practice incorporates major inspections for amusement rides. Section 2.1.1. discusses additional Workplace Health and Safety guides for developing a safety case outline and preparing a safety case.

Furthermore, to the amusement devices code of practice, there are two relevant Queensland codes of practice. The relevant codes of practice are How to manage work health and safety risks and Managing risks of plant in the workplace (Workplace Health and Safety Queensland 2021a). The design of the field measurement program needs to consider the work health and safety risks.

The code of practice for managing work health and safety risks includes general information on hazards and the risk management approach. Identifying hazards, assessing risks, and controlling risks are broadly discussed (Workplace Health and Safety Queensland 2021c). While not specifically for amusement rides, this code of practice covers key information in risk management. Risk management is foremost in maintaining safe amusement rides.

There are specific amusement ride considerations in the code of practice for managing the risks of plant in the workplace. These include controlling risks: from purchase to disposal, specific control measures, plant registration and keeping records (Workplace Health and Safety Queensland 2021b). To maintain compliance with legislation, the amusement ride operator must follow this code of practice.

2.1.3 Standards

The international and European standards are the technical standards and engineering principles used for the designing and manufacturing amusement rides. In Australia, theme park operators import amusement rides, as the manufacturer of amusement rides occurs overseas.

The international standards provide context and understanding of Australia's current amusement ride standard. The international standards document the guidelines for amusement rides. The two notable standards are EN 13814 and ISO 17842, which are standards. While these two standards are the most notable, there is another standard, ASTM F2291-22 Standard Practice for Design of Amusement Rides and Devices.

Moreover, ISO 17842 safety of amusement rides has three parts: design and manufacture, operation and use, and requirements for inspection during design, manufacture, operation, and use (International Organization for Standardization 2023). The International Organization for Standardization (n.d.) states that the ISO standards have a development time of around three years.

The European standard for amusement rides is EN 13814, the safety of amusement rides and devices. Chiari (2020) acknowledged that the ISO and TC 254 committees were joined in 2010 to revise and harmonise the European standard with the ASTM standard, substantially improving the content. Since creating the joint committee, the ISO 17842 and EN 13814 standards have been improved alternatingly. In 2015, the last update to the ISO 17842 standard was completed. In comparison, the EN 13814 standard was updated in 2019. The EN 13814 series of standards consists of three parts. Part one is the principles for an amusement ride's safe, reliable design. Part two focuses on maintenance and safe operation. Part three defines the requirements applicable to controls, including documentation, manufacturing, testing and electrical equipment.

While the ASTM F2291-22 standard is more up-to-date than the EN 13814 standard, it is less prescriptive. Therefore, the EN standard is the most up-to-date, relevant international standard for amusement rides imported into Australia. However, designing amusement rides internationally using any of these standards has varying safety considerations.

The relevant Australian series of standards for amusement rides are the AS 3533 amusement rides and devices standards. AS 3533 has four parts: design and construction, operation and maintenance (currently superseded pending revision), in-service inspection and specific requirements. AS 3533 parts one, two, and three align with the EN 13814 standards. The development of AS 3533 is lagging; parts one and two were last updated in 2009, and part three has not been updated since 2003. For this reason, approval was granted for the modified adoption of the EN 13814 standard to replace AS 3533 parts one and two. Part three is not being adopted due to the extra information contained within part three of AS 3533 (Hammon 2023).

Furthermore, other standards are relevant to amusement rides in Australia. IEC has a series of international standard for the electrical equipment of machines, IEC 60204 safety of machinery – electrical equipment of machines (International Electrotechnical Commission 2023). The safety of machinery standards are not directly for amusement rides; nevertheless, they contain pertinent information on electrical equipment of machinery, including protection against electrical shock, fault protection, motors, equipotential bonding, operator control stations, cables, and technical documentation.

AS/NZS 4024.1204 is often used for the electrical design verification of imported amusement rides due to the outdated nature of AS 3533. The safety of machinery standards in Australia are modified adoptions of the IEC 60204 standard (Standards Australia 2019). The most relevant of the series for electrical equipment is AS/NZS 4024.1204 safety of machinery – electrical equipment of machines. AS/NZS 4014.1204 includes specific safety considerations for the electrical equipment of amusement rides, such as control circuits and functions, operator interfaces, wiring practices, motors, technical documentation and verification of the documentation and testing requirements.

Standards are a guide to best practices in Australia. Engineers use the best practice standards and professional judgement to ensure installations are compliant and safe. Standards Australia are a not-for-profit organisation that produces voluntary standards (Standards Australia 2023b). . Queensland makes standards mandatory by enforcing it in legislation; however, this is only sometimes the case.

In Australia, requirements for the design, construction, and verification of electrical installations are in the AS/NZS 3000 electrical installations standard, also known as the wiring rules. The standard covers all electrical installations used by electricity consumers. The standard consists of two parts. Part two provides the installation practices, while part one provides the fundamental safety principles or minimum regulatory requirements for an electrical installation (Standards Australia 2018).

While AS/NZS 3000 is not for amusement rides, in Queensland, the Electrical Safety Regulation (2013) references the wiring rules, which makes compliance mandatory. The wiring rules do not include specific amusement ride considerations such as safety control systems, guarding, operator controls, isolation procedures or technical documentation (including considerations for transport, use, maintenance, decommissioning and disposal of electrical equipment). The wiring rules is inappropriate for amusement ride installations as it does not consider the rides' specific requirements.

2.2 Amusement industry organisations

The amusement industry has associations facilitating events and networking among industry professionals, including business owners, operators, and engineering professionals. Committee members volunteer their time to advise on areas such as education, safety, training, and special projects. The associations provide resources, information, training, industry trends, and statistics to members to improve their knowledge in the amusement industry.

2.2.1 International Association of Amusement Parks and Attractions (IAAPA)

IAAPA is the premier trade association representing the international amusement parks and attractions industry. IAAPA contributes professional knowledge and practices to the industry by hosting global events and conferences to enable members to provide safe guest experiences (International Association of Amusement Parks and Attractions 2023). They also contribute to the industry in other ways. An example is when the International Association of Amusement Parks and Attractions (2021) wrote a letter to the Pakistan Standards & Quality Control Authority to accept rides and devices to all the recognised global standards.

It is also important to highlight that IAAPA has worked to harmonise the international amusement ride standards with the American Society of Testing and Materials (ASTM) International, the European Committee for Standardisation (CEN) and the International Organisation for Standardisation (ISO). IAAPA highlights the unintended consequences, including manufacturers and suppliers having to make unique customisations, specialised training for inspection bodies and unique amendments to ride documentation.

IAAPA states that harmonising ASTM international F24 standards and EN 13814 allows consistent design and efficiencies in compliance verification, design, manufacturing quality, operation, maintenance, inspection documentation, and procedures. IAAPA also discusses the benefits for manufacturers, suppliers, operators, and government regulators, which allow for purchasing, operational and inspection productivity. The publication suggests that synchronised safety standards offer economic and social benefits to the industry.

2.2.2 Australian Amusement Leisure and Recreation Association (AALARA)

The peak national body, AALARA, represents Australia's amusement, leisure and recreation industry. AALARA provides valuable insight into the considerations of amusement ride risks by consulting with relevant stakeholders. AALARA is represented in Australian Standards committees involved in guidance for amusement, leisure, and recreation equipment, providing an industry voice within the government and the community (Australian Amusement Leisure and Recreation Association 2022).

AALARA contributes to amusement ride safety by completing relevant projects to provide information on how the industry can improve. Before the proposal to update AS 3533 as discussed in section 2.1.3, AALARA completed a project to compare AS 3533.1, 2, 3, and 4.3 with the EN 13814 standards to provide evidence and justification for updating the Australian standards (Hawley 2022). The national body has limitations in the scale of project work they can complete due to being a not-for-profit with an elected voluntary board of industry leaders.

Every year, AALARA holds a conference where regulators across Australia attend to share information to ensure an aligned approach to amusement ride safety. This year, the conference included three invitation-only regulator sessions; below is a summary of two sessions: the national regulators and engineers' session and the national regulators forum. The forum provides an opportunity to speak about the common issues from the regulators during amusement ride inspections. The first speaker was Aaron Holman, the Chief Safety Engineer from Queensland Industrial Relations. A central topic of discussion was major inspections. The areas of improvement include recommending a timeframe, including the inspection regime in the amusement ride manual, identifying what is necessary, including the pass-fail criteria, and improving the record-keeping (Gurrin 2023). The inspection of amusement rides is crucial to ensuring safety in amusement rides. Aaron discussed the importance of inspection and the need for a comprehensive report (Gurrin 2023). The conference provided insight into the identified regulatory issues and how the industry can be improved.

Moreover, another interesting speaker was Geoff Ooi, an engineer from WorkSafe Victoria. Geoff discussed the areas of improvement identified from the Thunder River Rapids Ride and the Airmaxx ride. Geoff acknowledged that he gave evidence in the Cha Cha ride, and while he could not discuss specific information, he revealed similar concerns across all three inquests (Gurrin 2023). Targeting the recurring themes can improve the safety of the amusement ride industry.

The regulator forum consisted of Queensland, New South Wales, Victoria, and South Australia representatives. The information and updates came from the representative in the applicable state. While the representatives came up with the topics for discussion independently, similar themes were identified by all. The forum was beneficial for the thesis as the topics included a discussion of improving amusement ride safety.

2.3 Overview of Coroner's findings

This section reviews the coronial inquest findings for amusement rides. The inquests make recommendations to government agencies from the lessons learned. These recommendations aim to improve the legislation, policies, and processes to prevent similar deaths. After the initial autopsy, the coroner can request an additional investigation. The additional information can include reports, testimonies, medical records, or information from detectives, police, doctors, engineers, workplace health and safety assessors, and witnesses. Once completed, the coroner consults with the family and may conduct a public hearing. Finally, the coroner will make written findings (Queensland Courts 2020a). The review discusses the key findings from the amusement ride inquests.

2.3.1 Thunder River Rapids Ride (TRRR)

This section discusses the amusement ride incident in 2016 that eventually led to the overall improvement of the industry. The Queensland Courts (2020b) published the findings of Coroner James McDougall in February 2020. The water ride, intended to be suitable for families and other patrons, consisted of circular rafts that travelled along a manufactured course. The momentum of the water flow pushes the raft along the 450-metre-long course, reaching speeds of up to 45 kilometres per hour. At the end of the conveyor near the drop-off area, one of the rafts became stranded on the steel support rails. The subsequent raft was lifted and pulled perpendicularly into the conveyor mechanism after the collision with a stranded raft. Two participants were able to free themselves, while the remaining four were caught in the ride mechanism and died. Following the accident, the investigation approach included a forensic crash unit investigation, document review, interviews, and technical advice from the Office of Industrial Relations (OIR) (Queensland Courts 2020b).

A series of events preceded the accident. When only one pump operated, the water level dropped below the safe operating level. The only water level monitoring was visual; with no official water guide, the operators referenced the water line on a wall. There was no audible or visual alert followed by the shutting down of the ride. The water pumps and conveyor operated independently without interlocks (Queensland Courts 2020b). The visual water level monitoring was an administrative control, and there was no engineering control; therefore, the control was insufficient. Implementing a safety system to monitor the water level would have controlled the risk. Several previous incidents included a drop in the voltage that shut down the south pump, rafts ramming into each other and a bearing failure on the south pump (Queensland Courts 2020b). The safety team organised further investigations from the previous incidents through the risk management software managed by the safety team.

Furthermore, the Queensland Courts (2020b) found a gap in the unloading area at the end of the conveyor and gaps between the slats and the conveyor. The safety machinery standards AS/NZS 4024 were referenced in the inquest as the standards provide examples of hazards, hazardous situations, and events. However, the inquest acknowledges that the movement of products, not people, is considered in the standard. Thus, the standard does not consider the gap at the unloading end of the conveyor a hazard. However, the standard is considered relevant, and the modification that produced the gap should have initiated a risk assessment of the ride. The risk of a raft or person falling through the gap would have been minimised by reinstating the slats and reducing the gap at the unloading area (Queensland Courts 2020b). A risk assessment could have highlighted the hazard and minimised the risk to the public resulting from the modification.

Several resulting faults identified from the incident reconstruction were excessive corrosion, no water backflow prevention, water running over electrical equipment in the pump enclosure, and unidentified controls (Queensland Courts 2020b). These incidents were unconnected to the incident; nevertheless, they highlighted the ongoing issues not addressed and indicated insufficient ride maintenance. The safety manager expressed his work as ‘a large amount of responsibility, which made it difficult for him to complete the reactive work required, let alone any proactive safety management.’ (Queensland Courts 2020b, p. 74). While the safety team was not performing preventative maintenance, the maintenance team conducted an annual ride shutdown. The Queensland Courts (2020b) stated that maintenance systems should consider technological improvements and safety obligations. The maintenance of the VSDs included reviewing the operation, visual checks, replacing filters and internal fuses, and checking the input and output voltages and currents. The maintenance did not consider the advancements made in the previous thirty years.

The Queensland Courts (2020b) stated that the primary cause was the failure of the south pump, which could have been from an Earth fault in the Danfoss variable speed drives (VSDs). The theory was that the Earth fault could have been slow motor insulation resistance degradation, although the cause could not be determined. There were frequent intermittent Earth fault alarms the week before the incident. Dreamworld knew the alarms, yet the ride still operated (Queensland Courts 2020b). There should have been a thorough investigation with the ride shut down to analyse the cause. The Earth fault is important to the thesis, as more water-based amusement ride research would permit elevated knowledge on VSDs and the possible safety implications.

The findings identify systematic failure in managing safety and maintenance, which contributed to implementing the best practice review. The Queensland Government (2022) provided recommendations that included major inspection requirements. Major inspections now include stripping down the ride to remove corrosion. Major inspections allow visual inspection to identify faults, improving amusement ride safety.

While the investigation identified contributing factors, the deaths resulted from an inadequate safety system (Queensland Courts 2020b). Queensland Courts (2020b) concluded that Senior Constable Cornish identified that an automated safety system would have prevented the incident. Amusement ride malfunctions occur within the industry. While shutting down the ride impacts the public, the inconvenience of being rescued decreases in importance compared to the amusement ride risks.

2.3.2 Airmaxx

The Airmaxx incident happened in September 2014, two years before the Dreamworld incident. The coroner’s findings were completed in June 2022 by Deputy State Coroner Ian White (South Australia Courts 2022). Although this is not a fixed water-based ride, the inquest findings evaluate the shortcomings identified by the coroner and identify areas of improvement in amusement ride safety. The carousel ride consists of twelve arms connected to a central tower. The arms move perpendicularly (using pneumatic actuators), with two rotating seats at each end. During the ride, the Airmaxx ejected Adelene from her seat at the 2014 Royal Adelaide show, where she rode unaccompanied. She sustained fatal injuries and later died in hospital. The South Australia Courts (2022) detailed that following the incident, there was a joint investigation by SafeWork and South Australia Police (SAPOL). The investigation involved owner, operator, employee and eyewitness interviews and scrutiny by an independent functional safety engineer.

Several issues led to the incident identified in the report by the coroner. These issues were contributing factors; however, the report does not state a direct cause. Therefore, the contributing factors are described in more detail to understand better the events leading to the incident. The coroner identified nine relevant issues (depicted below).

- Issue 1 - The purchase of the Airmaxx;
- Issue 2 - Registrations required for the Airmaxx to operate in Australia;
- Issue 3 - The assembly and initial inspection of the Airmaxx;
- Issue 4 - Harnesses and restraints;
- Issue 5 - Lack of communication between State and Territory regulators;
- Issue 6 - Training and operation of the Airmaxx;
- Issue 7 - Inspections and audits, investigation and prosecution;
- Issue 8 - Approval to operate at the Royal Adelaide Show in 2014;

- Issue 9 - The setting of the 'minimum height' for passengers to be permitted onto the ride at The Show. (South Australia Courts 2022, p. 9)

While the coroner did not identify one action as causing the incident, the oversights started with purchasing the Airmaxx. The amusement ride was purchased and imported into Australia from Spain (South Australia Courts 2022). The incident occurred in South Australia. Therefore, the South Australia legislation is relevant when discussing Airmaxx and the failings that occurred. The South Australia Work Health and Safety Regulation (2012) mandates the design and plant registration of amusement rides imported into Australia, similar to Queensland as previously discussed in section 2.1.1. The Airmaxx did not obtain design registration; the Airmaxx obtained the Victorian plant registration (PRN) with a Queensland plant design registration number (DRN) for a similar ride. The Royal Adelaide Show application also stated that the PRN was from NSW (South Australia Courts 2022). The lack of design registration meant the ride was unsafe for operation in Australia. The lack of design registration highlights a significant oversight: there is no national database for information sharing between State and Territory jurisdictions. The lack of a national database has been an ongoing topic of conversation within the amusement industry. The Safety Institute of Australia submitted a submission that suggests standards across Australia for compliance matters should be uniform and dependably recorded with relevant inspector and regulator access (South Australia Courts 2022). Legislation compliance is most important, yet this is not easy when the requirements across Australia vary across jurisdictions. Implementing consistent standards with access to relevant records by inspectors and regulators would ensure easy verification of claims. In turn, this would increase the safety of amusement rides.

Another contributing factor was the lack of an electrical inspection and non-destructive testing. A document identified as 'Record of Annual Inspection of Amusement Device' (South Australia Courts 2022, p. 40) provided as evidence indicates the completed actions taken, specifically, maintenance and inspections, electrical inspections, and non-destructive testing. South Australia Courts (2022) confirmed no electrical inspection or non-destructive testing. Moreover, the manufacturer's unaccompanied minor height of 140 mm set was not adhered to during the show. The safe height of patrons should have been increased after a previous incident in 2013 (South Australia Courts 2022). Compliance with the inspection and manufacturer requirements of amusement rides is fundamental to the safety of patrons.

There was a joint investigation following the incident by SafeWork and South Australia Police (SAPOL). SafeWork engaged a functional safety engineer to inspect the ride; three reports detailed the findings. The reports identify issues with locking the patron harnesses, the split pins, and the secondary lock. He also detected problems that he believed should have been detected in the annual inspection that had taken place. The concerns were across the ride's design, operation, and maintenance (South Australia Courts 2022). The inquest findings demonstrate the importance of consistent standards across Australia regarding legislation compliance and access to relevant amusement ride records for inspectors and regulators. In addition, it demonstrates the importance of design registration, inspections and complying with the manufacturer requirements for amusement rides.

2.3.3 Cha Cha

Less than one year after the Dreamworld incident, there was a death involving a carnival ride. The Cha Cha operated for the Melbourne Rye Easter Carnival in April 2017. The Coroners Court of Victoria has not yet completed and published the coroner's findings for the incident. The carousel consists of arms connected by beams to the centre turret. Each arm has several carriages at the end that spin. Riders are seated together in the suspended carriages. Eugene Mahauariki was riding with a younger friend when he was ejected from his seat and landed on the ground after hitting his head. Eugene later died when life support was turned off (Sweeney 2022). The report will likely identify similar issues to Thunder River Rapids Ride and Airmaxx, as discussed in section 2.2.2.

2.4 Mitigating risks of electrical equipment for amusement rides

To understand the risks associated with water-based amusement rides, the conditions that expose them to damage or reduce their expected life span must be investigated. From the 1st of June 2017 to the 31st of May 2018, 182 amusement ride incidents and 51 involved a fatality (Woodcock 2019). Given the sheer number of incidents, it is crucial to establish where risk management can be improved. This section explores previous research to identify amusement ride risks and explore the occurrence and influencing factors.

2.4.1 Vibration

In amusement rides, excessive vibration can cause damage to the motor, which can cause an amusement ride accident and put patrons at risk. Vibration monitoring detects changes in vibration indicating imbalance, misalignment, insulation or bearing failure of rotating electrical equipment. Moreover, condition monitoring of amusement rides uses vibration frequency analysis. The baseline vibration does not change over time unless something else is wearing or degrading; it is the distinctive signature of the machine. In cases of abnormality or failure, the vibration characteristics can determine the nature of the fault (Goel et al. 2014). Goel et al. (2014) created a study to review the condition monitoring for electrical equipment. The study included reviewing vibration signal analysis, acoustic emission testing, ultrasound and infrared thermography. The study reports on the condition monitoring techniques and details the fault types the methods are suitable for. Vibration analysis is popular within the electrical industry. According to Shen and Liu (2019), 'Vibration analysis is the most widely used technique (70%)' (Shen & Liu 2019, p. 449).

However, vibration analysis is not always suitable. In two studies by Wu et al. (2012) and Shen and Liu (2019) they agree that vibration monitoring is unsuitable for detecting early bearing failure due to the background noise; nonetheless, acoustic monitoring can detect early damage.

Similarly, there was a study conducted on motors' vibration, sound and thermal analysis for condition monitoring. Importantly, Orman and Pinto (2013a) state that acoustic and thermal evaluation of motors are beneficial methods for condition monitoring. The study verifies acoustic and thermal measurements using vibration analysis due to the established and recognised methods of vibration analysis within the industrial industry. The measurement tools used in the study were the ABB MACHsense-P condition monitoring tool, two Gfai Tech microphones, and a Fluke Ti32 thermal image camera. The methodology included conducting measurements in an industrial environment on two three-phase induction motors. The first motor was healthy, and the second had a combination of faults, static eccentricity and soft foot. The supply to the motors was 50 Hz, and the vibration analysis proved that static eccentricity was present at 100 Hz. The acoustic spectrum showed similar results with the static eccentricity present at 100 Hz. The thermal images illustrate a high temperature on the mounting bolt of the unhealthy motor.

2.4.2 Corrosion

Design, ongoing inspection, and maintenance processes of amusement rides need to consider corrosion. Corrosion is an important environmental consideration. A ride installed inland will have less corrosion than one installed near the sea (Sypher 2022). If there is no monitoring of the ongoing condition of the amusement ride, corrosion can lead to an amusement ride accident, as observed in the Fire Ball incident. Bever and Horton (2017) reported that corrosion led to the catastrophic failure of an amusement ride, the Fire Ball. The fire ball consists of six rows of seating, with four seats opposite each other to form a gondola wheel connected to a central tower. The arm moves like a pendulum, with the rotating gondola wheel at the end. The inspection and testing of the ride should have identified the corrosion before opening it to the public. There has been research into the corrosion of metallic structures to identify prevention techniques. In one study, Shen and Liu (2019) discussed cathodic protection currents to prevent corrosion in large oil storage tanks. The methods used in the study to detect corrosion were acoustic emission monitoring, electromagnetic ultrasonic testing, pulsed eddy current testing (without removing the insulation layer), ultrasonic thickness measurement, and magnetic flux leakage testing (Shen & Liu 2019). Further, research into the cathodic protection of amusement rides could determine if the theory could be applied.

2.4.3 Power quality

Power quality disturbances such as fluctuations in the supply, voltage variation, transients, and harmonic distortion can decrease the life expectancy of electrical equipment. Power quality problems can originate from the supply or the installation and load. The significant problems related to the installation and load are harmonic currents, earth leakage currents, and voltage dips and transients (Agarwal et al. 2012). The design and operation of the system can harm the power quality. Nonlinear loads such as a Variable Speed Drive (VSD) can generate harmonics, and large motors during starting can cause voltage dips and transients (Agarwal et al. 2012). Diagnosing power quality disturbances can be achieved using a power quality analyser. Reducing power quality disturbances could lead to increased life expectancy of electrical equipment.

2.4.4 Insulation failure

Factors that can cause insulation deterioration include aging, electrical stress, mechanical damage, vibration, and moisture. Overloading, overheating, poor power quality and harmonic distortion can cause degradation over time, leading to equipment failure. In one study, Yu et al. (2019) investigated detecting elevator AC-contactor faults due to insulation failure. The methodology included using an infrared instrument to detect the temperature of the contactor. The temperature was controlled to obtain the normal operating temperature, and then the temperature values were increased sequentially above the operating threshold. The resulting thermal images illustrate the cause of the fault. Thermography could detect insulation failure in electrical equipment.

Hwang et al. (2003) investigated wire insulation failure of inductor motor windings using partial discharge in another study. The methodology included assessing the insulation characteristics of forty induction motors constructed with eight different insulation methods. The study concluded that partial discharge is closely related to insulation strength in low-voltage induction motors. The detection of insulation failure in low-voltage motors could be detected using partial discharge.

2.4.5 Maintenance

The maintenance of electrical equipment is valuable to ensure it is safe and efficient. As discussed in section 2.3.1, a lack of maintenance is not the direct cause of an incident. Nonetheless, it is a contributing factor. James (2021) states that proper maintenance can ensure the reliability of amusement rides. The life expectancy of electrical equipment is often disregarded. The industry agrees that the life expectancy of electrical equipment ranges from twenty-five to forty years, with complete replacement recommended at the end of life. Replacing electrical equipment within the recommended timeline rarely occurs in practice. Replacement cost is a major factor in the decision to keep existing equipment. In addition, reliable maintenance records can document the history of the ride. These records are essential for determining the hazards associated with an amusement ride.

2.4.6 Inspection of amusement rides

A competent person must carry out regular daily inspections, annual inspections, and major inspections of amusement rides under the legislation (Work Health and Safety Regulation 2011). The company carrying out the inspection determines the process. This approach results in inspections that vary depending on the level of knowledge and expertise. The consistency of inspections is mainly relying on inspector knowledge. The SMS replaces the pass-and-fail inspections with risk-based inspections to make informed decisions about the safety of amusement rides (Workplace Health and Safety Queensland 2021a). The importance of amusement ride safety is paramount to the industry. Recognised support through training and formal knowledge sharing can assist inspectors with making risk-based decisions.

2.4.7 Identifying trends

The coroner reports identify common trends throughout the amusement ride industry. Avery and Dickson (2010) state that previous issues have arisen from design defects. The process from identifying a defect to incorporating a solution can take time due to a lag in information sharing. The industry requires owners and operators to liaise with the manufacturer to implement changes in the ride design. The lag in information sharing creates a situation where owners and operators must wait for updates from the manufacturer. An international database for reporting amusement ride incidents could improve information sharing and identify industry trends. Including information on specific ride types could prevent future incidents. A database will allow ride owners and operators to keep updated with the latest information and improve industry knowledge. The collaboration of amusement industry organisations to initiate a database will improve safety and public perception.

2.4.8 Emergency shutdown system

Computing technologies are rapidly advancing, offering innovations in systems engineering. An area of growth has been in very large-scale integration (VLSI). Dragffy (1999) investigated the design of a very large scale integrated (VLSI) chip for an emergency shutdown system. The study proposed applying a solid-state reliable alternative to programmable logic controllers (PLCs). The VLSI system achieved high reliability and incorporated safety features, including self-testing, redundancy, fault tolerance, and priority scheduling. Future research into the integration of VLSI could lead to increased reliability and testability for safety shutdown systems.

2.5 Assessing the electrical safety of water-based amusement rides

The research investigated risks affecting amusement rides. Prior research has overlooked water-based amusement rides, with most of the literature focussing on the rotating structures associated with amusement rides. The water-based amusement ride research conducted for the thesis was limited to the Thunder River Rapids Ride coroner report. The report identified several areas for improvement. One main area of concern was the lack of a safety system. An automated safety system with water level monitoring and interlocks for the electrical equipment would have implemented a shutdown before the incident occurred. Additional failings included unidentified controls, excessive corrosion, water running over electrical equipment and inadequate ride maintenance. The research into the coroner's findings identifies the variability of amusement ride incidents. More research into water-based amusement rides would increase industry knowledge, resulting in safer amusement rides.

The legislative requirements, codes of practice and standards highlight additional considerations for water-based amusement rides. Compliance with the legislation requires the completion of a safety case. Section 2.1.1 discusses a safety case, which is a detailed risk assessment of the amusement ride (Workplace Health and Safety Queensland 2021a). While the guide does not detail how to conduct the assessment, it encourages reviewing the processes against the requirements of the standards, conducting a gap analysis and considering the implementation of additional control measures (Safe Work Australia 2012). The Australian standard for amusement rides, AS 3533, is outdated and lagging in development, as discussed in section 2.1.3. Thus, assessing amusement rides for safety does not use the amusement ride standards in Australia. Consequently, evaluating amusement rides for safety uses the safety of machinery standards. The specific requirements of water-based amusement rides are not limited to these standards.

As outlined in section 2.1.3, the Queensland government legislates compliance with the wiring rules. In the prescriptive section, the wiring rules detail the minimum requirements for damp situations in section six, which applies to the following:

- (i) Baths, showers and other fixed water containers.
- (ii) Swimming pools, paddling pools and spa pools or tubs.
- (iii) Fountains and water features.
- (iv) Saunas.
- (v) Refrigeration rooms.
- (vi) Sanitization and general hosing-down operations. (Standards Australia 2018, p. 316)

The swimming pool requirements apply mainly to areas intended to be occupied for swimming, although the requirements also extend to electrical installations and in natural water, ponds and coastal areas. Even though the large bodies of water associated with water-based amusement rides are not for swimming, they must comply with the wiring rules. Part two of the wiring rules details that electrical equipment installed in water is required to be IPX8, designed and constructed for use in a swimming pool, and supplied from outside the specified zone at a maximum of 12 V AC or 30 V DC with no Earth connection (Standards Australia 2018). Water-based amusement rides consist of submersible motors. Therefore, they do not comply with the requirements of part two of the wiring rules. The operator must verify the amusement rides to comply with part one of the wiring rules. However, the bodies of water associated with amusement rides are not for swimming but for theming.

IAAPA and AALARA have worked with stakeholders to improve outcomes for safety. IAAPA has worked to harmonise international amusement ride standards. They engaged with community stakeholders to highlight the benefits of synchronised safety standards. AALARA have reviewed the international amusement ride standard and are currently working to update Australian amusement ride standards. The organisations provide information to members, improving safety knowledge on the risks associated with amusement rides.

There are several factors to consider when assessing the electrical safety of water-based amusement rides. The risks identified contribute to the electrical safety of all amusement rides. Determining specific risk mitigation techniques for water-based amusement rides would improve safety in the industry. More industry research into water-based amusement rides is required to determine the safety impacts of electrical equipment associated with water-based amusement rides.

Chapter 3. Field Measurement Program

This section explores preventative maintenance techniques to create a field measurement program. The field measurement program aims to identify potential problems with water-based amusement rides. The research considers the relevance and validity of the information. It is essential when constructing the field measurement program because it can provide vital evidence to determine the best approach for the field measurement program.

3.1 Preventative maintenance techniques

Shen and Liu (2019) created a study to verify condition monitoring for large mechanical equipment. The study verified the feasibility of condition monitoring with defined monitoring parameters. Subsequently, a sizable amount of research has focussed on the condition monitoring of electrical equipment. Including two studies created by Goel et al. (2014) and Orman and Pinto (2013a). The Condition monitoring of electrical equipment can identify potential problems before they occur. Predictive maintenance of electrical equipment reduces downtime and the associated costs. This thesis considers four preventative maintenance techniques: power quality monitoring, partial discharge testing, and thermal and acoustic imaging.

3.1.1 Power quality monitoring

The detection of power problems has been utilised within the industry to lower costs. Agarwal et al. (2012) studied power quality problems with adjustable speed drives. The study includes the detection of power quality problems and possible solutions. Agarwal et al. (2012) states that a preventative survey can detect potential power quality problems, reducing unexpected breakdowns. The reduction of unexpected breakdowns reduces the associated cost. Disturbances in the power system contribute to premature equipment failure. Improving power quality results improves reliability and reduces costs incurred from downtime.

Power quality monitoring requires considering the installation location of the analyser. The installation location depends on the power quality problem. Installing the power quality analyser near the power source will determine problems originating from the supply and, alternatively, installing the power quality analyser close to the load to evaluate a single piece of equipment (Agarwal et al. 2012).

Furthermore, specific equipment can affect the power quality of a site. For instance, Agarwal et al. (2012) stated that VSDs can generate harmonics. Moreover, Galceran et al. (2003) conducted a study on VSDs and the power quality problems that can arise. The study states that VSDs control motor speed by generating sinusoidal voltages and currents of the right magnitude and frequency, resulting in power quality disturbances. VSDs are prone to power quality disturbances due to their physical construction. The study conducted by Galceran et al. (2003) defines the physical construction of a VSD. The most common VSD comprises of several basic sections, shown below in Figure 3.1.

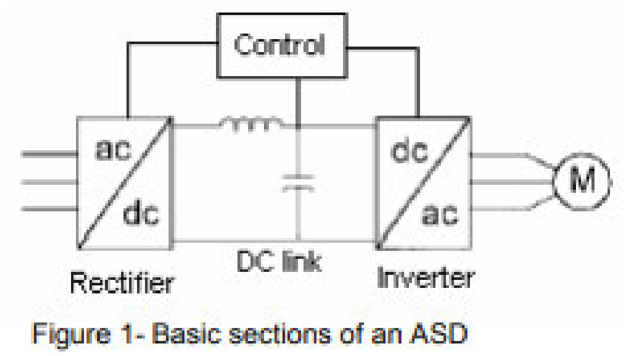

Figure 3.1 Basic sections of a VSD (Galceran et al. 2003, p. 257)

VSDs are a form of Pulse Width Modulation (PWM) inverter, which are mostly used in low voltage applications to adjust the magnitude and frequency of the output voltage. The most used inverter power devices are Insulated Gate Bipolar Transistors (IGBTs). To allow dynamic control of the load, IGBTs switch at high frequencies. The high frequencies generated (up to 20 kHz) can be a source of a power quality disturbance (Galceran et al. 2003).

Locating and identifying potential problems requires monitoring the power and accurately measuring the voltage and current waveforms. The analysis of the records includes methodically reviewing equipment malfunction and occurrences during that time, identifying events that exceed the equipment's limit and finally, identifying unusual or severe episodes (Agarwal et al. 2012).

A preventative survey requires analysing the waveform to determine if there are power quality disturbances. Ravi and Kannaiah (2022) detail different power quality disturbances and illustrate the waveforms. Figure 3.2 illustrates the waveforms from different power quality disturbances. The waveforms display the types of disturbances and how the voltage and frequency are affected. Power quality disturbances happen for a variety of reasons. Ravi and Kannaiah (2022) summarise power quality disturbances' possible causes and effects, Table 3.1 reproduces this information.

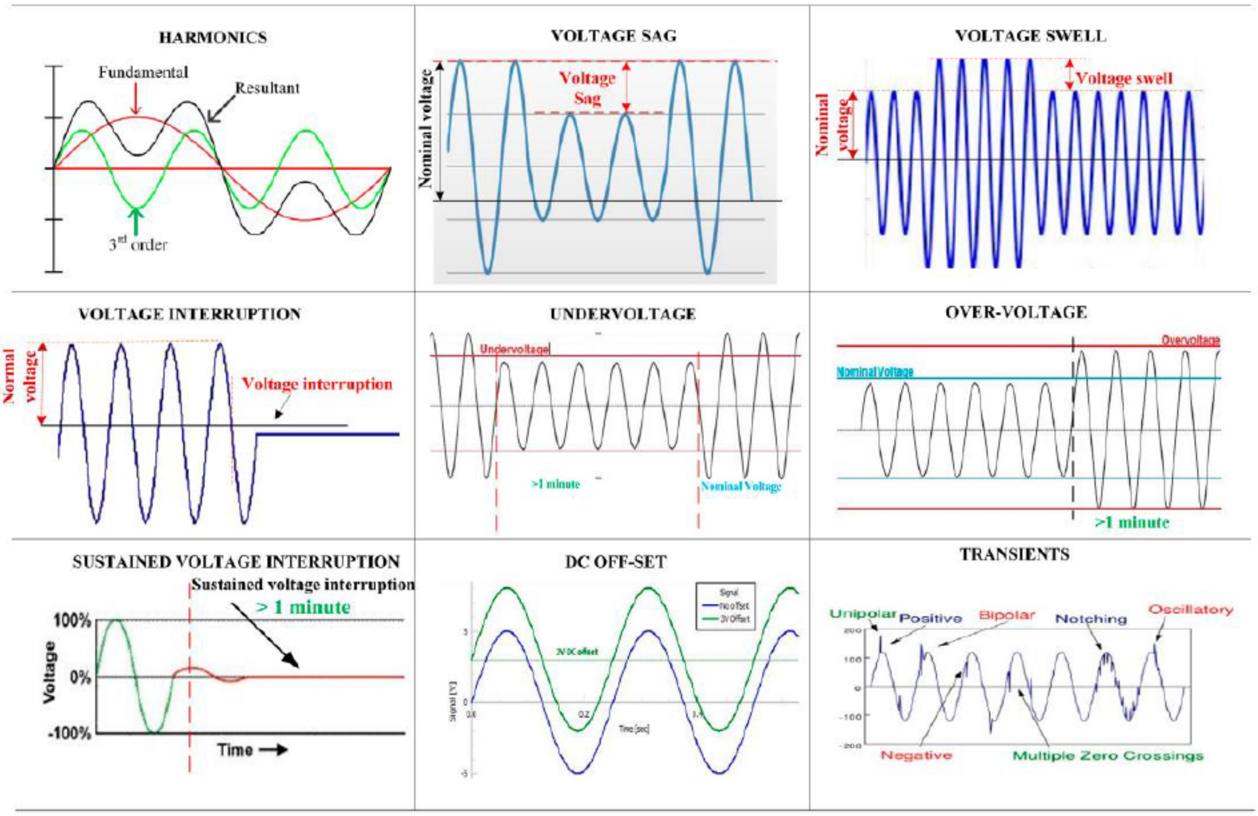

FIGURE 3
Waveforms of various power-quality issues.

Figure 3.2 Waveforms of various power-quality issues (Ravi & Kannaiah 2022, p. 5)

Power quality disturbance		Causes	Effects	Severity
Transients	Oscillatory transient	Line and facility load switching, cable switching, and back-to-back capacitor switching	Disruption in electrical equipment	Catastrophic
	Impulsive transients	Lightning		Catastrophic
Short-time voltage variations	Voltage sag	System malfunctions, source voltage fluctuation, starting of heavy loads, inadequate wiring, and inrush currents	Overloading issues, intermittent lockup, and grabbled data	Moderate
	Voltage swell	Source voltage fluctuation, stop of heavy loads, inadequate wiring, and inrush currents	Equipment damage, data loss, intermittent lockup, and grabbled data	Mild
Long-time voltage variations	Under voltage	Load switching	Flickering of lightning, and the chance of damage to equipment	Severe
	Overvoltage	Transformers taps are set incorrectly, large loads are switched off, or a large capacitor bank is energised		Severe

Power quality disturbance		Causes	Effects	Severity
	Sustained voltage Interruption	Protection device failure, insulation failure, or control malfunction	Equipment failures in the data processing system	Moderate
Waveform distortion	DC offset	Switching of transformer	Adversely affect the performance of relays	Moderate
	Harmonics	Nonlinear loads and switching operation of PE devices	Electrical equipment losses, motor and transformer overheating	Moderate
	Noise	Electromagnetic interference and improper grounding	Data loss, and disturbances in sensitive equipment	Mild
Power frequency variation		Heavy loads	It mainly effects sensitive equipment and motors	Mild

Table 3.1 Summary of power quality disturbances in the AC system (Ravi & Kannaiah 2022, p. 8)

One of the identified disturbances is harmonics. Standards Australia (2023a) describes the harmonic current levels for equipment between 16A and 75 A. The standards have a table for single-phase and three-phase equipment. Figure 3.3 shows Table 2 for single-phase equipment and Figure 3.4 shows Table 3 for three-phase equipment. The tables include a current harmonic percentage that varies depending on the harmonic.

Table 2 – Current emission limits for equipment other than balanced three-phase equipment

Minimum R_{sce}	Admissible individual harmonic current I_h/I_{ref} [a] %						Admissible harmonic parameters %	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	THC/I_{ref}	$PWHC/I_{ref}$
33	21,6	10,7	7,2	3,8	3,1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥350	41	24	15	12	10	8	47	47

The relative values of even harmonics up to order 12 shall not exceed $16/h$ %. Even harmonics above order 12 are taken into account in *THC* and *PWHC* in the same way as odd order harmonics.

Linear interpolation between successive R_{sce} values is permitted.

[a] I_{ref} = reference current; I_h = harmonic current component.

Figure 3.3 Single phase equipment current emission levels (Standards Australia 2023a, p. 16)

Table 3 – Current emission limits for balanced three-phase equipment

Minimum R_{sce}	Admissible individual harmonic current I_h/I_{ref} [a] %				Admissible harmonic parameters %	
	I_5	I_7	I_{11}	I_{13}	THC/I_{ref}	$PWHC/I_{ref}$
33	10,7	7,2	3,1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed 16/h %. Even harmonics above order 12 are taken into account in *THC* and *PWHC* in the same way as odd order harmonics.

Linear interpolation between successive R_{sce} values is permitted.

[a] I_{ref} = reference current; I_h = harmonic current component.

Figure 3.4 Three-phase equipment current emission levels (Standards Australia 2023a, p. 17)

The standard for voltage harmonics is AS/NZS 61000.2.4. Figure 3.5 and Figure 3.6 illustrate the harmonic compatibility levels for odd harmonics. Figure 3.7 depicts the even harmonic compatibility levels. The voltage harmonics vary depending on the class. Once there has been identification of the power quality problems, reviewing the overall design and equipment specifications can assist in determining possible solutions.

Table 2 – Compatibility levels for harmonics – Harmonic voltage components Odd harmonics non-multiple of three

Order h	Class 1 U_h %	Class 2 U_h %	Class 3 U_h %
5	3	6	8
7	3	5	7
11	3	3,5	5
13	3	3	4,5
17	2	2	4
$17 < h \leq 49$	$2,27 \times (17/h) - 0,27$	$2,27 \times (17/h) - 0,27$	$4,5 \times (17/h) - 0,5$

NOTE In some cases where part of an industrial network is dedicated to large non-linear loads, the class 3 compatibility levels for that part of the network may be 1,2 times the above values. In such cases precautions should be taken regarding immunity of equipment connected. However, at the PCC (public network) the compatibility levels from IEC 61000-2-2 and IEC 61000-2-12 take precedence.

Figure 3.5 Odd harmonic compatibility levels (non-multiple) (Standards Australia 2009, p. 10)

Table 3 – Compatibility levels for harmonics – Harmonic voltage components Odd harmonics multiple of three

Order *h*	Class 1 U_h %	Class 2 U_h %	Class 3 U_h %
3	3	5	6
9	1,5	1,5	2,5
15	0,3	0,4	2
21	0,2	0,3	1,75
$21 < h \leq 45$	0,2	0,2	1

NOTE 1 These levels apply to zero sequence harmonics.

NOTE 2 In some cases where part of an industrial network is dedicated to large non-linear loads, the class 3 compatibility levels for that part of the network may be 1,2 times the above values. In such cases precautions should be taken regarding immunity of equipment connected. However, at the PCC (public network) the compatibility levels from IEC 61000-2-2 and IEC 61000-2-12 take precedence.

Figure 3.6 Odd harmonic compatibility levels (multiple of three) (Standards Australia 2009, p. 11)

Table 4 – Compatibility levels – Harmonic voltage components even order

Order *h*	Class 1 U_h %	Class 2 U_h %	Class 3 U_h %
2	2	2	3
4	1	1	1,5
6	0,5	0,5	1
8	0,5	0,5	1
10	0,5	0,5	1
$10 < h \leq 50$	$0{,}25 \times (10/h) + 0{,}25$	$0{,}25 \times (10/h) + 0{,}25$	1

NOTE In some cases where part of an industrial network is dedicated to large non-linear loads, the class 3 compatibility levels for that part of the network may be 1,2 times the above values. In such cases precautions should be taken regarding immunity of equipment connected. However, at the PCC (public network) the compatibility levels from IEC 61000-2-2 and IEC 61000-2-12 take precedence.

Figure 3.7 Even harmonic compatibility levels (Standards Australia 2009, p. 11)

3.1.2 Partial discharge testing

Transient voltages cause irregular voltage distribution in motor windings, resulting in safety hazards. The adjacent air partially ionises, causing insulation breakdown known as partial discharge (Hwang et al. 2003). The partial discharge inception voltage (PDIV) is measured when the partial discharge starts. The study includes measuring the partial discharge extinction voltage (PDEV) when the high voltage reduces and the partial discharge disappears.

PD testing is widespread in medium voltage (MV) and high voltage (HV) applications on joints and terminations of cables and motors. There has been minimal research on using PD testing in low voltage (LV) applications. Lahrmann and Lahrmann (2012) produced a white paper to share about partial discharge testing and its applications. They conveyed that electric motors connected to the supply without a VSD are only subject to the peaks from the main's voltage; therefore, there would be no point in completing partial discharge testing. While it is not a scientific peer-reviewed paper, the whitepaper is based on over twenty-five years of experience with motor manufacturers and references research literature.

In a study examining the stator windings of induction motors for VSD applications, Hwang et al. (2003) found that partial discharge (PD) magnitude is related to the insulation strength in low-voltage inverter-fed induction motors. Section 2.4.4 The methodology included assessing the insulation characteristics of forty induction motors constructed with eight different insulation methods. The study uses a filtered power supply to remove the noise. Additionally, the study uses a radio frequency-shielded room for the testing. The corresponding breakdown voltages were acquired after insulation breakdown tests by high voltage pulses to analyse the insulation strength. The study measures the insulation as weak when the PD is over ten pC at 1,000 to 1,200 V. When PD occurs, the waveforms increase rapidly over ten pC, as depicted below in Figure 3.8. Hence, the partial discharge magnitude suddenly increases at the breakdown voltage. Therefore, the sudden increase rather than a set value determines the failure criterion.

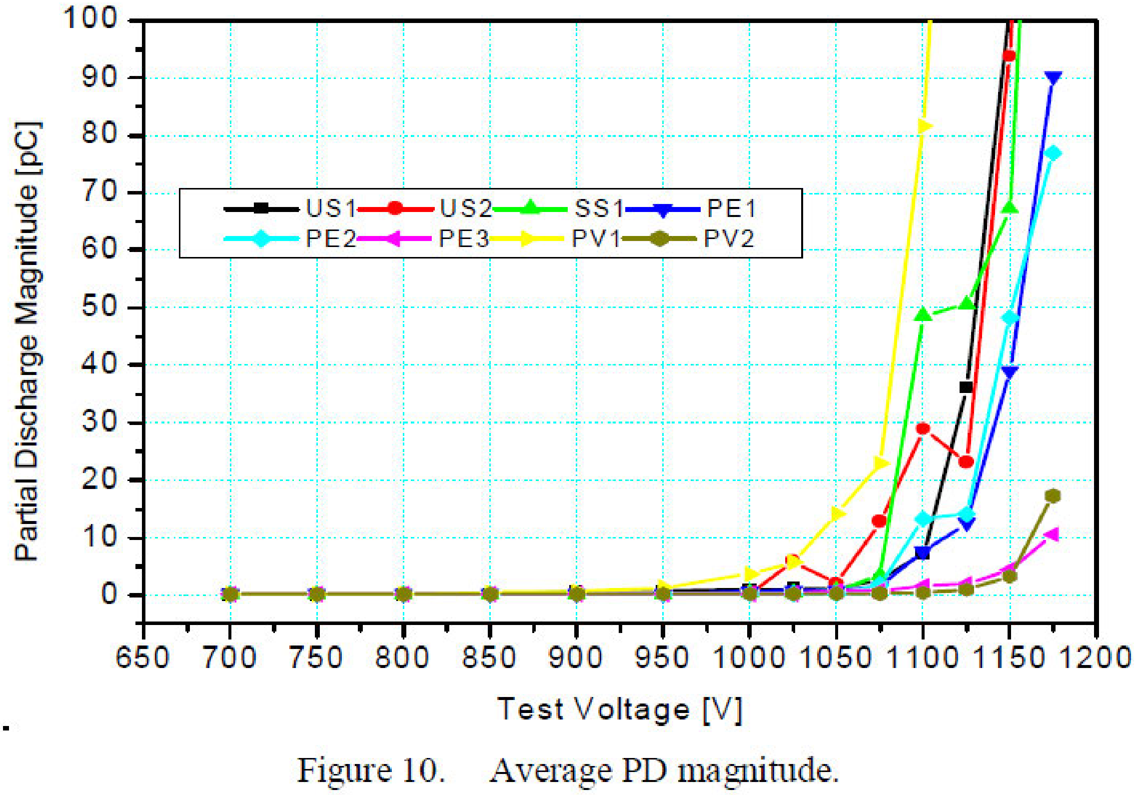

Figure 3.8 Average PD magnitude (Hwang et al. 2003, p. 435)

In another study, Tozz et al. (2011) established a severity index for partial discharge to estimate the severity, using the diagnostic criteria that may distinguish motors with partial discharge. The study examined four 400 V motors and completed off-line tests and on-line partial discharge tests. Motor B1 had a high amplitude but a lower repetition rate and remained in service. Motor B2 had a high amplitude and repetition rate, failing after 173 operating hours. Motor C1 did not have partial discharge except for the first hour of operation. Figure 3.10, Figure 3.11 and Figure 3.12 depicts the conditions. The severity index identifies the maximum magnitude and repetition rate in Figure 3.9.

$$I_x = Q_{max} \cdot N_w.$$

Figure 3.9 Severity index

In addition, Standards Australia (2001), The Institute of Electrical and Electronics Engineers (2014b) and Bélec et al. (2006) mention that the determination of partial discharge is not by partial discharge activity alone. Repetition is an essential factor in determining the severity of the PD.

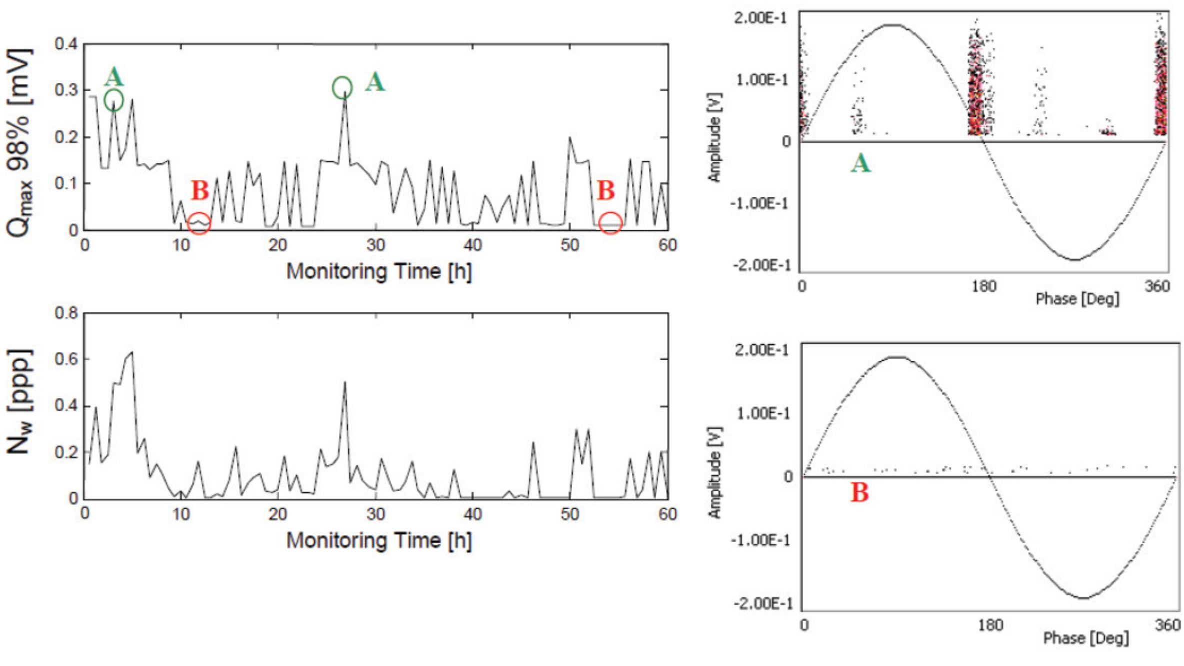

Figure 4. Variation of Q_{max} and N_w during 60 hours of monitoring motor B1. Partial discharge was detected during the monitoring session as shown in pattern A and was absent only for very short periods (pattern B and identified in red in the Q_{max} plot).

Figure 3.10 98th percentile of PD magnitude and phase plots for motor B1 (Tozz et al. 2011, p. 18)

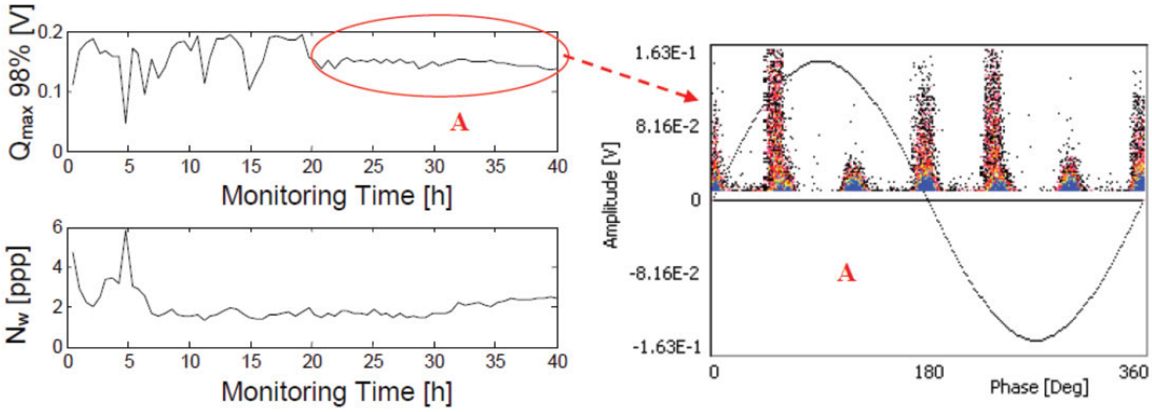

Figure 5. Q_{max} and N_w during 40 hours of running motor B2. A representative PRPD pattern acquired during the last 20 hours of operation is shown on the right.

Figure 3.11 98th percentile of PD magnitude and phase plots for motor B2 (Tozz et al. 2011, p. 18)

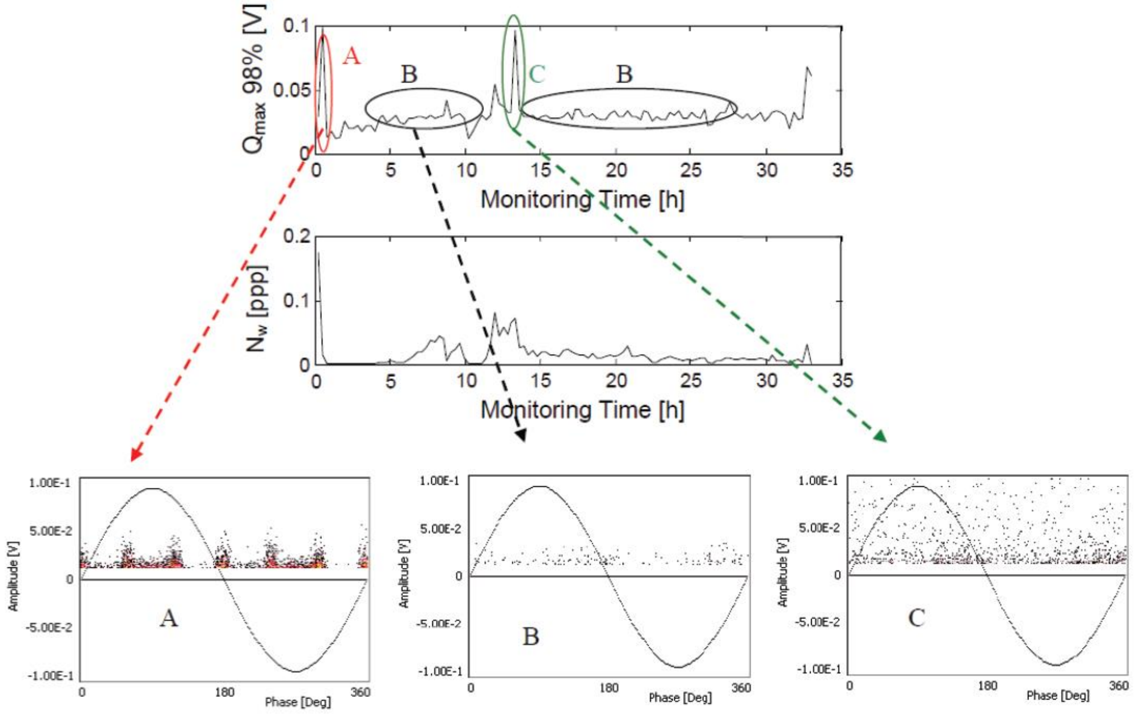

Figure 6. Q_{max} and N_w over the 33 hours of operating motor C1. Partial discharge was present for roughly the first hour (A). Thereafter only background noise was recorded (B and C).

Figure 3.12 98th percentile of PD magnitude and phase plots for motor C1 (Tozz et al. 2011, p. 17)

Tozz et al. (2011), study reviews the phase plots to inform the partial discharge results. The study indicates that the pattern B plot of motor B1 shows no partial discharge. The phase plot for motor B2 illustrates partial discharge. Pattern A of Figure 3.10, Figure 3.11, and Figure 3.12 show the partial discharge. The partial discharge is observed during the initial starting of the motors and then ceases; the study states that partial discharge during startup is normal. Pattern C of motor C1 in Figure 3.12 represents noise. The partial discharge testing of the motors provides information to assess the partial discharge patterns.

PD testing in LV cables is complex due to the lack of semiconductor layers. The semiconductor material in medium and high voltage cables has a high insulation resistance to reduce the leakage current in the cable. The lack of semiconductor layers in the low-voltage cable means the PD tester cannot distinguish between acceptable PD and the failure of PD (Paoletti & Golubev 1999). There have been small studies conducted for low-voltage cables. Even so, in one study, Tamus et al. (2009) realised the application of partial discharge for low-voltage cables. The approach involved measuring cable samples of coaxial communication and signal cables due to the simple construction of only one conductor. Whilst the study showed potential, the study recommends investigation of the samples with x-ray imaging to prove the results. The one conductor simple cable construction in the study signifies that varying types and sizes of low-voltage cables require more investigation than was completed in the study.

Additionally, PD has limitations in low-voltage applications due to the noisy environment. The study by Hwang et al. (2003) carries out partial discharge testing for motors in a noise-controlled environment; testing motors in situ would be the next logical progression. The electrical industry has yet to realise the benefit of partial discharge for low-voltage. More research is required to realise the benefit.

3.1.3 Thermal imaging

An established method for condition monitoring of electrical equipment is comparative qualitative thermography. This approach involves comparing the thermal pattern of one component to that of a similar component under similar operating conditions. The qualitative method detects hot spots in electrical equipment, hot electrical connections, and abnormally hot machine components (Standards Australia 2008).

In the condition monitoring study mentioned in section 2.4.1, Orman and Pinto (2013a) state that thermal imaging can detect soft foot by analysing the mounting bolt temperature. The higher temperature of the mounting bolt in Figure 3.13 appeared from the motor's vibration due to static eccentricity. A limitation of the research on thermal imaging is that monitoring abnormal temperature and temperature trends is not discussed in depth.

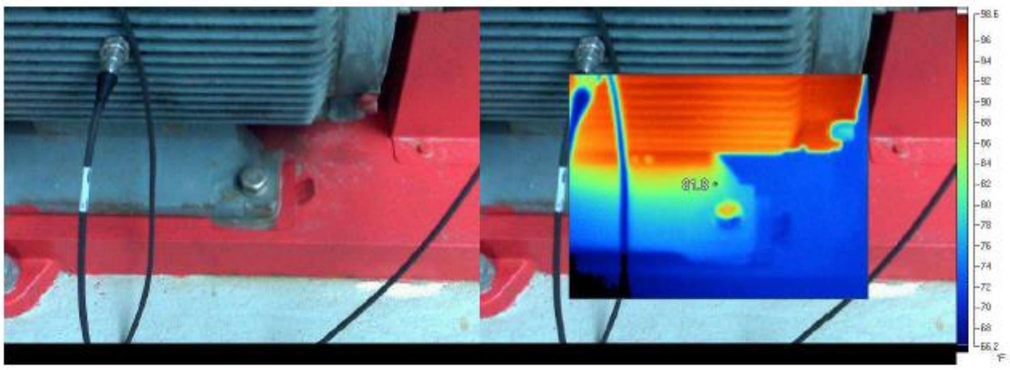

Fig.4. Thermal view of the foot bolt in case of the faulty motor.

Figure 3.13 Thermal view of the foot bolt in case of the faulty motor (Orman & Pinto 2013a, p. 466)

Shen et al. (2014) completed a study on over thirty amusement rides across five theme parks using FLIR infrared cameras. The study obtained the variation characteristics of the temperature and typical infrared images for electric motors and transformers. Figure 3.14 illustrates the results for a motor, and Figure 3.15 shows the results for a transformer. The research states that infrared thermography is a potential method for fault finding and monitoring amusement ride electrical equipment. The study shows initial promise but needs more detailed information on the methodology and the temperature variation results.

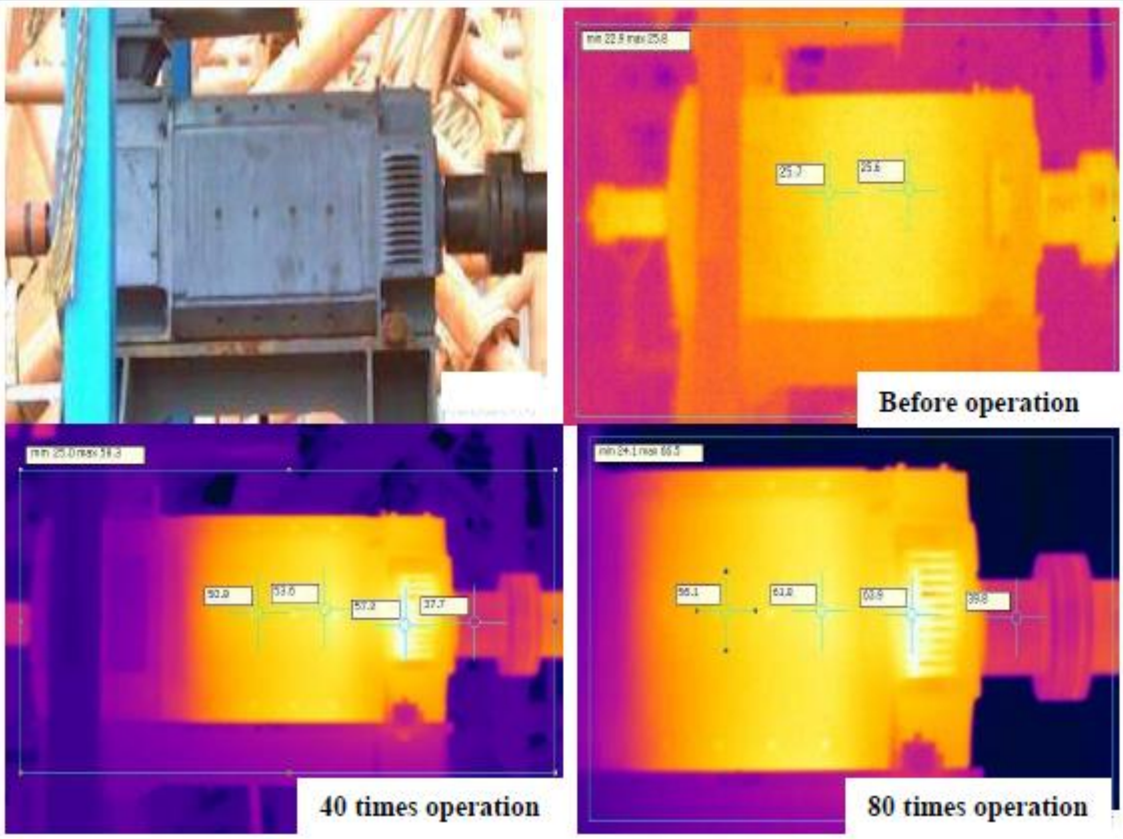

Fig.4 The photo and infrared images of a motor in a roller coaster

Figure 3.14 The photo and infrared images of a motor in a roller coaster (Shen et al. 2014, p. 3)

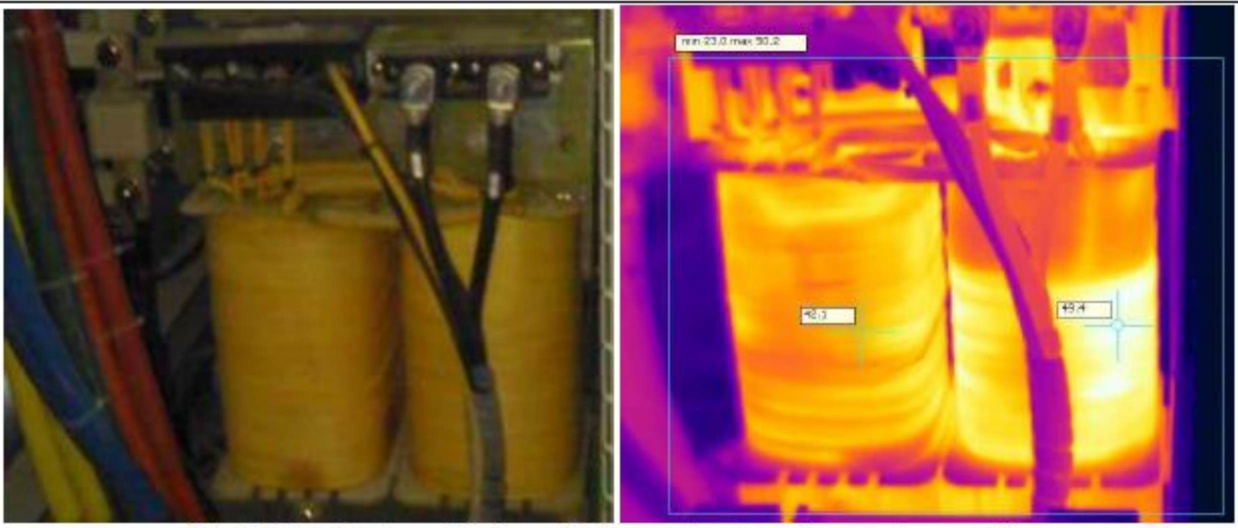

Fig.5 The photo and infrared image of a transformer in a surfers

Figure 3.15 The photo and infrared image of a transformer in a surfers (Shen et al. 2014, p. 4)

In another study by Shen et al. (2022), infrared thermography inspects rides to determine equipment safety. The peer-reviewed research discusses the temperature characteristics, approach and verification of the approach (Shen et al. 2022). The thermal images depict the infrared thermal imaging results. A healthy motor is shown in Figure 3.16, illustrated by the fan cover, which was lower in temperature than the casing. Although the casing temperature is high (approximately 36 °C), it has a uniform heat distribution with no abnormal temperature rises. The low temperature of the fan cover demonstrates proper natural air convection with no accumulation of heat. The temperature of the motors was compared to the ambient temperature of 25.3°C, showing a maximum temperature rise of more than ten degrees Celsius for the motors studied (Shen et al. 2022).

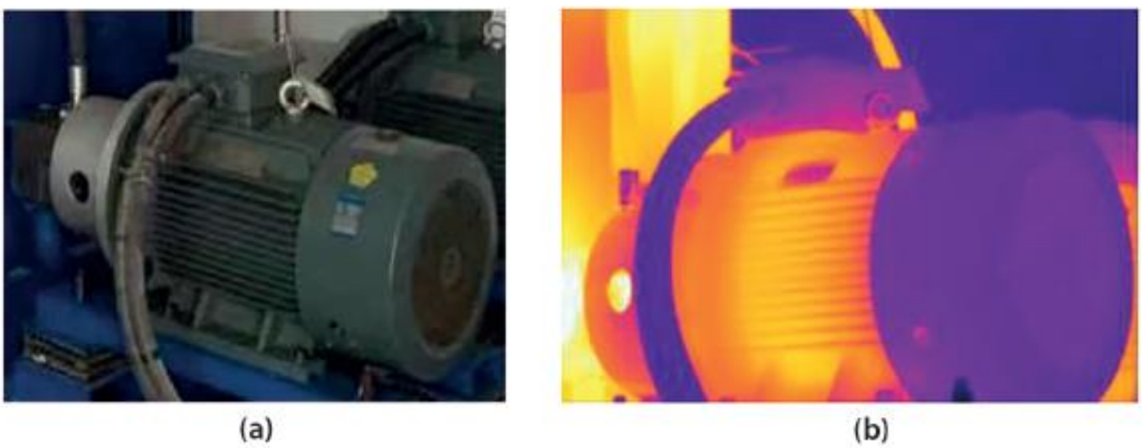

Figure 6. Visible image (a) and infrared thermal image (b) of a motor

Figure 3.16 Visible image (a) and infrared thermal image (b) of a motor (Shen et al. 2022, p. 15)

The study reviews the temperature rise of electrical components; Figure 3.17 shows the infrared thermography of electromagnetic relays. The white box depicts the high resistance of a conductor joint, which reached 31°C. The ambient temperature was 20°C, which meant the maximum temperature rise of the electrical components was (approximately) 12°C (Shen et al. 2022). Prior research has overlooked equipment degradation over time; therefore, the evaluation method included assigning a classification of degrees to the rise in temperature. The grading included four temperatures: normal, slightly high, very high and abnormal. The treatment method for each degree went no treatment, increasing inspection frequency, treating quickly and immediately. The results guided equipment and maintenance use by effectively identifying faults (Shen et al. 2022). Table 3.2 depicts the classifications and Table 3.3. depicts the temperature ranges.

Figure 9. Infrared thermal image of a typical electrical component

Figure 3.17 Infrared thermal image of a typical electrical component (Shen et al. 2022, p. 17)

Comprehensive degree	Rise in temperature and temperature	Degree of severity	Treatment method
I	Normal	Not serious	No treatment
II	Slightly high	Questionable	Increase inspection frequency
III	Very high	Serious	Treat quickly
IV	Abnormal	Very serious	Treat immediately

Table 3.2 Classification of infrared thermal imaging test results relating to large-scale amusement rides (Shen et al. 2022, p. 17)

Comprehensive degree	Rise in temperature grades for rolling bearings (ΔT)	Rise in temperature grades for electrical components (ΔT)	Hydraulic oil inlet temperature (t)
I	$\Delta T \leq 12℃$	$\Delta T \leq 1℃$	$t \leq 40℃$
II	$12℃ < \Delta T \leq 24℃$	$1℃ < \Delta T \leq 4℃$	$40℃ < t \leq 52℃$
III	$24℃ < \Delta T \leq 30℃$	$4℃ < \Delta T \leq 16℃$	$52℃ < t \leq 60℃$
IV	$\Delta T > 30℃$	$\Delta T > 16℃$	$t > 60℃$

Table 3.3 Criteria for the temperature rise grades of common parts of large-scale (Shen et al. 2022, p. 18)

The field measurement program could employ thermal imaging for electrical equipment and motors. The previous research details allow a good understanding of the expected results. While there is little published research on using thermal imaging for electrical equipment in amusement rides, there is ample research on using thermal imaging for electrical equipment.

Yu et al. (2019) imitated contactor fault conditions in another study. Thermal images of contactors help identify the defects and predict the remaining life of the contactor. The study described in section 2.4.4 concluded that the thermography effectively detected the varying abnormalities. Figure 3.18 illustrates the findings of the study. The images demonstrate the expected thermal imaging results for electrical equipment.

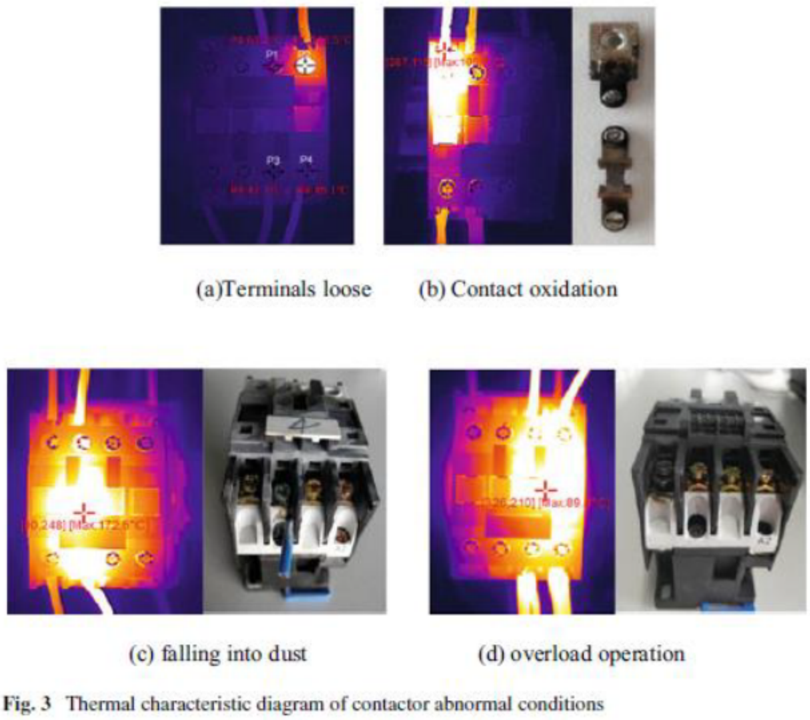

Figure 3.18 Abnormal conditions of thermal characteristic diagrams (Yu et al. 2019, p. 762)

Standards Australia (2008) states that quantitative thermography methods can be inaccurate for measurement if the emissivity is low. Standards Australia (2008) recommends qualitative methods in cases with low emissivity. Qualitative methods include comparing the thermal profile of similar equipment under similar operating conditions.

Experience and accumulation of data determine a severity criterion. The approach applies to different categories of equipment based on the design, manufacture, and installation conditions. The severity assessment criteria can determine the change in temperature and temperature rise above a defined reference. Historical information or statistically derived temperatures in the ideal condition set the criteria (Standards Australia 2008).

The research includes thermal imaging of electrical equipment in amusement rides. However, the research does not include water-based amusement rides. Measuring objects underwater is unable to be done with thermal imaging. The thermal camera cannot see through glass or walls; only the surface temperature can be measured (Sarawade & Charniya 2018).

3.1.4 Acoustic imaging

Acoustic imaging uses ultrasound to produce images of sound waves measured from a device. Acoustic monitoring of equipment has been growing in popularity. There has been research on acoustic imaging of amusement rides for condition monitoring. For example, Zhang et al. (2021) conducted a study on the rotating structure of an amusement ride to detect bearing anomalies. The study obtained the average RMS by testing carried out in the laboratory. The study used the average RMS to determine the baseline for comparison. While the research is relevant, removing an amusement ride to conduct laboratory testing is impractical.

Orman and Pinto (2013b) stated that acoustic imaging could detect static eccentricity, which can cause an increase in operating current, overheating and overload of bearings. The study compares the acoustic spectrum to the vibration analysis, which showed that for a 50 Hz supplied motor, eccentricity and soft foot presented at 100 Hz. The results are shown below in Figure 3.19.

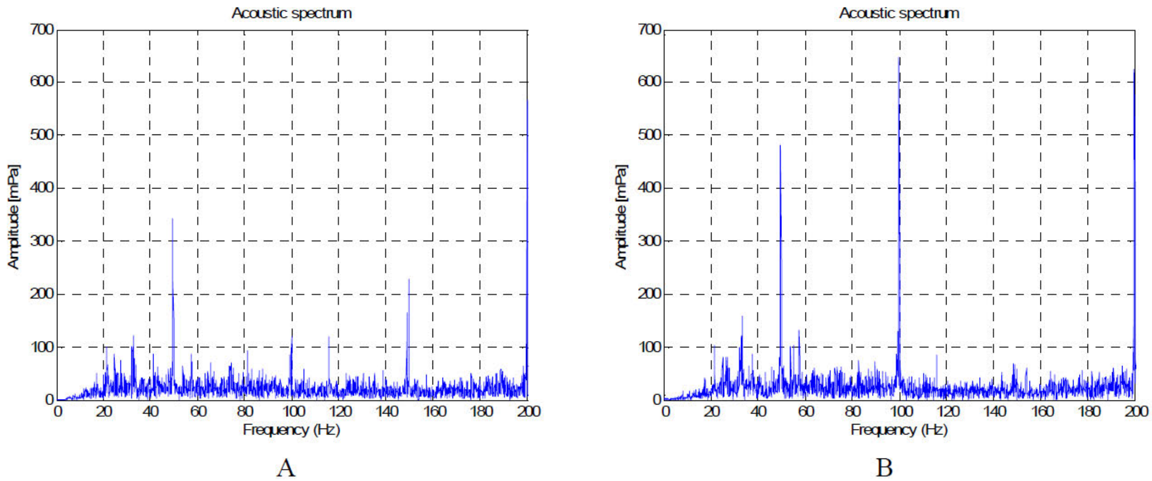

Fig.2. A – acoustic spectrum for healthy case; B – acoustic spectrum for combination of static eccentricity and soft foot

Figure 3.19 Acoustic spectrum of A a healthy motor and B a faulty motor (Orman & Pinto 2013a, p. 465)

The industry rarely conducts acoustic monitoring in an industrial environment due to the background noise. The study by Orman and Pinto (2013b) utilised the acoustic camera as it can localise the sound, consequently removing the background noise. The frequency at static eccentricity is in the low range; therefore, the study implements 0 Hz to 200 Hz for the testing. The 100 Hz acoustic image for the faulty motor is shown below in Figure 3.20. The red colour depicts the high motor sound at 100 Hz. Glowacz (2018) also tested faults in electric motors and stated that lower frequencies of less than 100 Hz are essential for condition monitoring.

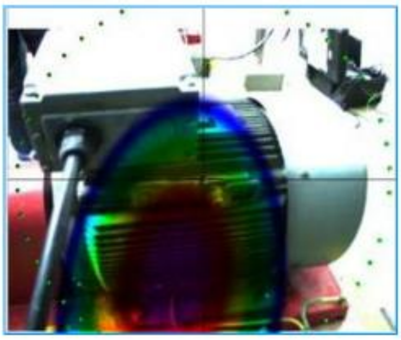

Fig. 4. Visualization of sound source

Figure 3.20 Visualisation of sound source (Orman & Pinto 2013b, p. 4)

Chapter 4. Methodology

The Chapter 3 review discusses predictive maintenance techniques for assessing the electrical safety of water-based amusement rides. There is a shortage of previous studies for amusement rides that investigate electrical safety, as outlined in section 2.5. Field testing will be carried out, analysed and discussed further to understand the electrical safety of water-based amusement rides. Initial field testing will be started during the thesis; the maximum long-term benefit will require regular testing with diligent record keeping. Due to the time restrictions, there will not be ongoing monitoring of the amusement rides. Initially, the ride drawings will be reviewed to ensure the hazards, testing locations and controls have been reflected in the testing procedure.

The most crucial consideration was the amusement rides for the testing. An existing relationship between Engenuity Solutions and VRTP was leveraged to obtain the required resources for the testing. Early in the consideration phase, Engenuity Solutions were approached to assist with the planning and executing process of the field testing. Engenuity Solutions agreed to assist, donate two power quality analysers, and hire a partial discharge tester for the amusement ride testing. From there, a proposal was produced to highlight the industry benefit and the methodology to gain VRTP's support in working with Engenuity Solutions to conduct field testing on their amusement rides. VRTP agreed to allow testing on their amusement rides, contribute site electricians, and use a thermal imaging camera. Moreover, another important consideration in field testing is the risks associated with people, property and the public. These risks have been considered, identified, and evaluated before testing.

Early detection of faults in amusement rides can prevent unexpected breakdowns, reducing time spent on fault finding and maintenance costs. The preventative maintenance field measurement program aims to extend the knowledge of techniques and implementation methods to improve the safety of electrical equipment for water-based amusement rides in the amusement industry.

4.1 Field testing techniques

The field testing considers four parts: power quality monitoring, partial discharge testing, thermal imaging, and acoustic imaging. This section discusses the techniques considered in the field testing.

4.1.1 Power quality monitoring

Detecting potential power quality problems can avoid interruptions to operation. The thesis will conduct a preventative power quality monitoring study to locate potential problems. Power quality problems can originate at the installation and the load, as discussed in section 2.4.3.

To review the amusement ride for all possible scenarios, power quality monitoring will be installed at the supply of the amusement ride and the largest load fed by a VSD where practicable. The power quality monitoring downstream of the VSD aims to identify if the variable speed drives generate harmonics. The testing will be over one week. This approach will require turning off the amusement ride for the connection and disconnecting the power quality analyser.

The testing will utilise a power quality analyser to conduct the testing. Engenuity Solutions has donated two power quality analysers for field testing: a Janitza UMG 512-PRO and a Fluke 435-II. The Janitza and Fluke analysers are class A meters as per IEC 61000-4-30. The IEC 61000-4-30 standard documents the standardised measurements for:

- Power frequency
- Magnitude of supply voltage
- Flicker (class F1)
- Supply sags and swells
- Voltage interruptions
- Unbalance
- Harmonics
- Interharmonics
- Mains signal voltage
- Downward and upward deviation
- Rapid voltage changes
- Measurements in the 2 kHz to 150 kHz frequency band
- Magnitude of the current
- Current unbalance
- Current harmonics
- Current interharmonics
- Recording of current along with voltage during events

Class A measurements lead to better evaluation and troubleshooting of power quality problems through accurate, dependable and comparable information. The identified analysers are an excellent choice for the power quality measurements of the amusement rides.

Figure 3.2 establishes the waveforms to ensure analysis of the power quality issues. The issues identified are 3.1.1 are harmonics, voltage sag, swell and interruption, under and over voltage, DC offset and transients.
To determine if there are any power quality problems with the amusement rides, the values to be measured

are:

- Line to line voltages
- Line to neutral voltages
- Active power
- Apparent power
- Reactive power
- Power factor
- Voltage,
- Current
- Frequency
- Hysteresis
- Transient events
- Flicker
- Harmonic voltage
- Harmonic current
- Total harmonic distortion

The power quality installation will consist of three voltage connections (one to each phase), a neutral connection and an Earth connection. The voltage connections can be installed anywhere at the main amusement ride switchboard, where the power to the ride is supplied.

In addition, four Rogowski coils will connect to the three phases and neutral to measure the AC. The polarity arrow on the Rogowski coils must point towards the load (including the neutral).

Upon completion of the installation, the readings on the meter will be inspected to ensure the power readings are positive, indicating that the Rogowski coils are in the correct direction. The power quality analyser will be left turned on to ensure the readings are stored. The results will be saved and analysed to detect potential power quality problems upon completion.

Section 3.1.1 details power quality monitoring and identifies possible problems. The analysis will review the testing results in accordance with the relevant Australian standards or industry guidelines. A guideline by The Institute of Electrical and Electronics Engineers (2014a) states the recommended practice for monitoring electric power quality. The guideline contains information about electrical characteristics with descriptions of power system phenomena. The guidelines could assist when analysing the data. For the voltage harmonics, the assumption is that the rides are class 3. Class 3 is where the point of coupling is inside the industrial plant. There are numerous standards; the analysis will discuss the reasoning behind the standards in more detail.

4.1.2 Partial discharge testing

PD testing detects loose connections and leakage current in motors and cables. PD testing can prevent outages through advanced warning. Long before the failure, PD testing can detect the progressive stages of leakage current. Partial discharge testing will be carried out during operation for the electrical equipment, including the switchboards and cables to the motors. The results will be recorded to establish baseline values.

The partial discharge research in section 3.1.2 illustrates the partial discharge through analysis of the severity of the partial discharge and the phase plots. The phase plots will be reviewed to assess if the partial discharge phase plots demonstrate partial discharge. In addition, Figure 3.9 depicts the severity index calculation that will be used to determine the severity, as previously discussed in section 2.1.2.

4.1.3 Thermal imaging

Thermal imaging effectively detects heating associated with high resistance, hot spots, excessive current flow, and hot machine components. The thermal imaging used the research from the literature review in section 3.1.3. Thermal imaging will be carried out for electrical equipment, including cable joints, equipment inside switchboards and control panels, and motors. The testing will be carried out during operating hours, as it requires the equipment to operate. The testing results will be recorded to establish the initial baseline values for the thermal imaging. The thermal imaging results will guide the maintenance of the electrical equipment, which can be used for targeted maintenance during outages to reduce unnecessary maintenance costs.

Following the thermal imaging, the results will be analysed against similar equipment under a similar load and categorised according to the temperature values in Table 3.3, as discussed in section 3.1.3. Due to the limitations of infrared thermography, underwater equipment will not be subject to thermal imaging. The equipment and suitability for thermal imaging of electrical equipment are important considerations in designing the field measurement program. Section 3.1.3 details that the Shen et al. (2014) study used Shen et al. (2014) FLIR thermal imaging cameras.

Teledyne FLIR (2019) declare that longwave spectral range (8 µm to 14 µm) thermal cameras are suitable for electrical inspections. For a general-purpose handheld camera, they recommend trying out the FLIR-Exx series. The series ranges from the FLIR E54 to the FLIR E96. The Teledyne FLIR (2021a) pamphlet details that the Exx thermal camera series is accurate to ±2°C or ±2% of the reading. Typical use will get two and a half hours of operation. Although the temperature range varies for the models, they all work from -20°C to 120°C. More specifications have been detailed in Table 4.1 below. The FLIR Exx series thermal cameras are suitable for electrical inspections; moreover, the advanced models are easier to use and cover a broader range of applications.

	FLIR E54	FLIR E76	FLIR E86	FLIR E96
Comparison	Entry	Good	Better	Best
Spectral range	7.5 – 14 µm	7.5 – 14 µm	7.5 – 14 µm	7.5 – 14 µm
IR resolution	320 × 240 pixels	320 × 240 pixels	464 × 348 pixels	640 × 480 pixels
Focus modes	Manual	Continuous and one-shot laser distance meter, one-shot contrast, manual	Continuous and one-shot laser distance meter, one-shot contrast, manual	Continuous and one-shot laser distance meter, one-shot contrast, manual
Digital zoom	1–4x continuous	1–4x continuous	1–4x continuous	1–8x continuous
Available lenses	None (fixed lens)	14°, 24°, 42°, macro (2x)	14°, 24°, 42°, macro (2x)	14°, 24°, 42°, macro (2x)

Table 4.1 FLIR Exx-series (Teledyne FLIR 2021a)

The measure of how effectively equipment radiates heat is labelled emissivity. Teledyne FLIR (2021b) asserts that a mirror that reflects all heat has an emissivity of zero, and a blackbody that absorbs all heat has an emissivity of one. An emissivity of 0.10 is expected from shiny metallic surfaces, and 0.90 is expected from matte paint. The surface of polished surfaces can act like a mirror, reflecting the temperature of the thermographer. Care must be taken when measuring polished surfaces to ensure the results do not reflect the temperature of the thermographer or the background temperature.

4.1.4 Acoustic imaging

The research carried out has been discussed in section 3.1.4. Acoustic imaging to detect bearing anomalies is impractical in testing an established amusement ride. For a fixed amusement ride, field testing of abnormalities of electrical motors with acoustic monitoring is feasible. The static eccentricity of a motor can lead to an increase in current and overheating.

The acoustic imaging was considered for the electrical motors associated with the water-based amusement rides to detect static eccentricity, as discussed in section 3.1.4. This approach is quick to perform and does not require removing power, making it an ideal predictive maintenance technique for an amusement ride.

Acoustic imaging was considered for the amusement rides' electrical motors. The acoustic monitoring frequency will be set between 0 Hz and 200 Hz. The camera will be aimed at the centre of the motor and positioned half a metre away. The results will be recorded and analysed.

The acoustic camera to utilise for field testing has been considered. Acoustic cameras typically operate in the bandwidth of kilo hertz due to being used primarily for leak detection and high-voltage partial discharge.

Fluke Corporation (2023) and Teledyne FLIR (2022) provide specifications for their acoustic cameras that start from 2 kHz. These would not be practical for the application due to the low range of frequency required; therefore, acoustic monitoring was not carried out due to the lack of suitable readily available equipment on the market.

4.1.5 Field testing summary

The initial field testing will be carried out for three water-based amusement rides. The results will be interpreted to ascertain the meaning and relevance of the information gathered. The test results and discussion will be written in the final six months of the thesis following the field testing.

4.2 Amusement Rides

In South East Queensland, VRTP has the largest number of amusement rides, which allows many rides for consideration. The legislative definition, as discussed in section 2.1.1, was used to select the amusement rides to ensure the validity of the results. Three water-based rides were selected from Movie World and Sea World. In this section, the physical characteristics of the rides have been discussed to provide context for the field testing.

4.2.1 Wild West Falls Adventure Ride

Figure 4.1 Wild West Falls final drop (Village Roadshow Theme Parks 2022a)

Wild West Falls is a family-friendly thrill ride located at Movie World. WhiteWater designed the ride, officially known as a Super Flume, a grander version of the Log Flume (WhiteWater 2022). The ride incorporates boats that hold up to eight riders. Riders are seated in pairs across four rows. Riders travel along a slow water channel where the momentum of the water pushes the boat along. The boat travels up the hill using a chain lift, where a turntable rotates the boat. A nine-meter reverse drop transports the riders in the dark over a small hill and back outside. The boat floats backwards to the end of a water channel and stops. Moving sideways, the boat slides along the back of the water channel and proceeds forward. Riders travel along another water channel where the speed increases. The boat transports the riders up the second lift hill and around the corner to another turntable. The boat rotates to face wooden doors, which slowly open. The boat launches forward down a twenty-meter drop where riders can reach speeds of up to 70 kilometres producing a substantial splash. After getting wet, the riders travel to a small conveyor and the unloading station (Village Roadshow Theme Parks 2022b).

4.2.2 Storm Coaster

Figure 4.2 Storm Coaster tunnel entrance (Seipelt 2013)

Storm Coaster is a water coaster ride with a 470-metre-long track designed by MACK Rides (Mack Rides GmbH & Co KG 2017b). The family thrill ride is located at Sea World. Riders are seated in a boat that holds up to eight riders across four rows. The Storm Coaster track is 470 metres long. Riders start in the water and travel along an indoor section of the roller coaster track. A chain lift transports the boat up 28 meters to the top of the track. Once at the top, the boat slants right and travels slightly down, curving to the right. Riders travel along a small, straight section of track. Once at the end, the boat launches down and round a loop at over 70 kilometres. At the bottom of the track, the boat travels into a short concrete tunnel and out down another slope. Riders travel through another tunnel in the dark where a 20-metre wave splashes them. The boat travels through the tunnel, including strobe lighting, sound effects and a small waterfall, to the end of the ride.

4.2.3 Battle Boats

Figure 4.3 Battle Boats ride (Warner World Australia & Village Theme Park Management 2020)

Located at Sea World is the interactive family ride Battle Boats. Designed by Mack Rides GmbH & Co KG (2017a), the interactive boat ride features eight seats fitted with on-board water cannons. Riders face outwards where they aim at the pedestrians. Additional water cannons are onshore for aiming towards the boats; the fun-filled family ride travels at approximately half a metre per second. The low speed and interactive water cannons make the ride a crowd favourite for the whole family.

4.3 Risk Management Plan

Engenuity Solutions has policies and procedures for hazards and risk management. The management team, including the principal RPEQ electrical engineer at Engenuity Solutions, carried out and reviewed a job safety and environmental analysis. Arc flash was a serious hazard considered. Engenuity Solutions' existing ride power systems models were used to analyse the arc flash. Engenuity continuously updates the power system models with installation changes to amusement rides. As Australia does not currently have an arc flash standard, it is accepted within the industry to utilise the IEEE Guide for performing arc flash calculations. The arc flash levels at the rides were assessed based on the IEEE 1584:2018 Guide for Performing Arc Flash Calculations and the Electrical Arc Flash Hazard Management Guideline published by the Australia Energy Council. The calculations were carried out before testing to assess the current arc flash levels.

In Australia, the industry sets the acceptable incident energy for bare skin at 1.2 cal/cm^2, the exposure that may inflict a curable second degree burn (AGL Macquarie 2018). For this reason, 1.2 cal/cm^2 was the level of exposure deemed acceptable to proceed with the testing. The partial discharge testing and thermal imaging are carried out while the equipment is in operation; therefore, these tests were not carried out if the arc flash level was over 1.2 cal/cm^2. As the amusement ride is isolated before installing the power quality monitoring, the testing would still be conducted after the isolation of the amusement ride.

4.4 Correspondence with Asset Owners

Engenuity and VRTP discussed the hazards and risk management to align on how the field testing would be completed. Due to insurance, it was decided that the existing VRTP electricians would install the power quality analysers and complete the field testing. The oversight of the field testing was covered by Engenuity Solution's insurance due to the pre-existing business relationship.

Additionally, the timing of the field testing was discussed with VRTP to find agreeable dates for both parties. It was agreed that the ride testing for the three amusement rides would be carried out in succession. It was decided that the ride testing would be conducted over three sequential weeks. On the day of testing, the amusement rides would operate as usual, except the rides would not be shut down at closing time. The timing of the testing is to ensure the testing is completed when the rides have been operational all day.

4.5 Expected Outcomes

The data obtained is the most important aspect of field testing; furthermore, it is also the most time-consuming. The information must be accurate and reflect the amusement ride installation. Inaccurate data will affect the rationality of the thesis.

The water-based amusement rides operate at Movie World and Sea World. The initial testing expects to show predictable results in the normal range. The results can be used as a starting point for long-term predictive maintenance to inform the expected values of the amusement rides when they are operating as expected.

The expected data is the testing results from the upstream and downstream power quality analysers, the partial discharge tester and the thermal imaging camera.

Power quality and thermal imaging are regularly carried out in industry with known expected values. Partial discharge is regularly carried out for medium and high-voltage equipment, but has yet to be assessed for low-voltage equipment. Therefore, the expected results are still being determined.

Chapter 5. Discussion

This section analyses the test results and presents the information. The discussion considers the data's methodology, reliability, and validity to assess the information's significance. It was important to analyse the ride drawings and the testing location when reviewing the test results for accurate understanding. Furthermore, it was essential to collect the operating state of the electrical equipment because the interpretation of the results varies depending on the operating state of the equipment. The drawings and test results for the amusement rides are labelled amusement rides one, two, and three to protect the intellectual property rights of the original ride manufacturer (OEM). The discussion includes the challenges, data collection and analysis of the results. Furthermore, the limitations of the field testing are acknowledged and discussed.

5.1 Challenges

The theme parks engage in continuous maintenance, new installations and themed events throughout the year. The field testing followed the term two school holidays to ensure the electricians had adequate time. The testing schedule had to account for maintenance and ride operating times to ensure personnel and ride availability. Rescheduling the testing was not an option due to the tight timeframe. After testing, one of the rides went into a nine-week maintenance shutdown; therefore, additional testing was impractical.

The power quality monitoring installation could not interrupt the normal operation of the ride. The power quality analyser also requires a power supply to record the harmonic information. However, there was not always a power source located locally. Additionally, the physical size of the power quality analyser added another element of complexity. The installation of the analyser had to be in a safe location out of reach of the public. There was one amusement ride where these requirements aligned to allow the installation of the power quality analyser downstream of the variable speed drive. Unfortunately, the power quality analyser did not retain the recorded information upon review.

In addition, the water-based amusement rides have submersible motors. The underwater location of the motors makes maintenance and condition monitoring challenging. The motor location meant thermal imaging was not advisable. As expected, the thermal imaging camera could not detect the temperature of the motors.

5.2 Data collection

The power quality information from the Fluke power quality analyser was downloaded between sites, as it could be completed quickly. The Janitza power quality analyser requires a more extended timeframe to download the data. Moreover, the information was downloaded from the Janitza for the three amusement rides at the end of the testing. During the thesis, data was collected from the partial discharge tester and the thermal imaging camera the day after the testing. To allow time to download, transmit the information and ensure the information was collected for each amusement ride.

5.3 Analysis of the Results

The results have been reviewed and summarised. The results contained a mixture of expected and unexpected information. This section scrutinises the data and deliberates on the possible causes of the discrepancies. The amusement rides are installed in different locations at Sea World and Movie World. Consequently, the rides are fed from different transformers. Additionally, the high-voltage infrastructure is owned by VRTP at one of the sites. The high-voltage infrastructure is not owned at the other site where the electricity supply authority owns the high-voltage infrastructure; the requirements in the standards differ for assets owned by the electricity supply authority.

All three rides consist of a main switchboard that supplies the electrical equipment, including the motors, brakes, power supplies, and downstream distribution boards. The short-circuit current at the ride switchboard has been mentioned for each water-based amusement ride. Electrical equipment subjected to higher short-circuit currents is at greater risk of catastrophic failure; therefore, the short-circuit current is an important consideration in a preventative maintenance program. The short-circuit current for each ride has been specified on the drawings located in the appendices.

5.3.1 Power quality monitoring

The ride drawings in Appendix B show the installation of the power quality analyser at the amusement ride incomer. The settings varied between analysers: ten-minute intervals for the Janitza power quality analyser and five-second internals for the Fluke. Shorter intervals calculate the average calculation interval. Shorter intervals on the Fluke analyser are used to calculate the average interval. Rogowski coils were used for the measurements. A study by Ward and Exon (1993) states that Rogowski coils are used for a wide frequency range with transient DC offsets. While a current transformer can be unreliable in the early stages of a transient, Rogowski coils can cope with large current fluctuations. Upon reviewing the power quality analyser information, two amusement rides showed that one phase had less current than the other. The two amusement rides affected had the Janitza power quality analyser installed for the readings. The Amusement Ride 2 current graph is shown in Figure 5.1 below.

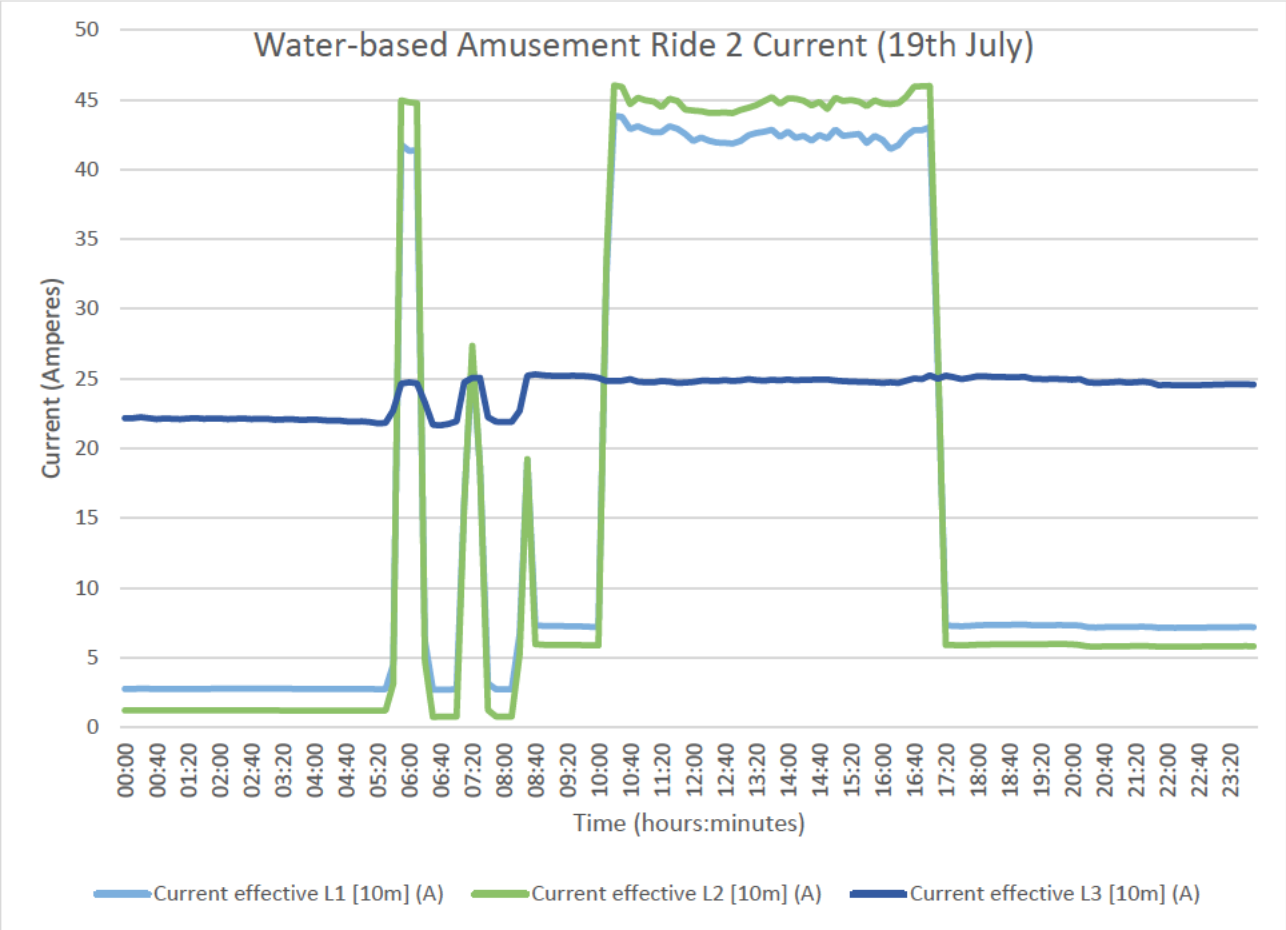

Figure 5.1 Water-based Amusement Ride 2 three-phase current on the 19th of July 2023

The graph indicates that the L3 current for the water-based Amusement Ride 2 is on overnight at 22 A, while the other two phases have a current of less than 5 A. The current for all three phases should be zero, as the amusement ride is on standby. During the testing of Amusement Ride 3, there was an additional challenge: the main isolator handle broke apart when it was time to re-energise the amusement ride, leaving the ride power unable to be restored. The graph in Figure 5.2 is from the day of testing for Amusement Ride 3. The failure happened after business hours, so a new handle was purchased the following day. It would have been impossible for the current to have been on when indicated in the graph.

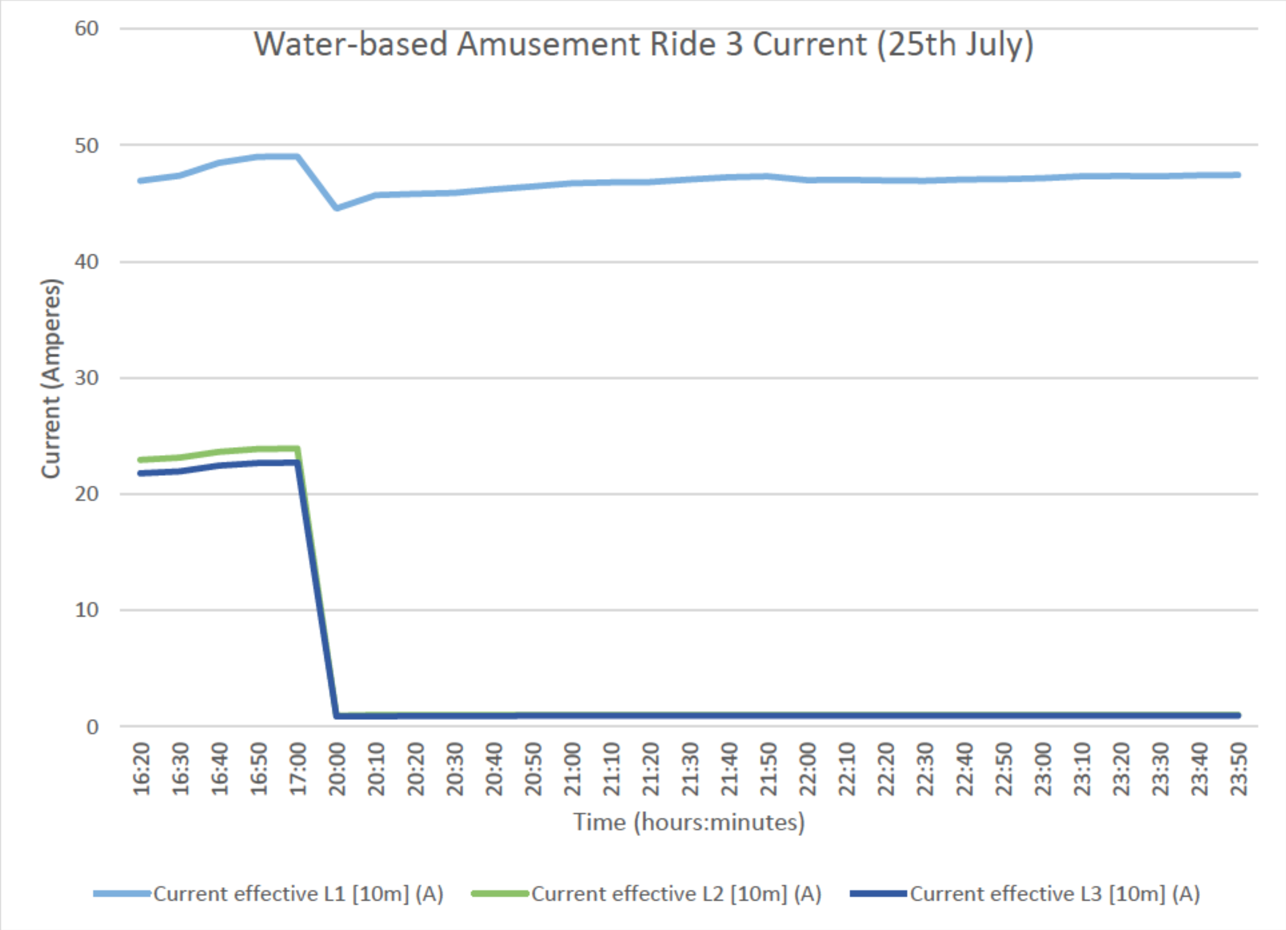

Figure 5.2 Water-based Amusement Ride 3 three-phase current on the 25th of July 2023

The Janitza and Fluke, power quality analysers were connected to a known supply and compared to confirm the hypothesis. The power quality analyser measures the power for two hours; the Rogowski coil then moves to the following input to identify the issue. Figure 5.3 shows that the L1 current is 1 A below L2 and L3. The Fluke power quality analyser measured approximately 0.8 A more than the Janitza L2 and L3 measurements. The current transformers were measuring lower when connected to the L1 input.

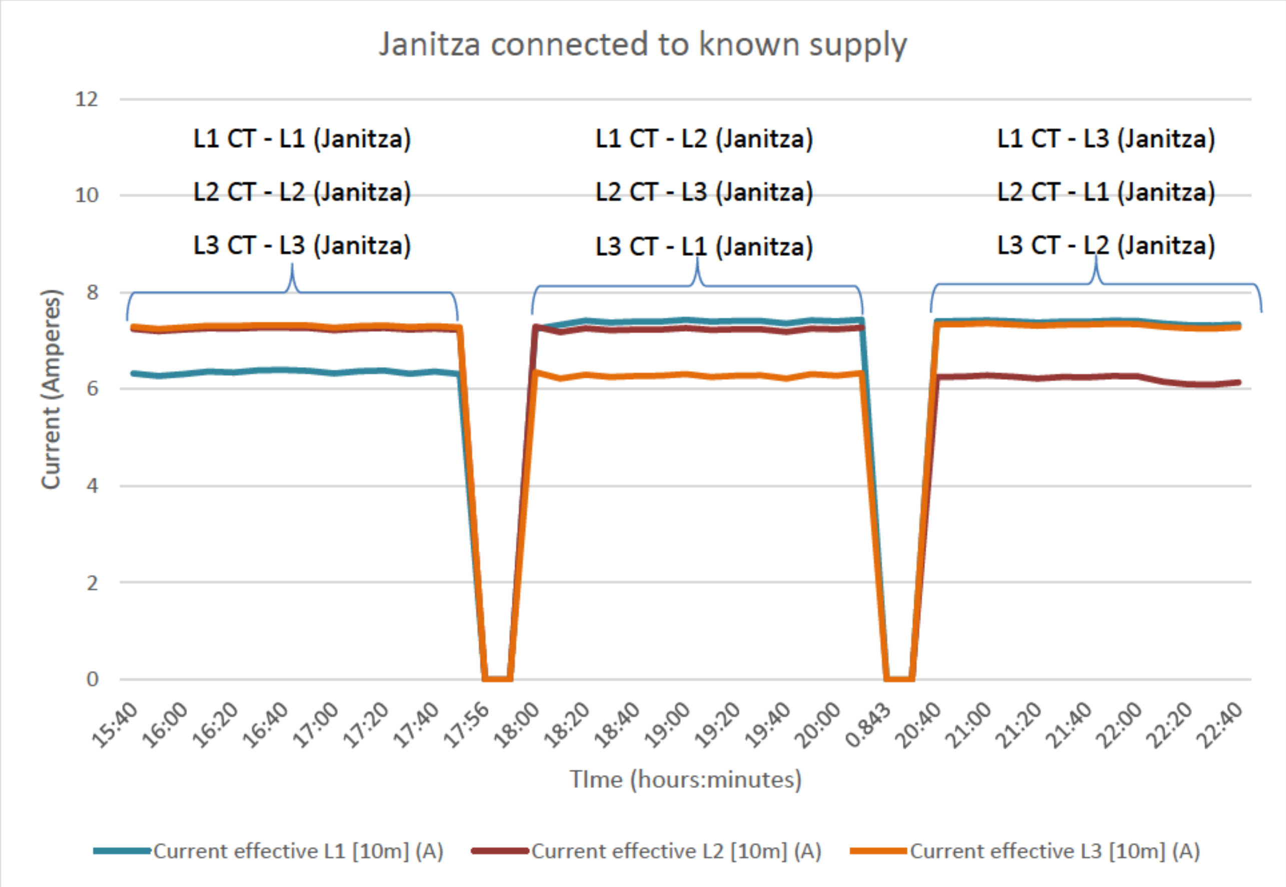

Figure 5.3 Janitza power quality analyser current measurements

Upon review, the Janitza settings were programmed correctly with the correct current transformer ratio and the same settings across the three phases. Once the testing had been carried out with the Janitza analyser in the current state, the connections for the current transformers were opened to check the terminations. It was discovered that the L3 plug had a disconnected Earth connection, and the L4 plug had a disconnected wire. The Janitza has four transducers that convert the signal for measurement. The next step is to do the same test on the Janitza, moving the connections between the transducers, to see if the results indicate an abnormality with the transducers. Consequently, the information cannot be relied upon for accuracy. The remainder of the power quality discussion will focus on the water-based Amusement Ride 1.

Amusement Ride 1 consists predominantly of three-phase motors, which are inductive. The inductive motors produce power that opposes the desired flow, reducing the power factor. The power factor results were plotted in Figure 5.4 to explore the theory. The results show that the power factor is 327.67, outside the acceptable range between zero and one. The large power factor result is impossible; it is theorised that the irregularity is due to a processing error in the power quality analyser. Additionally, the graph shows considerable power during the start of the amusement ride. A shorter startup cycle was plotted in Figure 5.5 to allow additional analysis.

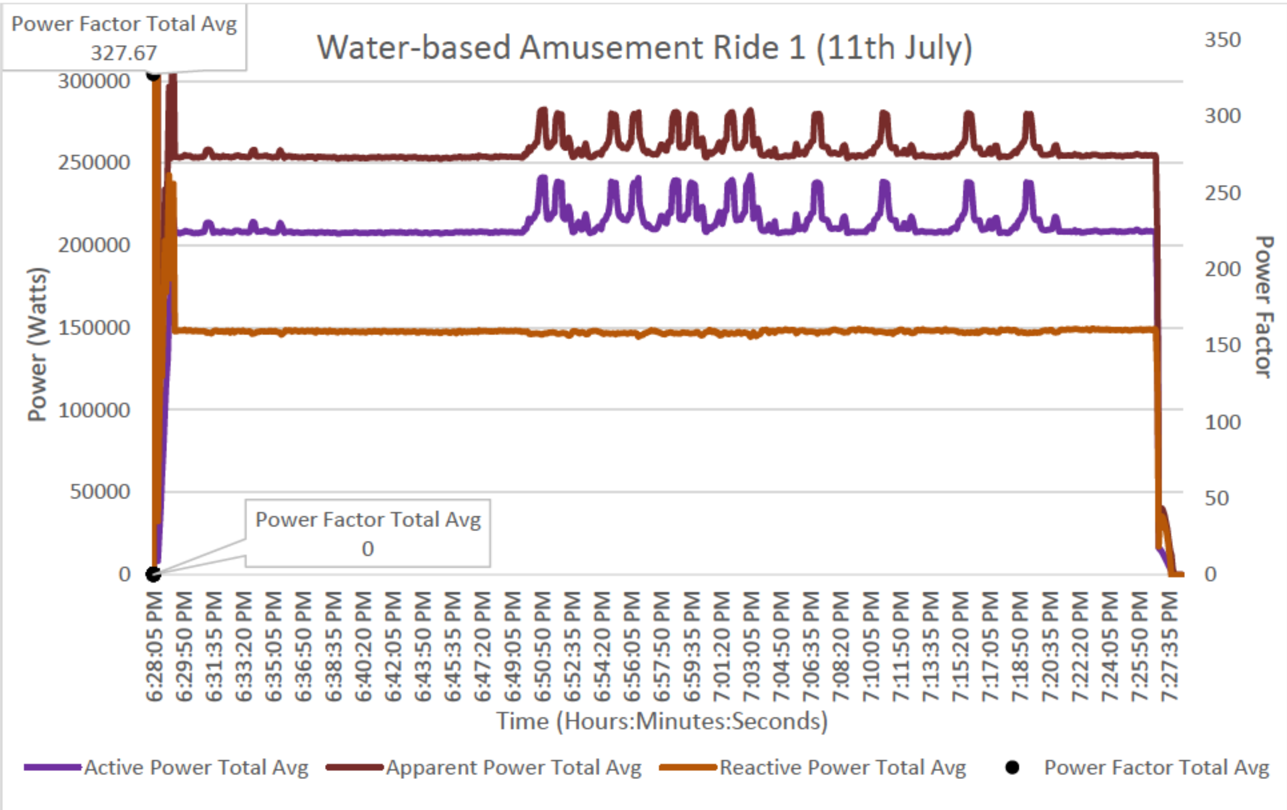

Figure 5.4 Water-based Amusement Ride 1 three-phase power on the 11th of July

The results show a low power factor when the reactive power is highest during the start. The power factor then increases to 0.82 when the reactive power is lowest. During starting, the considerable reactive power reduces after 10 seconds and stabilises after 1 minute and 10 seconds. Reactive power is the consequence of the voltage and current not being in phase. The results were further analysed to obtain the current readings during the startup of the ride.

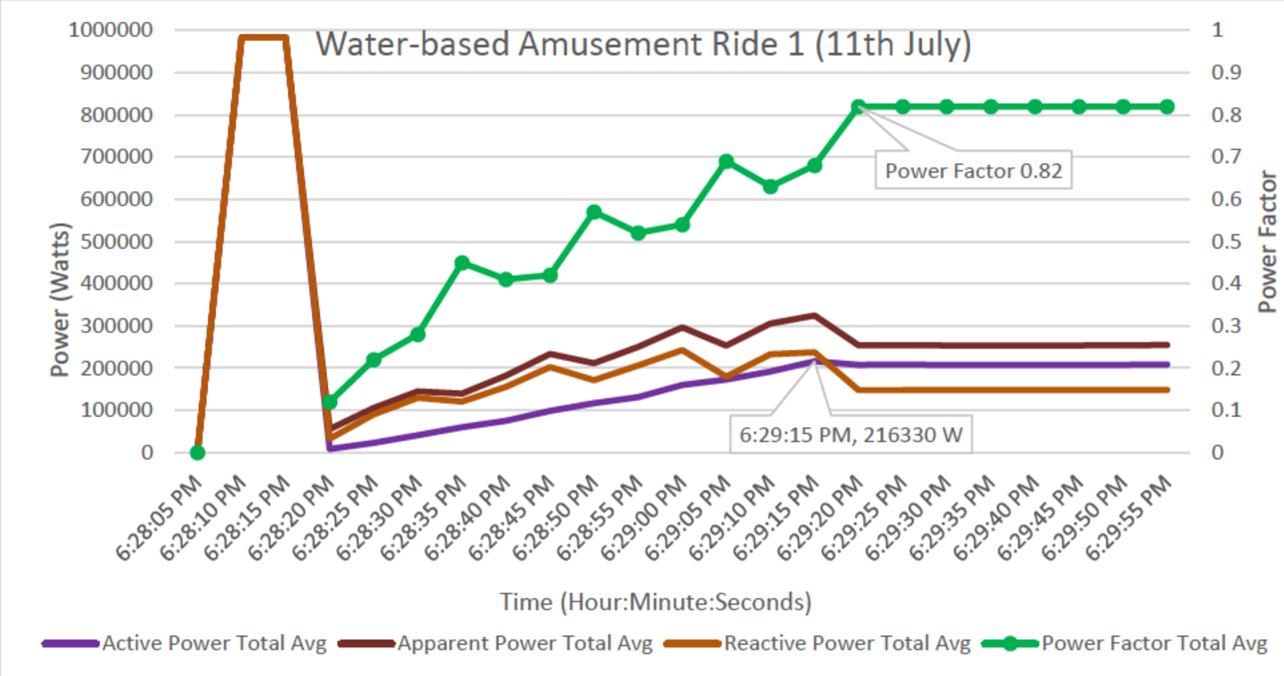

Figure 5.5 Water-based Amusement Ride 1 three-phase power and power factor

The current results were inconsistent across the ride's three phases, with the largest phase being L1. The current recorded was 6277 A; this current did not change the magnitude of the two readings. The inconsistent results indicate that the power quality analyser measurements are incorrect. Further analysis of the voltage and current waveforms show transients. Figure 5.6 illustrates the L1 transient on the 11th of July. Oscillatory transients happen when there is a sudden change in the steady-state condition during the switching of inductive or capacitive loads. The load resists the change, resulting in an oscillatory transient. In this case, the transient occurs during the startup of the ride. The transients were present at startup during the power quality monitoring. The current leads the voltage, leading current occurs in circuits with capacitive loads.

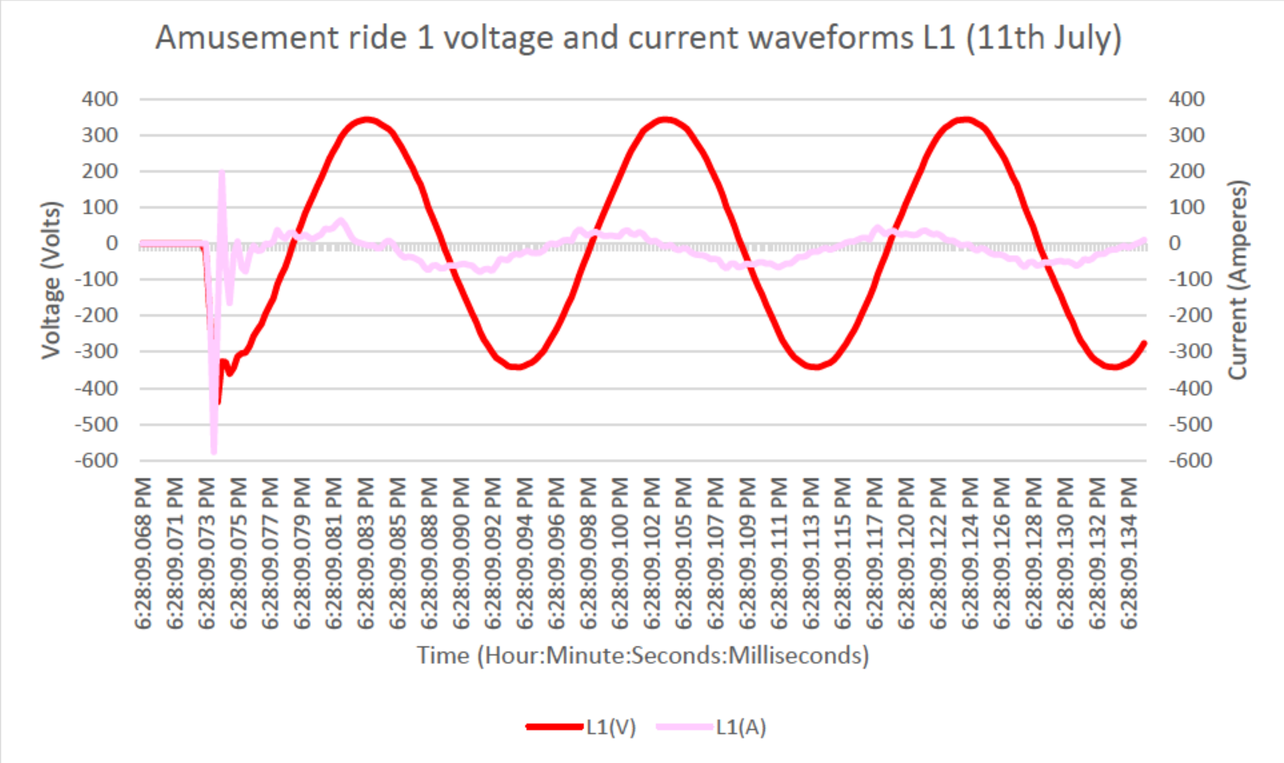

Figure 5.6 Water-based Amusement Ride 1 L1 voltage and current waveforms

The Institute of Electrical and Electronics Engineers (2014a) discusses transient waveforms in power quality analysis. Introducing a capacitor to a circuit can cause a switching current, resulting in a corresponding voltage transient. The waveforms are inspected, and voltage transients were present in Figure 5.7. The voltage transients are from the introduction of a capacitor. The capacitor draws current from the supply when the capacitive load is introduced to the circuit. They are resulting in the voltage transient's leading edge being negative. Introducing a capacitive load to an inductive power system with resonant frequencies can result in an oscillatory transient (The Institute of Electrical and Electronics Engineers 2014a).

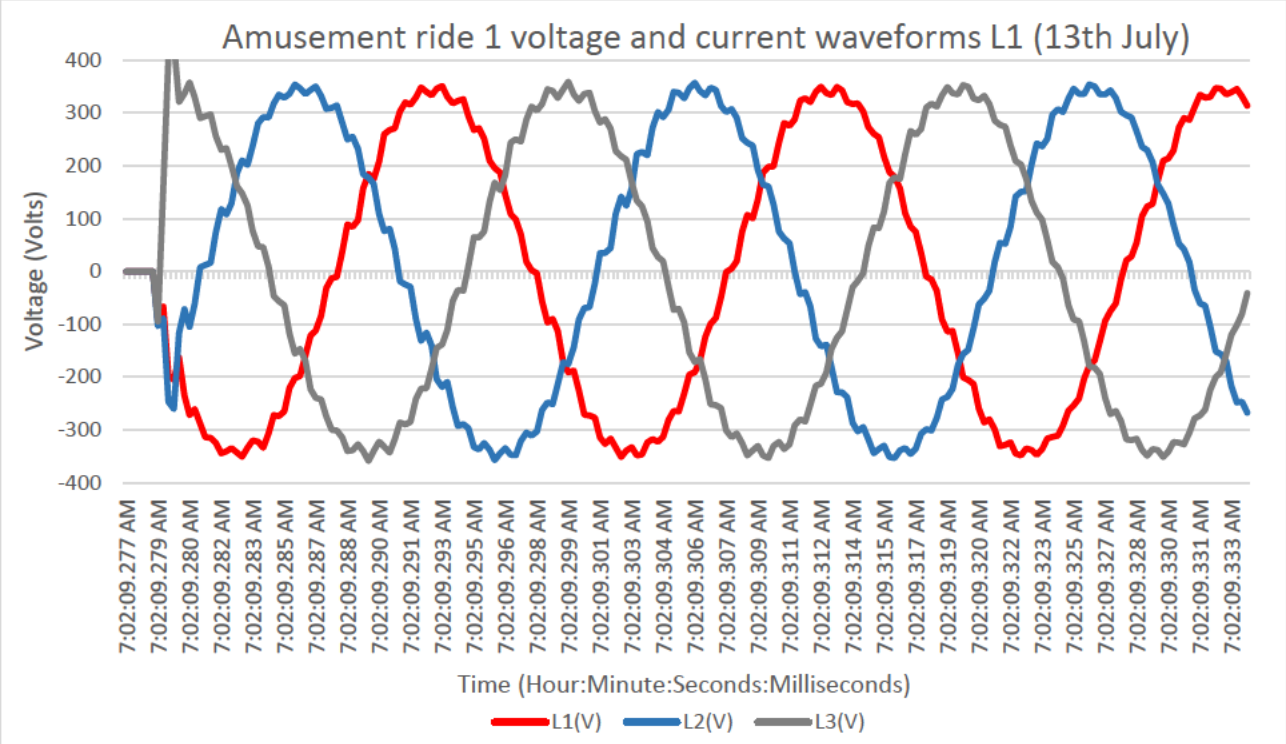

Figure 5.7 Water-based Amusement Ride 1 L1 voltage waveforms

The oscillatory current transient is shown in Figure 5.8. The design has considered capacitor switching with the installation of line filters to dampen the oscillatory transient. The transients last 200 milliseconds or 0.2 of a second. In addition, the three-phase current waveforms are displaced from the zero point. Displacement from the zero point is typical where there is DC present in an alternating current power system, and the phenomenon is labelled DC offset. The presence of transients during startup is not a critical event. However, the presence of a DC offset is unexpected.

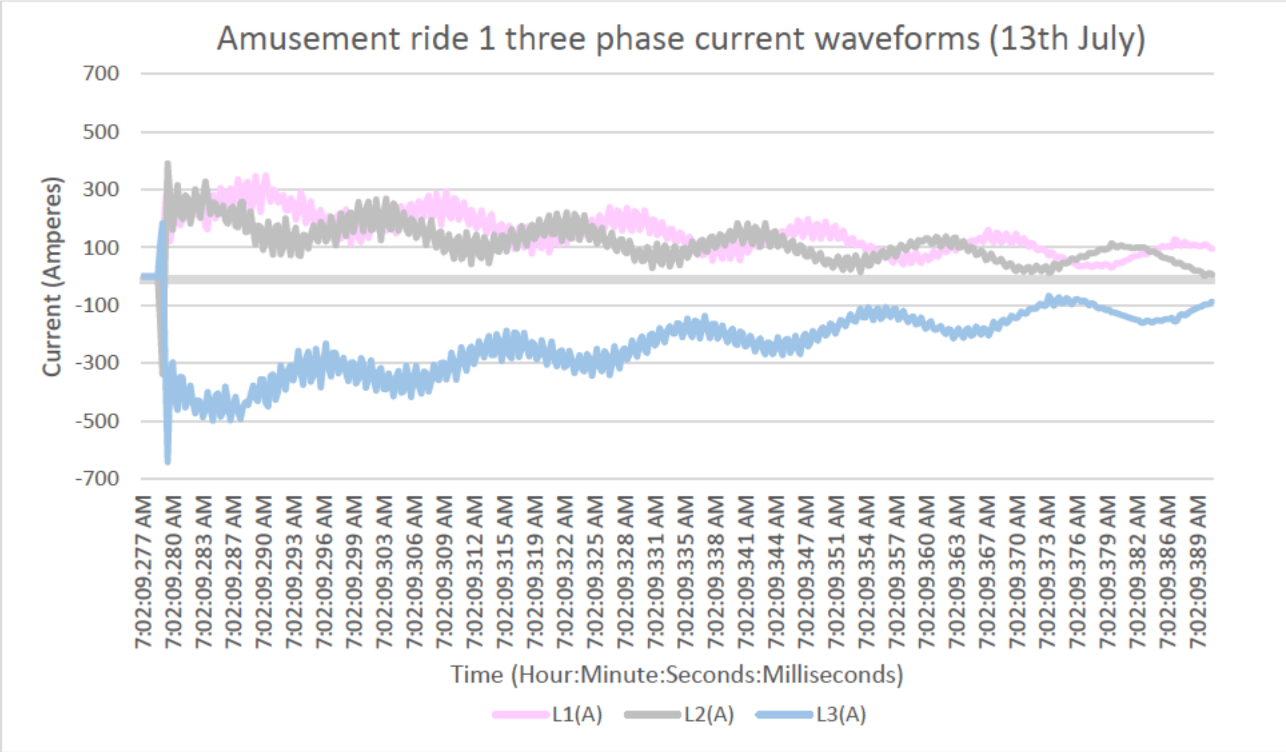

Figure 5.8 Water-based Amusement Ride 1 three-phase current waveforms

DC offset can be caused by inducted voltages or failure of AC to DC power converters. The current waveforms also show noise superimposed on the transient. Power electronic equipment, control circuits, and arcing are possible noise causes. Further ride testing is recommended to identify the cause of the DC offset.

As previously discussed in section 4.1.1, the testing includes an examination of the harmonic distortion. There are two considerations regarding harmonics: the current and the voltage harmonic distortion. Supply harmonics can be generated by non-linear loads drawing non-sinusoidal currents. The resulting non-linear voltage drops distort the voltage waveform. Currents or voltages with a frequency that is a multiple of the fundamental frequency are defined as harmonics. The supply current harmonics are illustrated in Figure 5.9 for the water-based Amusement Ride 1.

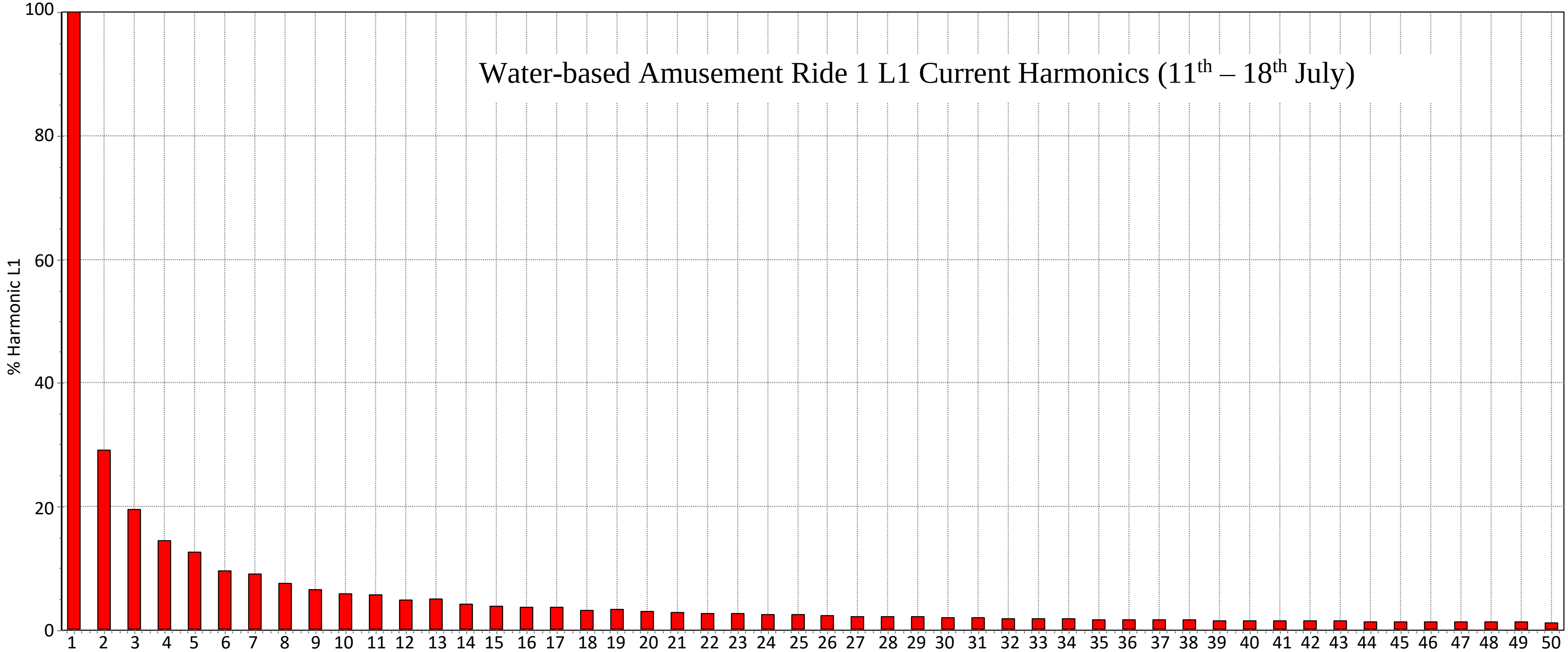

Figure 5.9 Water-based Amusement Ride 1 L1 current harmonics on the 11th until the 18th of July

The fundamental or first harmonic is 100%, and the current harmonics decrease as the frequency increases. The results for the current harmonics are very high, with the second harmonic at 29%. The water-based Amusement Ride 1 includes VSDs, which generate harmonic currents associated with the variable output frequency. The VSDs include line filters to reduce the harmonics, meaning the expected values should be less than is indicated. To analyse the results, there must be an understanding of the expected harmonic levels. Upon review, it was found that Standards Australia (2023a), identifies that harmonic current levels are evaluated during steady-state operation and, therefore, do not include transients. Harmonics and transients are different phenomena that are analysed differently. Transients are brief frequency changes lasting only microseconds, resulting from lightning or a switching event. In comparison, harmonics are present during steady-state operation. In the harmonic analysis, it was necessary to recognise that introducing transients could provide results that are not reflective of the actual harmonics in the system. The time window for the current harmonics was reduced to ensure only harmonics during steady-state operation were exported. The results are illustrated in Figure 5.10, which shows a substantial decrease in the current harmonics.

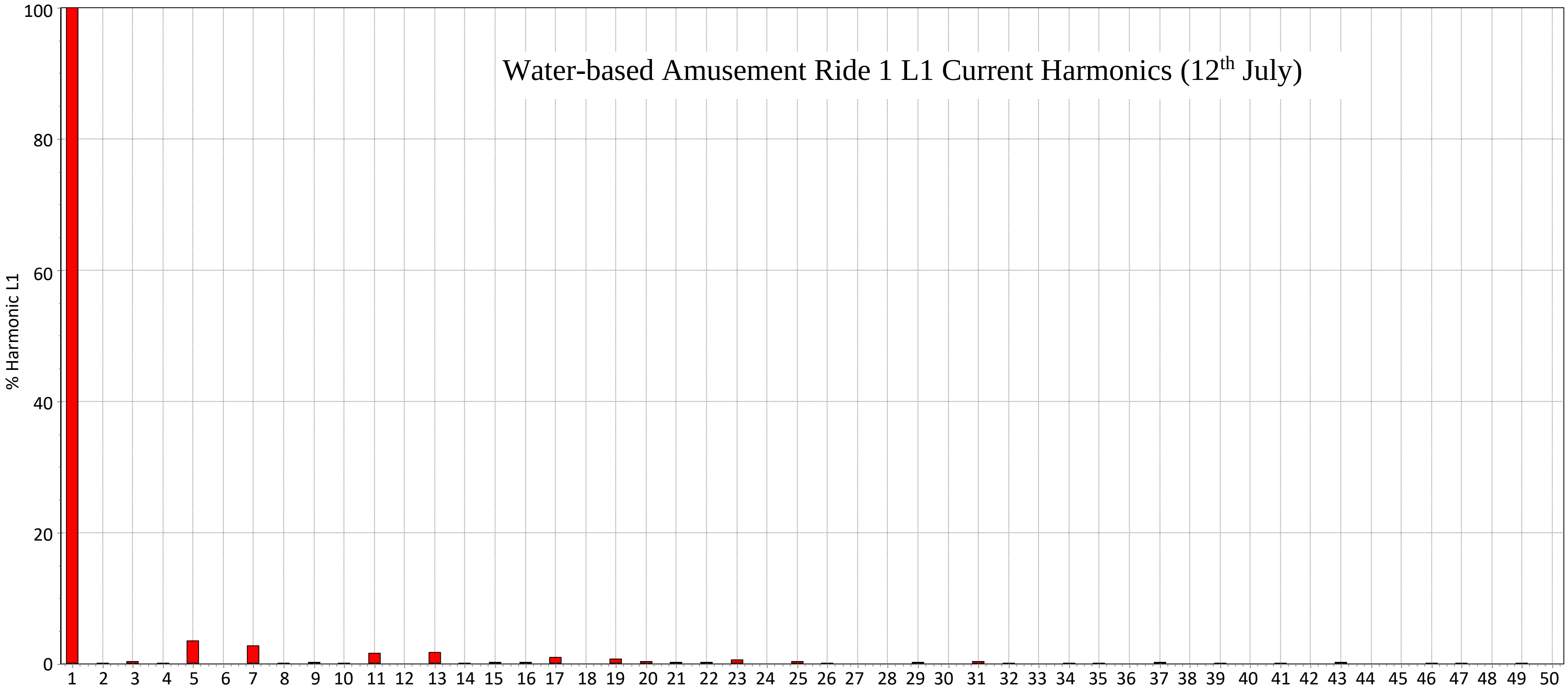

Figure 5.10 Water-based Amusement Ride 1 L1 current harmonics on the 12th of July

The fifth harmonic current is 3.70%, and the 7th is 2.90%. High harmonic currents in the fifth and seventh harmonic usually occur where three-phase rectifiers are present (The Institute of Electrical and Electronics Engineers 2014a). The consideration of harmonics is important in the water-based amusement rides due to the number of three-phase rectifiers. Two Australian harmonic standards limit harmonic current emissions into the supply system: AS/NZS IEC 61000.3.2 and AS/NZS

IEC 61000.3.12. AS/NZS IEC 61000.3.12 is intended for equipment above 16 A and equal to or less than 75 A. This standard was chosen for the analysis as the smallest drive has a current rating of 19 A. Standards Australia (2023a) applies to equipment connected to the public supply system. As discussed in section 5.3, VRTP owns the supply system; thus, the requirements do not apply. Figure 3.4 in section 3.1.1 shows the current emission limits for balanced three-phase equipment with the fifth harmonic range from 10.7% to 40%, depending on the short-circuit ratio of the equipment. The seventh harmonic is less, ranging from 7.2% to 25%. Nevertheless, the harmonic currents are well below the identified limit. In addition, the results from the neutral current harmonics were reviewed. The neutral-to-ground current harmonics are of a greater magnitude.

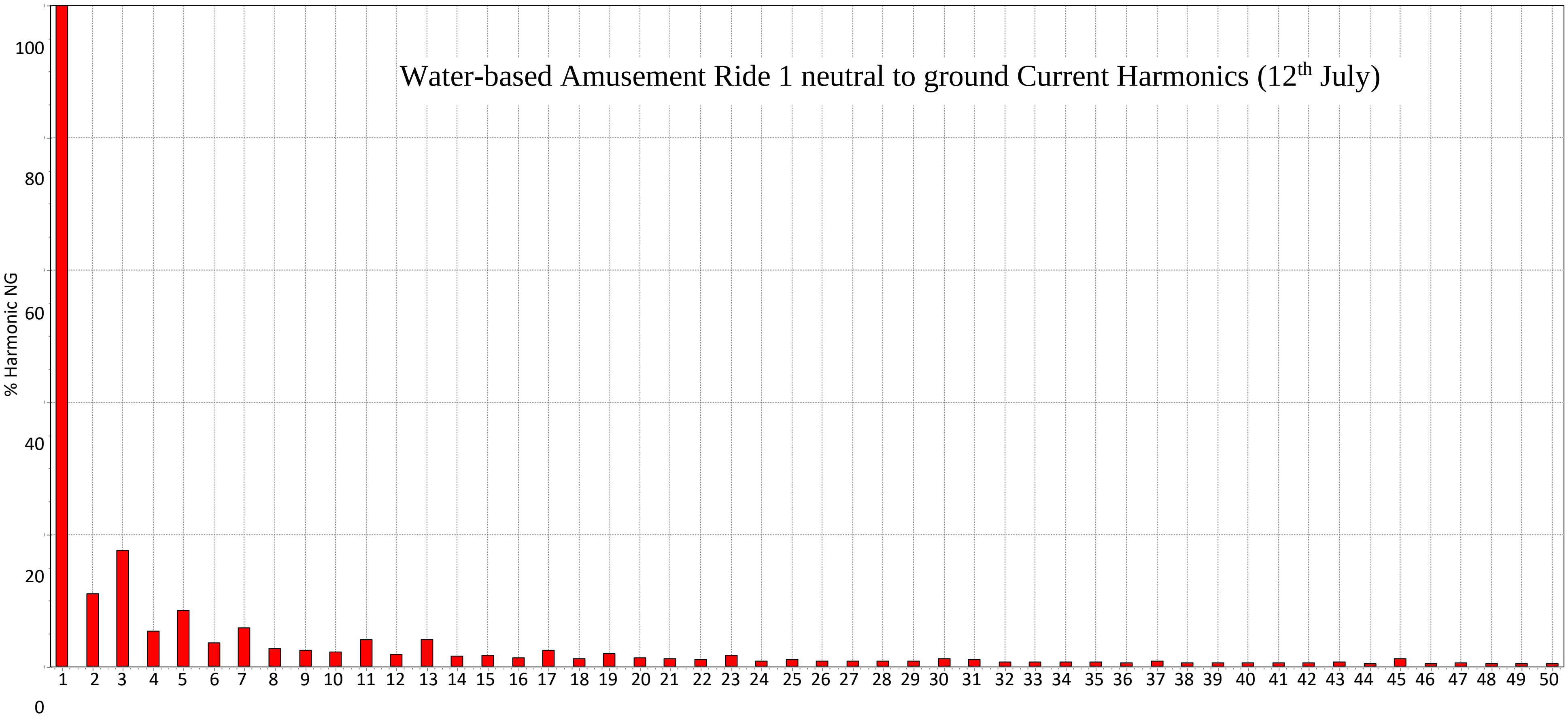

Figure 5.11 Water-based Amusement Ride 1 neutral to ground current harmonics on the 12th of July

Figure 5.11 confirms that the third harmonic is 17.63%. While measuring the results were not for individual equipment, the harmonics have been reviewed against the standard to analyse if the results are within the expected values. Figure 3.3 in section 3.1.1 shows the maximum current harmonic for the third order is 21.6 %. In comparison, the measured value is lower. Single-phase loads usually produce the third harmonic, known as a triplen harmonic. The currents add together at the neutral due to the star-connected system. Subsequently, the current at the neutral can be three times the phase currents. The heat a cable can dissipate at the maximum temperature determines the cable carrying capacity. The solution is to derate the neutrals carrying triplen harmonics.

Furthermore, delta wye transformers reflect triplen harmonics to the winding, absorbing the effects. Therefore, the supply is not affected by the triplen harmonics. The ride design consists of full-sized neutral conductors, with a neutral installed for each phase. Furthermore, the delta wye transformer upstream of the amusement ride will absorb the effects of the triplen harmonics.

Figure 5.12 depicts the voltage harmonics. The research in Section 3.1.1 discusses the standard for harmonic voltages in industrial plants: AS/NZS 61000.2.4. Standards Australia (2009) states that the maximum fifth harmonic voltage is 8% within the plant. The largest harmonic voltage is the fifth harmonic at 0.93%, with a THD for the 12th of July of 1.56%; this is below the limit. Additionally, Standards Australia (2019) states that the harmonic distortion limit for electrical machines is 12% from the 2nd to the 30th harmonic. The fifth harmonic voltage is well below both identified levels.

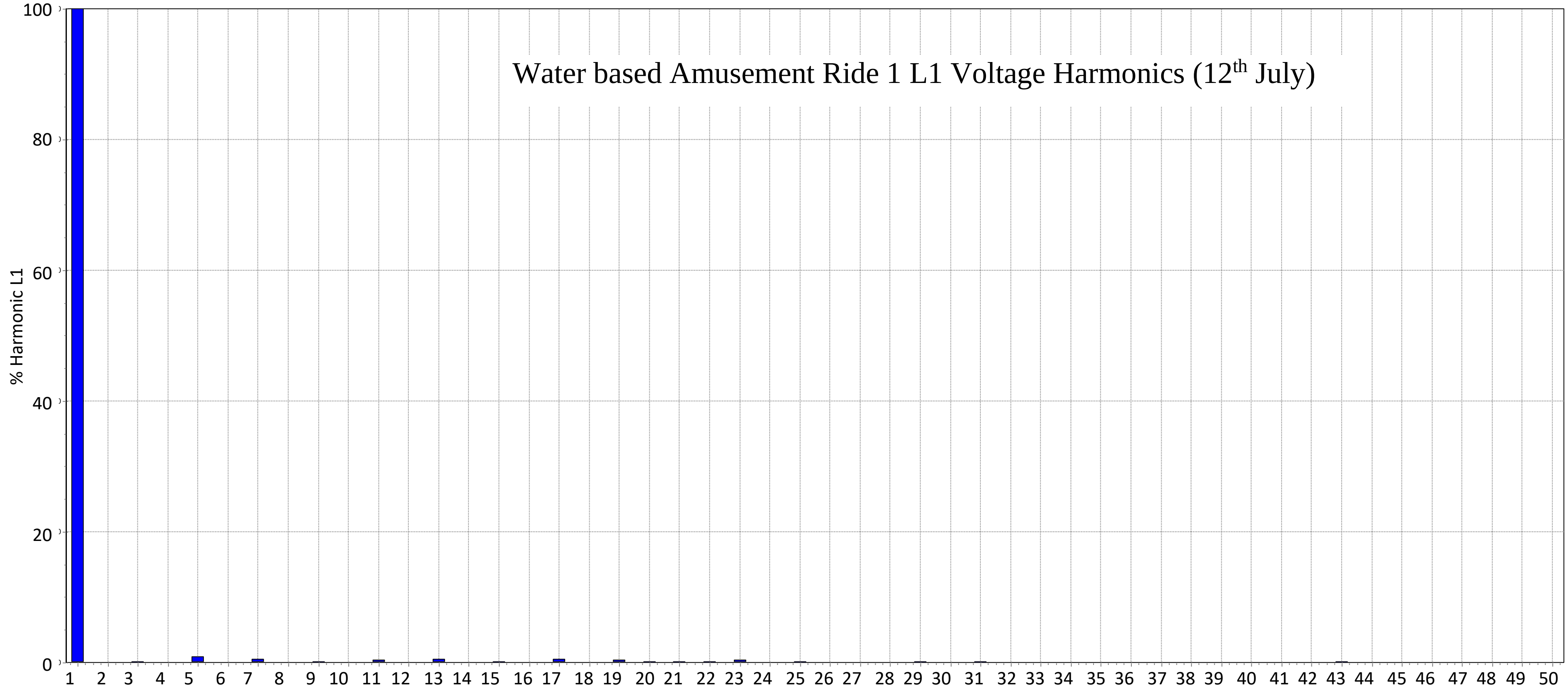

Figure 5.12 Water-based Amusement Ride 1 L1 voltage harmonics on the 12th of July

5.3.2 Partial discharge testing

The partial discharge was completed for the three amusement rides. The 98th percentile for the partial discharge was used to obtain the pulse repetition rate. The pulse repetition rate and the magnitude were used to work out the severity of the partial discharge for comparison between the amusement rides, per the calculation in Figure 3.9. The partial discharge 98th percentile magnitude for Amusement Ride 2 is depicted in Figure 5.13. The partial discharge is in the 98th percentile over the testing period for short periods. The short periods indicate a low repetition rate, as per Figure 3.12 in section 3.1.2. The average severity identified was 0.48; the results were similar across all three amusement rides. The phase-resolved plot was also reviewed to analyse the partial discharge pattern.

$$Severity = PD\ maximum\ magnitude\ (mA) \cdot\ repetition\ rate\ (pulses\ per\ cycle) \tag{1.1}$$

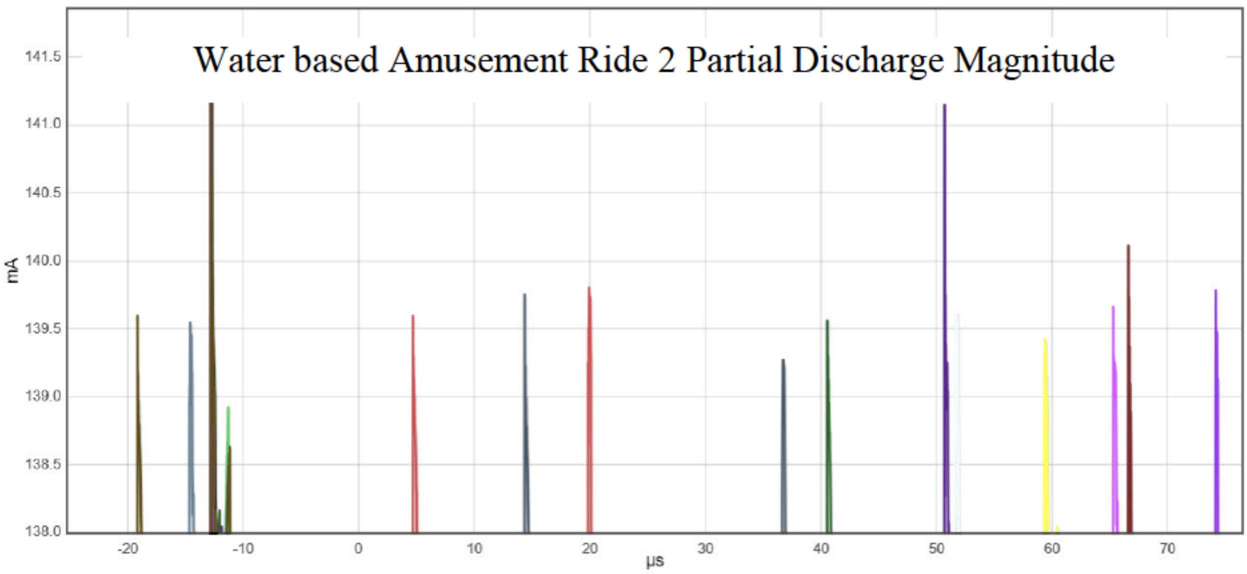

Figure 5.13 Water-based Amusement Ride 2 98th percentile of partial discharge

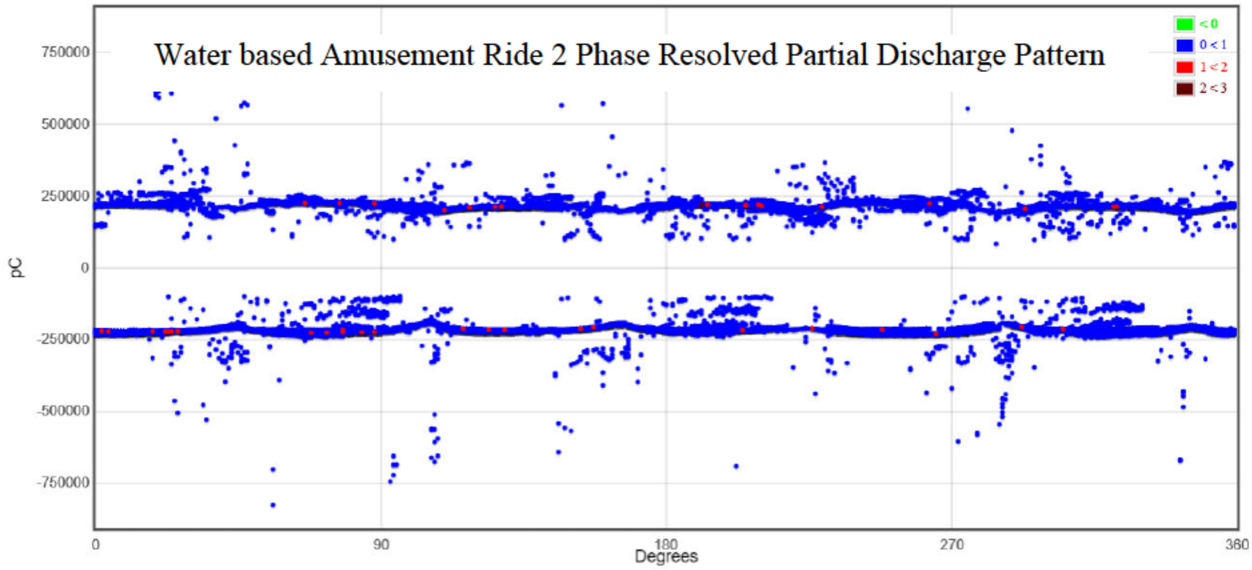

Figure 5.14 Water-based Amusement Ride 2 partial discharge phase plot

The phase-resolved plot for the water-based Amusement Ride 2 is illustrated in Figure 5.14. The plot is mainly flat without the recurring cycles that would be expected from a sine wave. The phase plot does not show partial discharge per pattern A in Figure 3.11 identified in section 3.1.2. The magnitude and phase plots for the partial discharge indicate noise rather than partial discharge from the research conducted. It was reasoned that the results did not indicate partial discharge; it represents noise. The results were similar across all three amusement rides.

5.3.3 Thermal imaging

The thermal images taken do not have any historical data to determine the severity criteria. The equipment's design, manufacture, and installation conditions will be reviewed to analyse the thermal images. The information is indicative; however, the results could be more conclusive with historical data. The manufacturer information will be reviewed to analyse the thermal images and theorise the possible causes.

There had to be an understanding of the theory of thermal imaging to review the results. The low emissivity of metallic surfaces was previously discussed in 4.1.3. The surface reflecting the background temperature was sighted in Figure 5.15 at the water-based amusement ride 3. The cables are encased within a shiny metallic sheath depicted in Figure 5.16. the background temperature of the background objects is being reflected; therefore, the thermal image is not indicative of the actual temperature rise. Reflection was considered carefully during the review of the testing results.

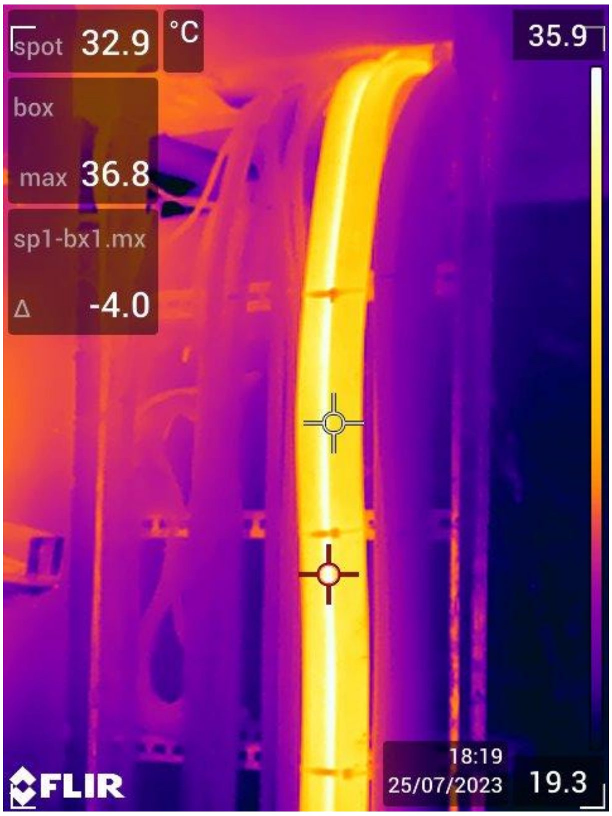

Figure 5.15 Water-based Amusement Ride 3 thermal image of pump 1 cables

Figure 5.16 Water-based Amusement Ride 3 photo of pump 1 cables

Section 3.1.3 discusses that thermal imaging cannot be conducted on underwater equipment. The water-based amusement rides have a substantial amount of equipment located underwater due to the nature of the ride. Where the motors for the amusement rides were not located in the water, the thermal images indicated uniform heat distribution. The uniform heat distribution is illustrated in Figure 5.17, which shows a thermal image from The water-based Amusement Ride 1. The thermal image shows consistent colouring on the body of the motor, with the fan casing being lower in temperature. The hottest part of the motor is the fan-bearing at the end of the fan casing. The motor thermal images were consistent with the results of the previous amusement ride condition monitoring studies (Shen et al. 2014; Shen et all. 2022). The heat was consistent with normal operation due to the consistent colouring. However, the precious study reported by Shen et al. (2022) does not include the higher temperature at the fan-bearing. Ongoing monitoring would enable trends to be observed and indicate if the fan-bearing temperature was abnormal. Two noteworthy images from The water-based Amusement Ride 1 illustrate temperature rise in components.

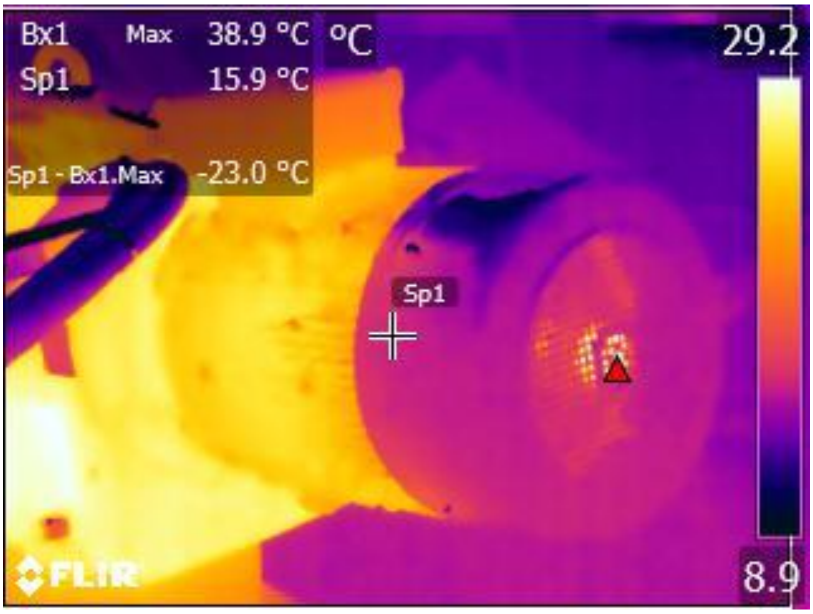

Figure 5.17 Water-based Amusement Ride 1 thermal image of motor

Figure 5.18 identifies heat rise between moulded case circuit breakers Q03 and Q04, denoted with the red triangle. The black cross signifies the comparison temperature between Q05 and Q06, of 61.5 °C. The temperature indicated between the Q03 and Q04 circuit breakers is 87.4 °C, with a difference of 25.9 °C. The temperature difference in a thermal imaging study was much lower at 12 °C (Shen et al. 2022). However, the thermal images do not demonstrate the fault characteristics shown in the infrared study on contactors (Yu et al. 2019). Contactors are simpler in construction than circuit breakers, and the thermal images during fault conditions may differ from the reference images. However, due to the ride being operational, it was deemed that thermal images do not illustrate a fault. The ride was running at full load when the thermal image was taken. The manufacturer information for the moulded case circuit breakers states that the maximum operating temperature is 155 °C (Siemens AG 2001a). Thus, the circuit breaker is working within the manufacturer's limits. The equipment's current carrying capacity and ambient temperature were also considered.

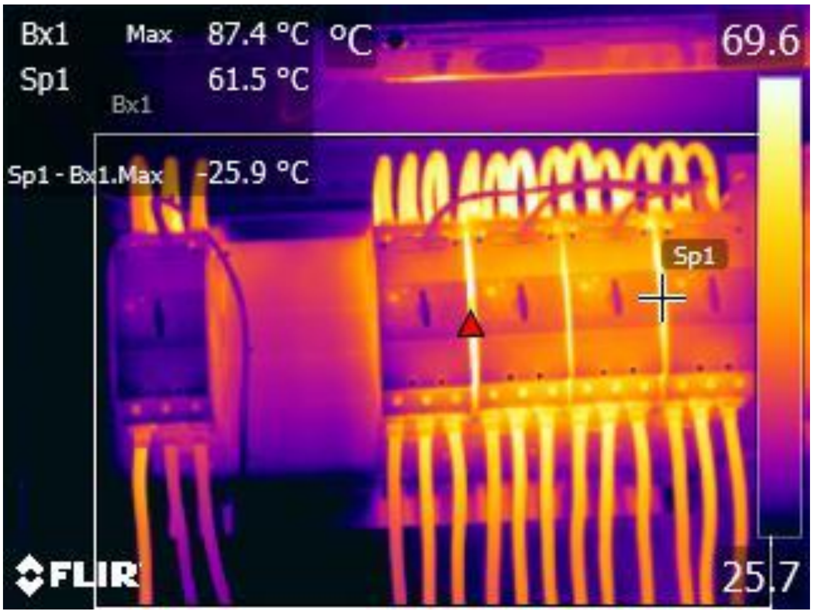

Figure 5.18 Water-based Amusement Ride 1 thermal image of motor circuit breakers

The operating temperature can affect the current rating of circuit breakers; the technical data for the circuit breaker was reviewed to assess the limitations. In the installation manual, Siemens AG (2001b) details the rated current (In) for the circuit breakers as 90 A, whereas the short-circuit current is multiplied by the rated current or 1,170 A. The rated current of the circuit breaker is not affected until the ambient temperature exceeds 60 °C. It can be seen in Figure 5.18 that the ambient temperature in the cabinet is as low as 25.7 °C. Additionally, the switchboard is located within an air-conditioned switchroom. There is no risk to the equipment operating at the temperatures in the thermal image.

Moreover, the temperature difference between the circuit breakers is not near where the contacts would be expected. Siemens AG (2001b) details the conditions that allow installation adjacent to other circuit breakers. While the installation has been completed in line with manufacturer recommendations, mutual heating could be causing the temperature rise, as seen in Figure 5.18. The historical information for the ride is required to determine if the values are within the expected range for the installation. Given the space, the high-temperature rise could be lowered by moving the circuit breakers further apart in the cabinet. Furthermore, the conductors also show a temperature rise depicted by the lighter colour.

A temperature rise of 27.2 °C between the conductors is shown in Figure 5.19. The thermal image was taken directly below the circuit breakers discussed above. The expected temperature was calculated to assess the expected temperature rise of the conductors. The expected value includes assumptions and theory from AS/NZS 3000 and AS/NZS 3008.1.1.

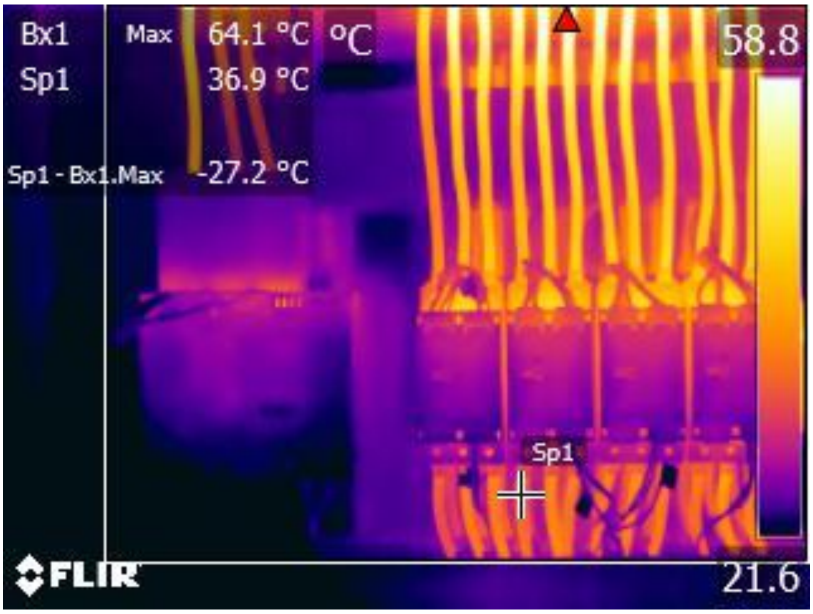

Figure 5.19 Water-based Amusement Ride 1 thermal image of conductors

The conductor surface temperature was estimated from the heat transfer coefficient formula. Çengel et al. (2022, p. 562) states that the formula for the rate of convection heat transfer is:

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)\ (in\ Watts) \tag{1.2}$$

where

$$\dot{Q}_{conv} = \ heat\ transfer\ rate$$
$$h = \ convection\ heat\ transfer$$
$$A_s = \ surface\ area\ of\ the\ wire$$
$$T_s = \ conductor\ temperature$$
$$T_\infty = \ surface\ temperature$$

Rearranging the rate of convection heat transfer formula (1.2) provides the estimated surface temperature of the conductor:

$$T_s = T_\infty + \frac{\dot{Q}_{conv}}{A_s h} \tag{1.3}$$

The formula above incorporates the heat transfer rate, which is the heat loss from the conductor. The heat loss due to the conductor power consumption is the heat loss or heat transfer rate:

$$\dot{Q} = VI\ (in\ Watts) \tag{1.4}$$

where

$$V = \ voltage\ drop\ across\ conductor$$
$$I = \ current\ in\ conductor$$

The cable voltage drop per ampere-metre length was obtained to assess the heat transfer rate. Standards Australia (2017, p. 110) states that the three-phase voltage drop for a 35 mm2 multicore at 75 °C with circular copper conductors in Table 42 is:

$$V_c = 1.11\ mV/A.m.$$

The circuit length, voltage drop per ampere-metre and circuit current were used to calculate the actual voltage drop in the circuit. Standards Australia (2018, p. 480) states the formula for actual voltage drop is:

$$V_d = (L \cdot I \cdot V_c)/1000 = (0.5 \cdot 85 \cdot 1.11)/1000 = 0.04718\ V \tag{1.5}$$

where

$$L = \ circuit\ length$$
$$V = voltage\ drop\ aper\ ampere - metre$$
$$I = \ circuit\ current$$

The heat loss was calculated using the actual voltage drop and current in the conductor. Substitution of the values for (1.4) gives:

$$\dot{Q} = VI\ (in\ Watts) = \ 0.04718 \cdot 85 = 4\ W \tag{1.6}$$

Nexans (2023, p. 2) defines the diameter of a 35mm^2 cable as 9.4 mm. This value was used to calculate the surface area of the cable:

$$A = \pi DL = \pi(0.0094)(0.5) = 0.01477\, m^2 \tag{1.7}$$

where

$$D = \ diameter\ of\ conductor$$
$$L = \ conductor\ length$$

The convection heat transfer of air in the switchboard was estimated. Çengel et al. (2022, p. 562) state the typical value of the convection heat transfer coefficient of gases (air) in motion from Table 16-5 is:

$$2 - 25\, W/m^2 \cdot K$$

A conservative value of $10\, W/m^2 \cdot K$ was chosen for the convection heat transfer of air. Finally, the surface temperature of the conductor was calculated using (1.3):

$$T_s = T_\infty + \frac{\dot{Q}_{conv}}{A_s h} = 64.1\ °C + \frac{4}{(0.01477\ \ m^2)(10\, W/m^2 \cdot K)} = 64.1°C + 27.09°C = 91.19\ °C \tag{1.8}$$

While the above calculation makes assumptions as to the convection heat transfer coefficient in the switchboard, the surface temperature of the conductor is calculated as 91.19 °C. The calculated conductor surface temperature is less than the temperature limit for PVC conductors, which is 160 °C for five seconds (Standards Australia 2017, p. 122). It was deemed that the conductor temperature was within acceptable limits. However, historical values are required to determine if the temperature rise is typical for the installation. Similarly, Amusement Ride 3 also illustrates a conductor temperature rise.

A thermal image from The water-based Amusement Ride 3 (Figure 5.20) illustrates a three-phase supply where the red phase was 4.8 °C above the other two. The red triangle highlights the temperature increase. The upstream installation of the cables was reviewed to see if the temperature increased in the red phase of the cables. Figure 5.21 illustrates the upstream connections; however, the trefoil conductor installation meant the thermal camera could not distinguish between the conductors' phase temperatures. The conductors upstream are on the right side of Figure 5.21. The results were not definitive.

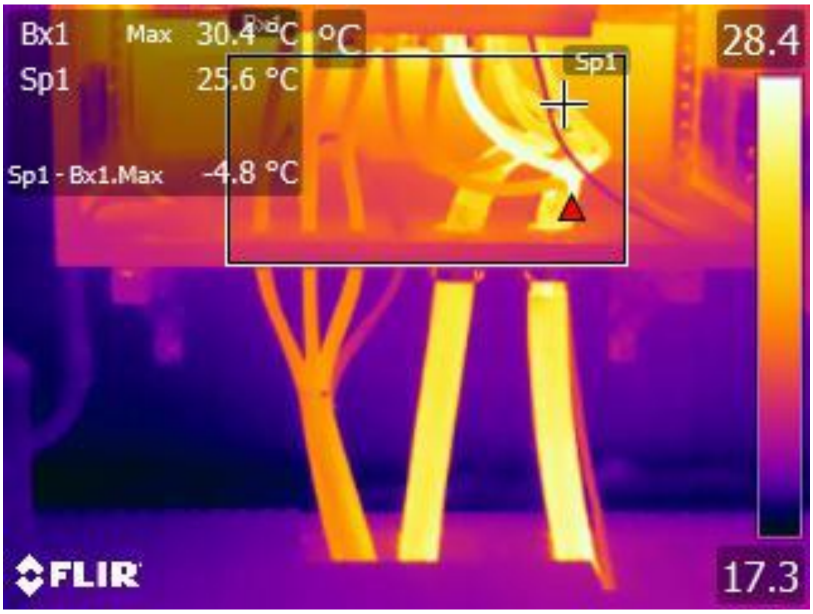

Figure 5.20 Water-based Amusement Ride 3 thermal image of pump 1 at the VSD

Figure 5.21 Water-based Amusement Ride 3 thermal image of pump 1 at the MCC

The temperature difference of 16.5 °C is below the expected conductor temperature to indicate a fault. Although the difference between the phases could indicate a fault, the lack of historical information to identify the change in temperature means the information is inconclusive. The possible causes for conductor temperature differences in a three-phase motor include a winding breakdown, a shorted winding turn, or a reversed coil connection. Further testing of the motor and cables could include insulation resistance testing to determine if there is an insulation breakdown in the motor or cables.

5.4 Summary

The field measurement program evaluates preventative maintenance techniques for the water-based amusement rides. The testing was completed across two sites with different supplies and infrastructure, which could have contributed to the differing results. Initial testing was carried out to provide benchmark results. Given that good preventative maintenance requires information from testing to establish the criticality of the results, it is still being determined if the results are within the expected range.

Inspecting the equipment connections before testing would have drawn attention to the equipment faults. The test equipment is a vital part of the testing, and the inadequate inspection before starting meant the results were deemed unusable. The poor equipment condition impacted the thesis results and the overall quality of the testing. It is recommended that a detailed inspection of the equipment is carried out in future before completing testing.

The power quality results indicate transients occurring due to introducing a capacitor into an inductive circuit. In addition, the transients show a DC offset. It is still being determined why the DC offset is present, which requires further investigation. The results indicate higher values in the fifth and seventh current harmonics due to three-phase rectifiers. The higher results in the third harmonic current for the neutral indicate the presence of triplen harmonics due to single-phase loads. The voltage and current harmonics at the incomer comply with the requirements in the standards.

The partial discharge results confirm a low repetition rate. The partial discharge pattern does not indicate partial discharge and is indicative of noise. The partial discharge testing is the first known study into low voltage partial discharge for motors in situ. Additional research into varying types and sizes of low-voltage cables is required to provide definitive results across multiple situations. The benefit of implementing partial discharge for low-voltage applications may be realised in time after additional research.

A thermal imaging course would provide more information on conducting thermal imaging. Due to the limited knowledge, the thermal imaging methodology used a qualitative method. The lack of knowledge also contributed to the limitations in analysing the results. Standards Australia (2008) describes qualitative thermography and states that the patterns are not assigned temperature values because the surface emissivity has not been measured and put into the thermal imaging camera. Therefore, the temperatures described in Section 5.3.3 may not be accurate or reflective of the actual temperature.

The thermal imaging showed even heat distribution across the motor body, demonstrating normal operation. The moulded case circuit breakers and conductor results showed temperature differences of 25.9 °C and 25.2 °C, respectively. The results were within the normal operating parameters for the equipment. However, it was recommended to move the circuit breakers further apart due to mutual heating. The results for Amusement Ride 3 demonstrate a temperature difference of 4.8 °C between phases for the pump one conductors. The results were inconclusive; however, the difference could indicate a winding breakdown, a shorted winding turn, or a reversed coil connection.

Further testing was recommended. The thermography research did not include thermal images of cables in situ. Greater research depth would improve the cable analysis. There needed to be more knowledge of thermal imaging, as a thermal imaging course was not undertaken. There needed to be follow-up testing completed to verify the actual cause of the results in the analysis due to the limited time. Additional testing would have allowed for verification of the significance of the information. The result analysis would have been more definitive with additional investigation and testing.

In summary, the analysis recommendations are:

1. Further testing of the water-based Amusement Ride 1 to identify the cause of the DC offset.
2. Moving the moulded case circuit breakers Q03, Q04, Q05 and Q06 further apart within the Amusement Ride 1 switchboard.
3. Insulation resistance testing of pump one and the cables at amusement ride 3.
4. Further preventative maintenance testing to inform future research.

Chapter 6. Conclusions and Further Work

6.1 Conclusions

The research contained within this thesis contributes to understanding the risks of electrical equipment with water-based amusement rides. The contribution to water-based amusement ride research is original and significant. The thesis provides information on preventative maintenance and practical implementation. The power quality and partial discharge testing is the first known study to investigate preventative maintenance of electrical equipment in water-based amusement rides. Thermal imaging advances the current research into the analysis of motors, electrical equipment and cables. The testing found that thermal imaging does not interrupt daily operations, making it an ideal safety inspection technology.

The thesis included conducting background research on amusement ride incidents and accidents. The results indicate recurring areas that require improvement, including safety systems, risk analysis, maintenance and inspection. Establishing major inspections will reduce the likelihood of corrosion leading to failure. Research into the possible safety implications of VSDs could improve industry knowledge. In addition, it identified that the national development of a database for information sharing between states and territories would improve the safety of amusement rides.

Information was provided on the relevant legislative requirements, standards and codes of practice relating to amusement rides. The collaboration of the amusement industry organisations has improved the consistency of amusement ride standards globally. The cooperation of the organisations to implement an international reporting system for incidents could reduce the information lag between designers and amusement ride stakeholders, improving safety. The organisations continue to contribute to safety by updating the Australian amusement ride standards per European requirements. The addition of the Queensland amusement ride code of practice will have a positive impact on the industry.

The research into the amusement ride risks impacts all amusement rides. The research areas include vibration, corrosion, power quality, insulation failure, maintenance (including records), inspection, identifying trends and an emergency shutdown system. The thesis identifies areas for further research.

The thesis includes developing a preventative maintenance program that extends water-based amusement ride research into power quality, partial discharge and thermal imaging. Testing information was collected and analysed. Additional research into mitigation techniques was carried out, and engineering recommendations were provided. The analysis discusses risks with water-based amusement rides to facilitate discussion. The application of electrical safety for water-based amusement rides is studied. The objectives were met; however, time was needed to permit an investigation into a system to monitor and predict equipment failure. The initial testing results provide a benchmark of the expected values to compare to future test results.

6.2 Further Work

The thesis is the first known research into water-based amusement rides. The ongoing monitoring of the amusement rides will not be completed. Ongoing monitoring would enable trends to be observed. Therefore, it is recommended that further testing be carried out to inform future research. Carrying the research out regularly over a more extended period would improve the accuracy and results. More research into water-based amusement rides would increase industry knowledge, resulting in safer amusement rides.

There are areas of further work that could be developed for water-based amusement rides. An investigation into VSDs would elevate knowledge and determine possible safety implications. Downstream and upstream monitoring of VSDs could determine the possible harmonics generated and the safety implications. Testing at multiple water-based amusement rides could improve the industry' knowledge.

In addition, some research areas did not form part of the testing. Cathodic protection of amusement rides could be further investigated to determine if the theory could be applied to amusement ride installations. The water-based amusement rides have large volumes of water that could benefit from preventative methods for corrosion.

The initial research into an emergency shutdown system utilising VLSI offers a reliable solid-state alternative. Future research into the integration of VLSI could lead to increased reliability and testability for safety shutdown systems.

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Appendix A Project specification

ENG4111/4112 Research Project

Project Specification

For:	Kendra Gurrin
Title:	Safety of electrical equipment in water-based amusement rides from an engineering perspective.
Major:	Power engineering
Supervisors:	Tony Ahfock
Confidentiality:	The report will have all the confidential information, such as the company name, the amusement rides, and any identifying factors removed to ensure there is no breach of confidentiality.
Enrolment:	ENG4111 – ONL S1, 2023
	ENG4112 – ONL S2, 2023
Project Aim:	To investigate the safety of electrical equipment in water-based amusement rides, define the major factors that affect the safety of electrical equipment in water-based amusement rides and the implications for improving water-based amusement ride design.

Programme: Version 1, 3rd March 2023

1. Conduct background research on amusement ride incidents and accidents.
2. Research relevant legislation, standards and codes of practice relating to amusement rides in Australia.
3. Conduct literature review of electrical safety of amusement devices including vibration, corrosion, power quality, insulation failure, maintenance (including records) and inspection of amusement rides.
4. Depending on outcome of the literature review complete option A or B.
5. Option A - Design a field measurement program and collect relevant data for water-based amusement rides, as appropriate.
6. Option A – Process and evaluate the field data of the water-based amusement rides.
7. Option A – Investigate mitigation measures and techniques for electrical safety of water-based amusement rides.
8. Option B – Investigate a system to monitor and predict equipment failure.
9. Provide engineering recommendations.

If time and resources permit:

10. Model the amusement ride(s) and simulate faults to gain a greater understanding of the safety of electrical equipment in water-based amusement rides.
11. Provide recommendations for ongoing research.

ENG4111/4112 Research Project

Project Specification

For: Kendra Gurrin

Title: Safety of electrical equipment in water-based amusement rides from an engineering perspective.

Major: Power engineering

Supervisors: Tony Ahfock

Confidentiality: The report will have all the confidential information, such as the company name, the amusement rides, and any identifying factors removed to ensure there is no breach of confidentiality.

Enrolment: ENG4111 – ONL S1, 2023

ENG4112 – ONL S2, 2023

Project Aim: To investigate the safety of electrical equipment in water-based amusement rides, define the major factors that affect the safety of electrical equipment in water-based amusement rides and the implications for improving water-based amusement ride design.

Programme: Version 2, 24th March 2023

1. Conduct background research on amusement ride incidents and accidents.
2. Research relevant legislation, standards and codes of practice relating to amusement rides in Australia.
3. Conduct literature review of electrical safety of amusement devices including vibration, corrosion, power quality, insulation failure, maintenance (including records) and inspection of amusement rides.
4. Design a field measurement program and collect relevant data for water-based amusement rides, as appropriate.
5. Process and evaluate the field data of the water-based amusement rides.
6. Investigate mitigation measures and techniques for electrical safety of water-based amusement rides.
7. Provide engineering recommendations.

If time and resources permit:

1. Investigate a system to monitor and predict equipment failure.
2. Provide recommendations for ongoing research.

Appendix B Water-based amusement ride 1 drawings

CONTINUED ON DRG. RIDE 1-2

MCC

TAG No.	DEVICE	SETTINGS
Q01A	CIRCUIT BREAKER EATON NZMN4 AE800	In=800A, Ir=0.9xIn (720A), Im=8xIn (6400A)
Q01B	CIRCUIT BREAKER SIEMENS 3RV2011-1JA20	In=10A, Ir=10A, Im=FIXED
Q01C	CIRCUIT BREAKER SIEMENS 3RV2011-CA20	In=2.5A, Ir=1.8A, Im=FIXED
Q02, Q07, Q08	CIRCUIT BREAKER SIEMENS 3RV1041-4MA10	In=100A, Ir=100A, Im=FIXED
Q03-Q06	CIRCUIT BREAKER SIEMENS 3RV1041-4LA10	In=90A, Ir=85A, Im=FIXED
Q09	CIRCUIT BREAKER SIEMENS 3RV1041-4KA10	In=75A, Ir=62A, Im=FIXED
Q11-Q16	CIRCUIT BREAKER SIEMENS 3RV2011-JA20	In=10A, Ir=8A, Im=FIXED

PRELIMINARY
NOT FOR CONSTRUCTION

DOC No.	TITLE	No.	DATE	DRN	CHK	DES	APP

REFERENCE DOCUMENTS

REVISION

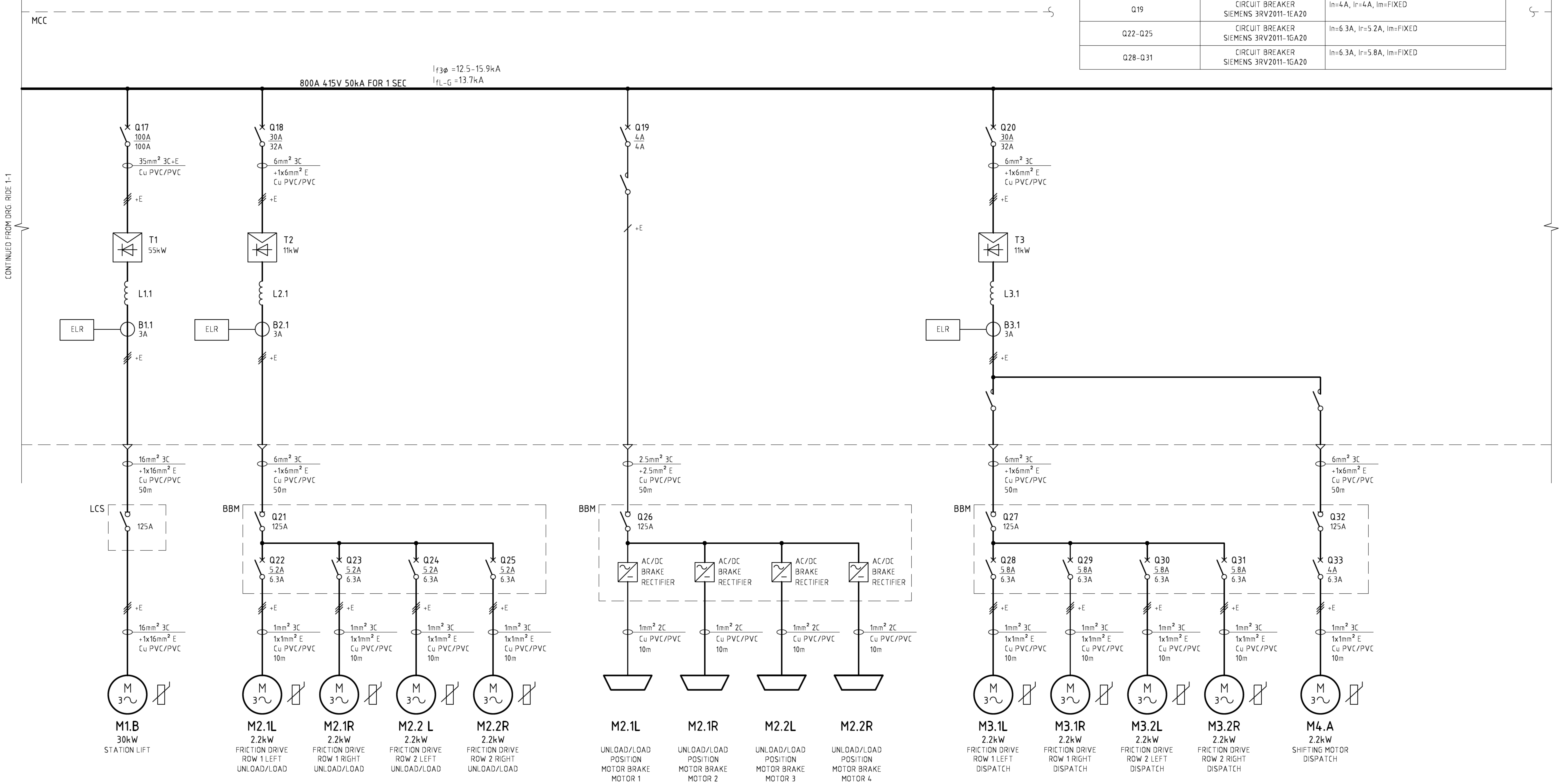
DRAWN:
CHECKED:
DESIGNED:
APPROVED:
DATE:
FILE NAME: RIDE 1-1
JOB No.:

CLIENT:

WATER BASED AMUSEMENT RIDE 1
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 1 OF 3

SCALE: A1 DWG No. RIDE 1-1 REV.

MCC		
TAG No.	DEVICE	SETTINGS
Q17	CIRCUIT BREAKER SIEMENS 3RV1041-4MA10	In=100A, Ir=100A, Im=FIXED
Q18, Q20	CIRCUIT BREAKER SIEMENS 3RV1031-4EA10	In=32A, Ir=30A, Im=FIXED
Q33	CIRCUIT BREAKER SIEMENS 3RV2011-1GA20	In=6.3A, Ir=4A, Im=FIXED
Q19	CIRCUIT BREAKER SIEMENS 3RV2011-1EA20	In=4A, Ir=4A, Im=FIXED
Q22-Q25	CIRCUIT BREAKER SIEMENS 3RV2011-1GA20	In=6.3A, Ir=5.2A, Im=FIXED
Q28-Q31	CIRCUIT BREAKER SIEMENS 3RV2011-1GA20	In=6.3A, Ir=5.8A, Im=FIXED



PRELIMINARY
NOT FOR CONSTRUCTION

DOC No.	TITLE	No.	DATE		DRN	CHK	DES	APP
REFERENCE DOCUMENTS		REVISION						

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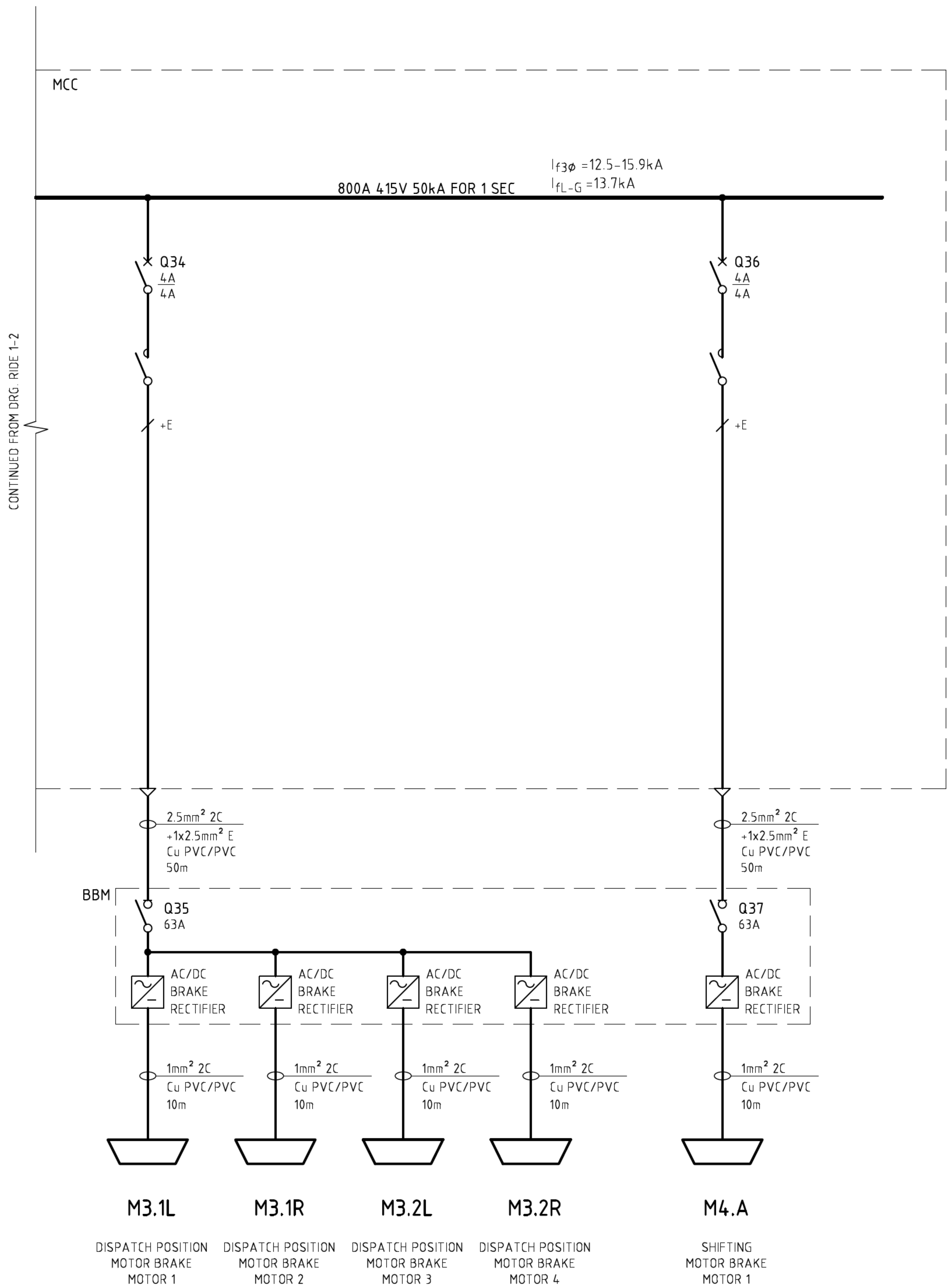
WATER BASED AMUSEMENT RIDE 1
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 2 OF 3

SCALE: A1 DWG No. RIDE 1-2 REV.



MCC		
TAG No.	DEVICE	SETTINGS
Q34, Q36	CIRCUIT BREAKER SIEMENS 3RV2011-1EA20	In=4A, Ir=4A, Im=FIXED

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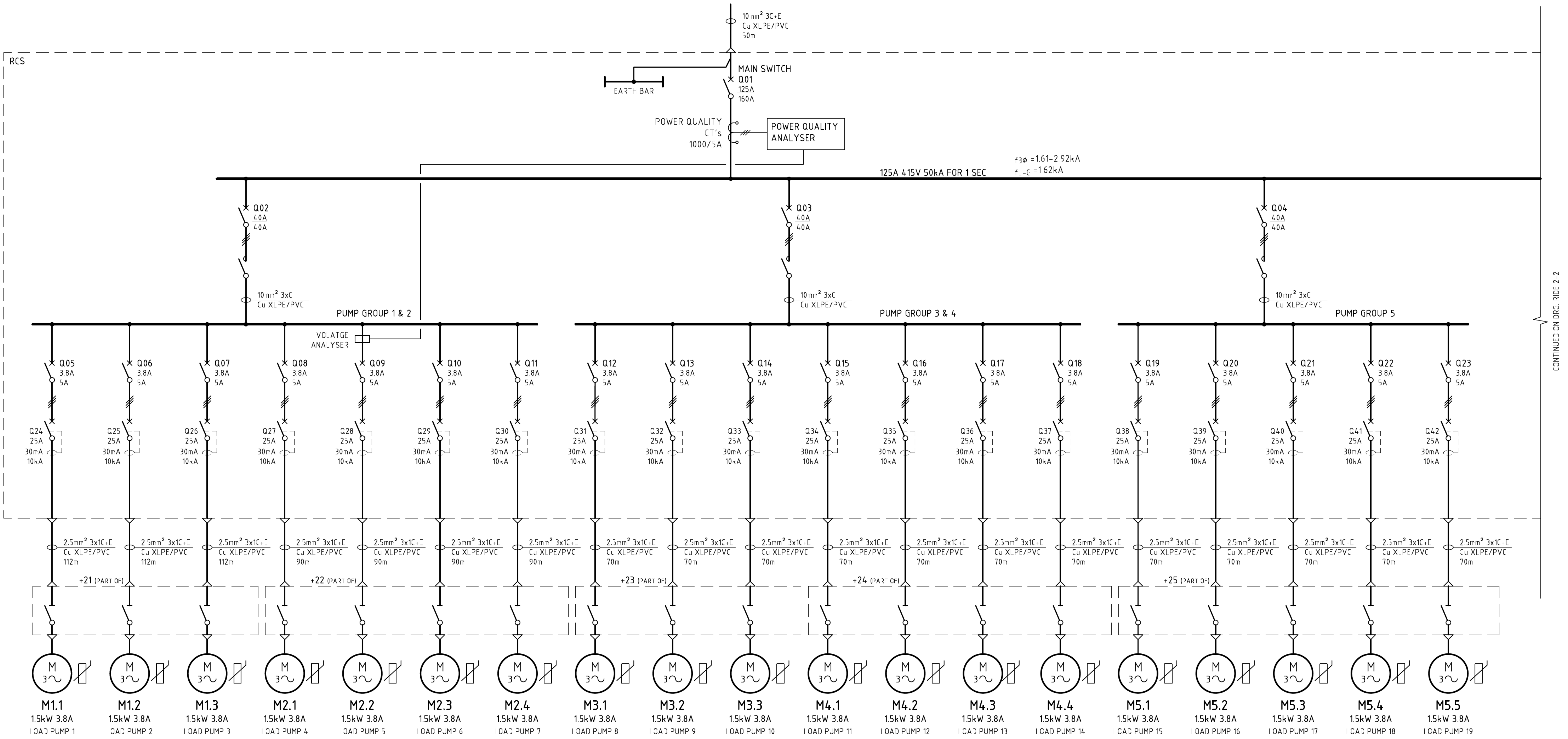
WATER BASED AMUSEMENT RIDE 1
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 3 OF 3

SCALE: A1 DWG No. RIDE 1-3 REV.

Appendix C Water-based amusement ride 2 drawings



RCS		
TAG No.	DEVICE	SETTINGS
Q01	CIRCUIT BREAKER EATON NZMN2-A160	In=160A, Ir=0.78xIn (125A), Ii=6.0xIn (960A)
Q02-Q04	MOTOR STARTER SIEMENS 3RV1031-4FA10	In=40A, Ir=1.0xIn (40A), Im=520A
Q05-Q23	CIRCUIT BREAKER SIEMENS 3RV2011-1FA10	In=5A, Ir=0.76xIn (3.8A), Im=65A
Q24-Q42	RESIDUAL CURRENT CIRCUIT BREAKER SIEMENS 5SM331212-6	25A, 30mA, 10kA

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FILE NAME:	RIDE 2-1
JOB No.:	

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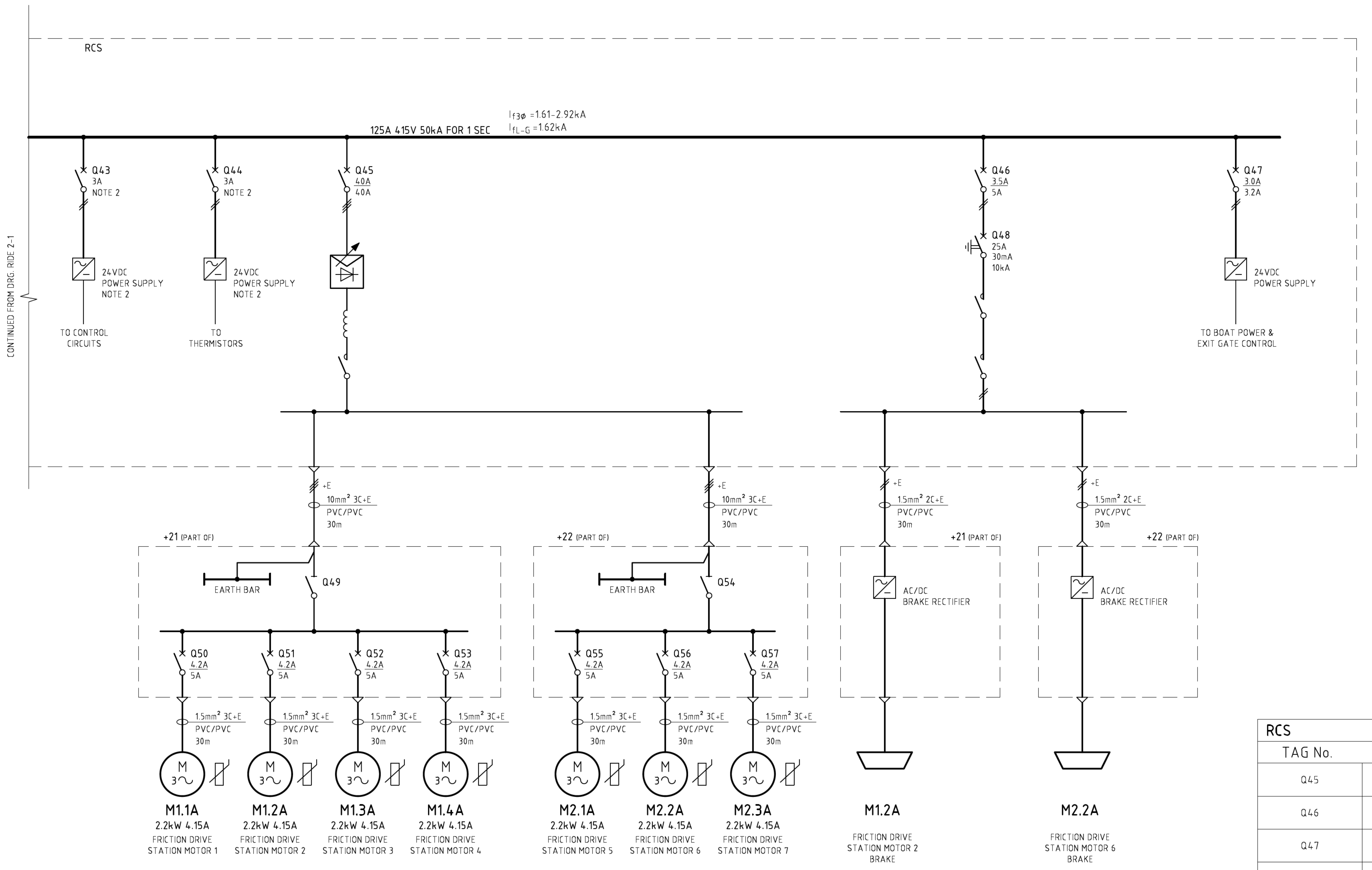
WATER BASED AMUSEMENT RIDE 2
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 1 OF 2

SCALE:	A1	DWG No.	RIDE 2-1	REV.



RCS

TAG No.	DEVICE	SETTINGS
Q45	MOTOR STARTER SIEMENS 3RV1031-4FA10	In=40A, Ir=1.0xIn (40A), Im=520A
Q46	CIRCUIT BREAKER SIEMENS 3RV2011-1FA20	In=5A, Ir=0.7xIn (3.5A), Im=65A
Q47	CIRCUIT BREAKER SIEMENS 3RV2011-1DA20	In=3.2A, Ir=0.94xIn (3.0A), Im=42A
Q50-Q53, Q55-Q57	CIRCUIT BREAKER SIEMENS 3RV2011-1FA10	In=5A, Ir=0.84xIn (4.2A), Im=65A

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DOC No.	TITLE	No.	DATE	DRN	CHK	DES	APP

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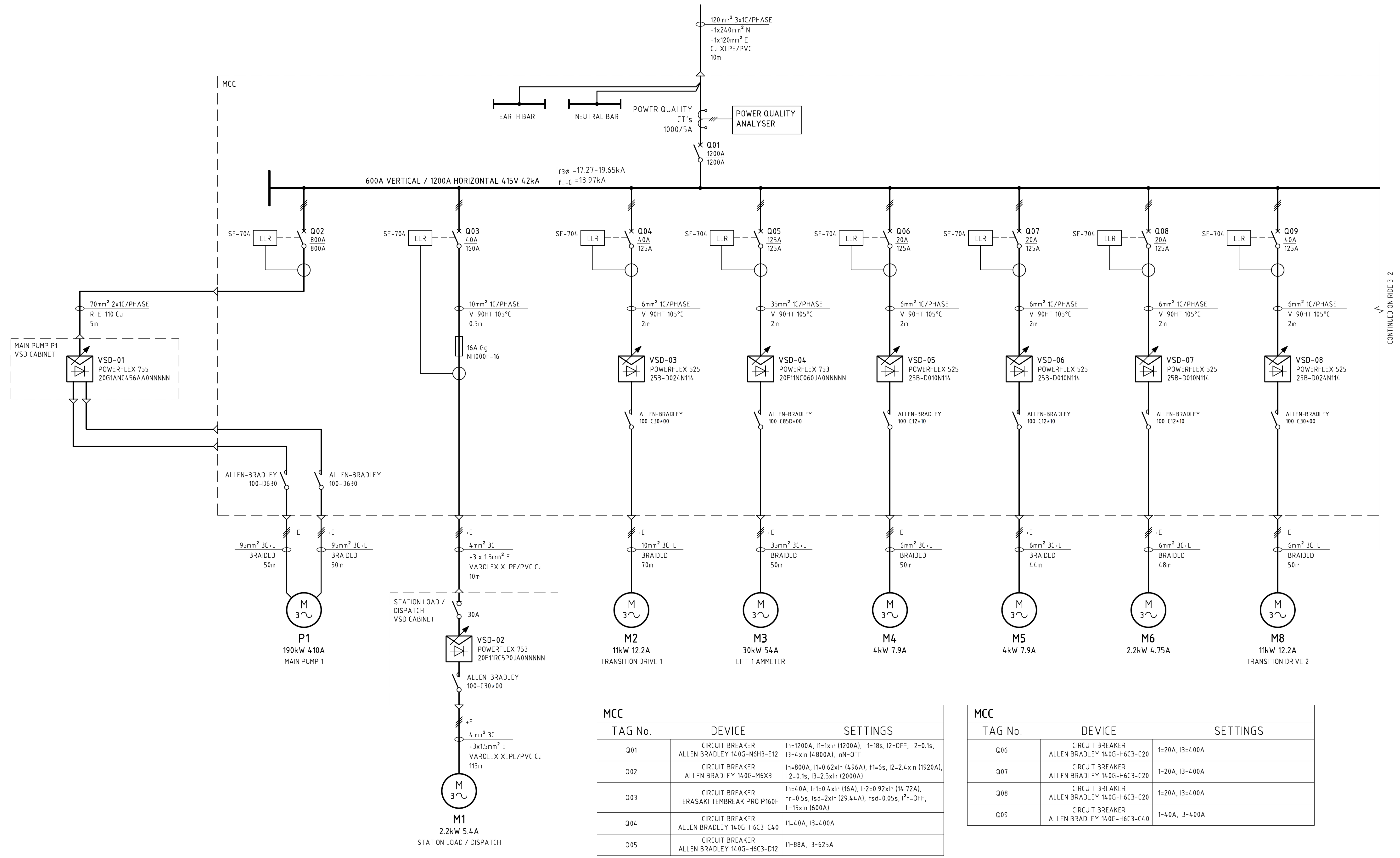
WATER BASED AMUSEMENT RIDE 2
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 2 OF 2

SCALE: A1 | DWG No. RIDE 2-2 | REV.

Appendix D Water-based amusement ride 3 drawings



MCC

TAG No.	DEVICE	SETTINGS
Q01	CIRCUIT BREAKER ALLEN BRADLEY 140G-N6H3-E12	In=1200A, I1=1xIn (1200A), t1=18s, I2=OFF, t2=0.1s, I3=4xIn (4800A), InN=OFF
Q02	CIRCUIT BREAKER ALLEN BRADLEY 140G-M6X3	In=800A, I1=0.62xIn (496A), t1=6s, I2=2.4xIn (1920A), t2=0.1s, I3=2.5xIn (2000A)
Q03	CIRCUIT BREAKER TERASAKI TEMBREAK PRO P160F	In=40A, Ir1=0.4xIn (16A), Ir2=0.92xIr (14.72A), tr=0.5s, Isd=2xIr (29.44A), tsd=0.05s, I²t=OFF, Ii=15xIn (600A)
Q04	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C40	I1=40A, I3=400A
Q05	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-D12	I1=88A, I3=625A

MCC

TAG No.	DEVICE	SETTINGS
Q06	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q07	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q08	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q09	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C40	I1=40A, I3=400A

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JOB No.:	

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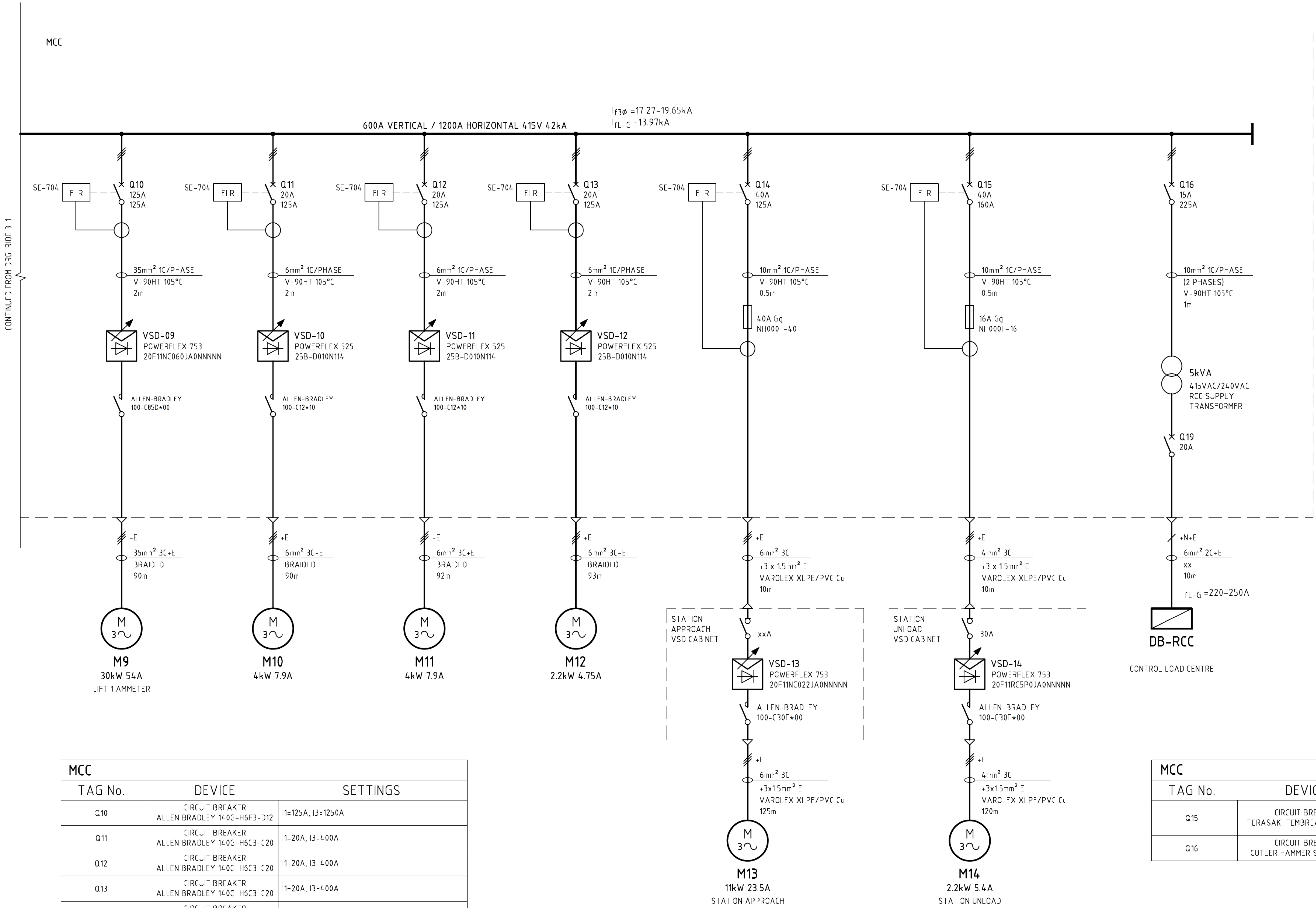
WATER BASED AMUSEMENT RIDE 3
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 1 OF 2

SCALE: A1 | DWG No. RIDE 3-1 | REV.



MCC

TAG No.	DEVICE	SETTINGS
Q10	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6F3-D12	I1=125A, I3=1250A
Q11	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q12	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q13	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C20	I1=20A, I3=400A
Q14	CIRCUIT BREAKER ALLEN BRADLEY 140G-H6C3-C40	I1=40A, I3=400A

MCC

TAG No.	DEVICE	SETTINGS
Q15	CIRCUIT BREAKER TERASAKI TEMBREAK PRO P160F	In=40A, Ir1=0.4xIn (16A), Ir2=0.92xIr (14.72A), tr=0.5s, Isd=2xIr (29.44A), tsd=0.05s, I²t=OFF, Ii=15xIn (600A)
Q16	CIRCUIT BREAKER CUTLER HAMMER SERIES C HFD	I=15A

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JOB No.:	

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WATER BASED AMUSEMENT RIDE 3
MOTOR CONTROL CENTRE
SINGLE LINE DIAGRAM SHT 2 OF 2

SCALE: A1 DWG No. RIDE 3-2 REV.