Monitoring of EMI Events in the Proximity of MRI Scanners

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Abstract—**This thesis gathered information from several papers in the field of electromagnetic interference and Power Quality. Electromagnetic interference (EMI) and power quality issues can damage equipment and with large medical equipment, failure can be dangerous and costly. A Power Quality Monitor was then tested for accuracy and ability to record EMI events before being placed at the University of Twente's Techmed building. This building contains many large medical equipment such as X-rays, CT Scanners, and MRI machines. Two of these devices were placed in the proximity of the MRI, however in different areas. The goal was to collect data and observe if EMI events or MRI scans could be seen by analyzing the voltage RMS data collected. This is important as an increasing number of electrical devices are being added to the grid especially ones that have sensitive and non-linear components. With the data that was collected no EMI events were detected and it was not possible to predict when an MRI scan was conducted using the voltage RMS data. This is likely due to limitations that the Power Quality Monitor has and potentially due to the building having a strong grid.**

I. Introduction

From buildings to boats to low voltage grids, power quality issues are causing disturbances and interfering with the reliability of the electricity received and the performance of electrical equipment [1]. The effects of low power quality are more apparent due to the increase in the use of sensitive and nonlinear electrical devices [2]. Power quality issues can have major consequences and it can be particularly hard to identify the cause without monitoring [2]. Consumers are experiencing various issues such as increased power losses, overheating issues, mechanical stress, and reduced lifetime of electrical hardware [2]. These issues can occur downstream in the grid and propagate to other networks and devices causing issues while the main electrical distribution point measures high power quality that is within the required standards [3].

One example of a power quality issue is of Dutch hospitals having their emergency generators tested, during this testing, it was discovered that power electronics that cause large inrush currents caused the generator to fail upon starting up [4]. Not all problems may be as serious as a power failure in a hospital, but many can cause inconvenience, disturbance, or damage. The risk is increased in hospital environments as well as the restart and calibration of medical devices can be time-consuming and prevent patients from receiving life-saving care [5].

Current research in the field of power quality focuses on the design of measurement systems or the measurement and diagnosis of power quality disturbances. Although the research takes place in different contexts than the intended research context of a hospital environment the methods and strategies implemented are still applicable. Matthee et. al [4] focused on the design of a measurement setup. This setup is designed to measure the electricity of either a low-inertia power grid or a power-distributed user network (PDUN). Voltage, current, and harmonics are measured at multiple points along a complex system. The measurements are also synchronized in time to allow the tracking of faults within the PDUN. This method was tested by analyzing the transient stability of a grid with several loads attached. The researchers then disconnected the loads from power to allow them to discharge and then reconnected. After being reconnected, there were large inrush currents which caused a fault. This method of multi-point measurement of a PDUN is useful in determining the circumstances which cause failure within the system and overall monitoring its health.

Sudrajat et. al [1] researched the real-life implementation of multi-point measurement setups. The most common method for measuring power quality issues and grid disturbances is to use a power quality monitor, this device is set up to track different parts of the grid at once and is connected to the internet or via LAN to collect the results at a computer [1]. These device measurements are intended to measure electrical characteristics that can help identify Electromagnetic Interference (EMI) events [1]. These events are voltages sags, surges, dips, flicker, interruption, and harmonic distortions [1]. The authors in [1] also consider Rapid Voltage Changes (RVC) to be a relevant event to track and states that RVC was not considered to have a large detrimental effect on the grid and that research has now discovered that RVC will cause power quality issues. Each paper aimed to investigate a different topic or scenario in the world of power quality disturbances and each paper also came to their own conclusions even if their approaches were similar. Sudjarat et. al [1] investigated EMI events on a 440V power distribution subsystem on a boat. They were able to set up a multi-node or multi-point measuring system and collect data to be analyzed and characterize the EMI events. Then they would correlate events to each other and evaluate the likelihood that an EMI event at one point caused an EMI event at another point by using a coincidence ratio. They found that RVC in the 440V distribution output had a 70% and 93.8% coincidence ratio of causing a voltage sag at the inputs of two uninterruptible power supplies. While a solution was not researched the results of this research highlight the effects of RVC and that to minimize and mitigate EMI events and power quality issues that RVC should be included as an event.

Smolenski et. al [3] similarly monitored a low voltage grid using multi-point measurement. They do not go into depth on which EMI events are affecting the grid specifically, however, the paper conducts research with the assumption that EMI events are occurring and attributes it to the large and growing amount of renewable energy that is connected to the low-voltage grid. Their research investigates several types of energy storage solutions that will help mitigate power quality issues in the low-voltage grid. The paper does not conclude with a one best low-voltage energy storage systems, however, it does compare the options with factors such as size, cost, and performance.

Grootjans and Moonen [2] similarly focused on the design of a measurement device as opposed to a setup. This device can connect to the mains and power itself while taking measurements and storing processed data either locally or transmitting them over Wi-Fi if possible. The main purpose of designing this measurement system was to fill a gap in the market since there are high-end expensive measurement devices and low-end cheap measurement devices. The researchers proposed to design a device that is in between the high-end price ranges. The low-end price range is less than 50 euros and the high-end prices are above 1000 euros. Grootjans and Moonen [2] made a device with a parts cost of 100 euros and can provide accurate results with customization. In the end, a power quality monitor was developed which has a parts cost of 100 euros and whose accuracy qualifies for classification as a Class A meter. Similarly, to Matthee et. al [4] the implementation of a multi-point measurement network is showcased. The paper shows how it can be used to identify issues within the system being monitored. This is done by measuring the voltage at multiple points such as an LED or motor and observing the effects of a power quality event and how that affects the other devices connected to the grid since the data is synchronized with time [4].

This thesis discusses the problems in the context of conducted EMI and the power quality disturbances that cause degradation. This was done to establish relevancy and increase understanding of power quality in a hospital environment. This includes a focus on grid monitoring and event labeling. All papers discussed used or designed multi-point measurement systems to aid in the observation, processing, and correlation of EMI events.

This thesis will use the previously discussed methods by using Power Quality (PQ) Monitors from the Power Electronics group of The University of Twente. These will be used to measure and monitor the electrical grid of the Techmed building, which operates large medical devices such as MRIs, CT Scanners, and X-ray machines. The PQ Monitors will be placed in proximity to MRI machines. The paper will first discuss the characterization of the device which was done to validate the accuracy of the values measured. Next, the ability of the device to measure EMI events as described in several IEC standards will be tested using a grid emulator. Finally, the data collected from the Techmed building will be analyzed to determine if there was any effect on the building's grid from the operation of MRI machines.

II. IEC Standards and EMI Events

For this research, the International Electrotechnical Commission (IEC) standards regarding EMI and power quality are used to define events. The IEC standards are used internationally and serve as a recommendation for the development of many products [6]. The IEC treats power quality as a section within EMC [7]. The IEC 61000-2-4 standard covers phenomena such as voltage deviations, voltage dips and short interruptions, and voltage unbalance [6]. Additionally, these phenomena count for electrical systems that are 50 or 60 Hz up to 35kV. The EMI events related to Voltage RMS measurements are voltage deviations that occur due to varying loads on the electrical network [6]. Additionally, voltage unbalance occurs in polyphase systems when there are different RMS voltages between the lines. Lastly, short interruptions occur when a voltage dip reaches 100%, usually caused by a fault in the grid, and can last up to 180s before the fault is cleared [6].

A. *Voltage Dips*

One of these EMI events is a Voltage Dip or Voltage Sag, depicted in Fig. 1.

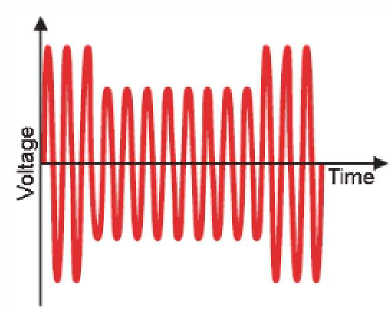

Fig. 1. Voltage Dip from [8]

This is defined as a drop in voltage somewhere in the electrical network that is below a certain level of the normal RMS amount. This level is 230V and 50 Hz in The Netherlands [9]. This is usually due to short circuits or large current draws from equipment connected to the grid [6]. The severity of a voltage dip is measured in two ways, with the depth of the voltage dip and the duration until the voltage recovers [6]. Additionally, the severity of the observed dip changes based on the distance away from where the fault occurs. This also means that near a short circuit, the voltage can drop to almost 100%, however, in events caused by large load variations the drop can be shallower [6]. The most common durations of voltage dips occur from half a period to one second, however, the dips can occur for a longer duration [6]. Voltage Dips also depend on the depth of change of voltage, often this is defined as a drop from the normal voltage RMS of 90% to 10% [10]. The percentage drop is usually measured using either the declared input voltage or a sliding reference [11]. The declared input voltage or U_{din}. would be the stated voltage value from the power supply [11]. In the case of the mains voltage level, this should be 230V RMS ideally. The sliding reference is an average of the RMS voltage for one minute preceding an EMI event [11]. The definition provided in [10] does limit the time of the voltage dip to 60 cycles which would be just over one second for the grid in The Netherlands [9]. However, [6] allows for dips that occur for longer periods as long as they are more than 10% or more lower than the normal RMS value of 230V.

B. Voltage Swells

Voltage swells are similar to voltage dips, but instead of a temporary voltage decrease, there is an increase as shown in Fig. **??**.

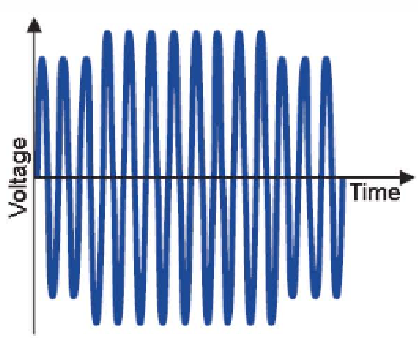

Fig. 2. Voltage Swell/Surge from [8]

Voltage swells are also compared to a reference voltage as mentioned earlier, either a declared input voltage or a sliding reference. The commonly used threshold for voltage swells is more than 10% increase from the normal voltage whether this is measured using declared input voltage or sliding reference [11].

The sliding reference has to be calculated using the 10 or 12-cycle voltage RMS which means that the measurement device must have a high sample rate, otherwise, the declared input voltage must be used [11]. A common duration of a voltage swell is not mentioned in [11], it only states that a voltage swell starts when the voltage breaches the threshold and ends when the voltage returns below the threshold.

III. Characterization

The device that will be used for the data collection is a Power Quality Monitor or PQ Monitor which was developed by the Power Electronics Group at the University of Twente. A simplified schematic of the device is shown in Fig. 3. The device measures data from the mains line using an energy meter from Analog Devices. This data is processed and sent to a website using a Wi-Fi-enabled ESP-32. Additionally, there is a battery so that the device can still take measurements for some time if there is a loss of power. The device also has an SD card where it can save data if there is no internet connection or if the connection is too slow. Lastly, there is an LED to indicate that the device has power and a temperature and humidity sensor to accompany the electrical measurements.

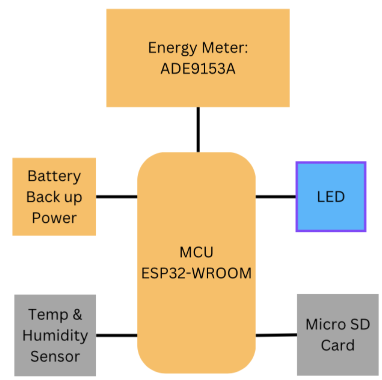

Fig. 3. Simplified Schematic of PQ Monitor

The device measures important electrical statistics such as Voltage and Current RMS, Apparent Power, and Reactive Power. A full list of measurement data is provided in Table I.

The PQ Monitor is intended to be used with single-phase devices compatible with a type F outlet. The device will be used to monitor the effect of the operation of MRIs within the Techmed building to emulate a hospital environment. Additionally, the device has a sampling rate of 0.5 Hz, or one sample every two seconds. Due to this only EMI events such as voltage digs, surges/swells will be observed. Rapid voltage changes or RVC will not be measured as the sampling rate is not high enough to observe. Additionally, only grid voltage RMS is used since the device at the MRI cannot have the MRI plugged through it directly, therefore the PQ Monitor will not have any load attached and will not observe readings for current or power. Lastly, the measurements for frequency, temperature, and humidity do not add any insights to the intended research. This is especially true for frequency as the device does not measure frequency harmonics which are used to assess EMI and power quality [11].

A. Validation of the Device Accuracy

To validate the accuracy of the device, measurements will be taken and compared to the Yokogawa WT500. The Yokogawa WT500 has an accuracy of 0.1%. [12] The measurement setup is shown in Fig. 4.

TABLE I
TABLE OF MEASUREMENTS TAKEN BY PQ MONITOR

Data Type:	Unit:	Function:
Line Current RMS	mA	Current RMS of Loads
Line Voltgae RMS	mV	Voltage RMS of the Grid
Line Mean Active Power	mW	Average Active Power Draw of the Load
Line Mean Reactive Power	mvar	Average Reactive Power Draw of the Load
Voltage Frequency	Hz	AC Frequency of the Grid
Line Power Factor		Real power relative to apparent power
Phase Angle	Degrees	Phase of AC Voltage Signal
Line Mean Apparent Power	mVA	Average Apparent Power Draw of the Load
Forward Active Energy	mWhr	Active energy delivered from the grid
Reverse Active Energy	mWhr	Active energy delivered to the grid
Absolute Active Energy	mWhr	Absolute active energy
Forward Reactive Energy	mVARhr	Reactive energy delivered from the grid
Reverse Reactive Energy	mVARhr	Reactive energy delivered to the grid
Absolute Reactive Energy	mVARhr	Absolute reactive energy
Metering Status		
System Status		
Temperature	C	Temperature inside the device
Humidity	%	Humidity inside the device
Timestamp	UTC	Time of sample in UTC format

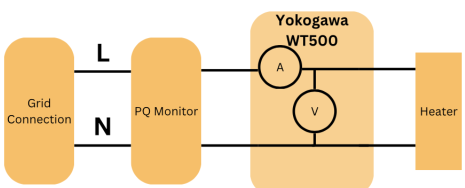

Fig. 4. Characterization Measurement Setup

The measurement setup uses a heater as a load which could be switched between three heat settings to mimic different resistive loads. The three heat settings are labeled on the heater as 1, 2, and 3. Videos of the power analyzer were taken with a laptop to synchronize the time, these values were manually written down later to compare to the data taken by the PQ Monitor. This setup is shown in Fig. 5.

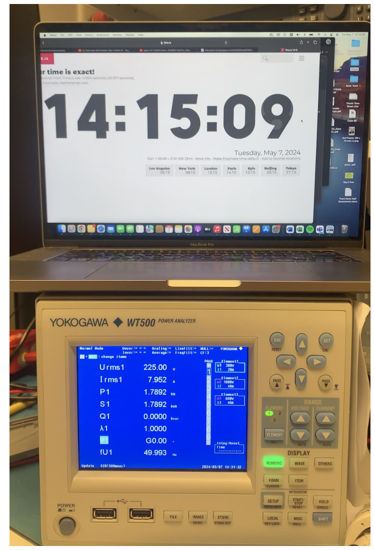

Fig. 5. Test Setup with Time Synchronization

The voltage and current measurement probes were set up by cutting and splitting a power cable. They were then connected inside a box so leads could come out for voltage and current measurement inputs to the Yokogawa WT500.

Each load was tested five times to account for variations in trials. The Active Power, Voltage RMS, and Current RMS were averaged over a 30-second period. The average error of the five trials compared to the reference measurement of the WT500 is shown in Table II.

TABLE II
TABLE OF CHARACTERIZATION RESULTS

	Load 1	Load 2	Load 3
Error Voltage RMS (%)	0.053	0.196	0.482
Error Current RMS (%)	0.148	0.171	0.746
Error Active Power (%)	0.240	0.367	1.249

The Power Analyzer (Yokogawa WT500) was used as the reference where its values were assumed to be accurate, at least within 0.1%. The errors were calculated using the following equation in Eq. 1 taken from [13].

$$\%Error = 100 \left| \frac{y_{\text{PQ}} - y_{\text{PA}}}{y_{\text{PA}}} \right| \quad (1)$$

Where y_{PQ} represents a given quantity of interest such as voltage, current, or active power measured with the PQ monitor, and y_{PA} is the corresponding quantity measured using the power analyzer.

After the experiment and the results from Table II it is clear that the error stays below 2% which qualifies the device as a Class A energy meter and will be suitable to use for measurements in terms of accuracy [2].

IV. Grid Emulator: Emulated EMI Events

The events described in Section II will be emulated using an IT7624 Programmable AC Power Source. This is done to test whether the PQ Monitor can detect certain EMI events before data is collected from the Techmed building. This device has many settings that can be altered to create the desired signal. This includes voltage amplitude, frequency, and phase angle. These settings can also be programmed into steps so that the values can be changed over time. This can be done by making a list and setting a certain amount of time for each row before the values change and move to the next row. With this, it is more clear what kind of changes occurred to cause these events.

Voltage dips and Voltage swells will be emulated for the recommended threshold of a minimum of 10%. Additionally, the experiment will be run multiple times with varying durations of events. The duration of the events will be 0.5 cycles, 60 cycles, and two seconds. These values correspond to the common minimum and maximum duration of voltage dips mentioned in [6] and [10]. Additionally, the two-second duration was added as this is the minimum resolution in time of the PQ Monitor being used. By emulating these events, it can be determined whether certain events will be detectable or if not what will they look like when measured by the PQ Monitor.

The lists configured into the AC Power Source can be found in Table III.

TABLE III
AC Power Source Configurations

	Voltage Amplitude (V)	Time (s)
Voltage Dip 0.5 Cycles	230	30
	207	0.01
Voltage Dip 60 Cycles	230	30
	207	1.2
Voltage Dip 2 Seconds	230	30
	207	2
Voltage Swell 0.5 Cycles	230	30
	253	0.01
Voltage Swell 60 Cycles	230	30
	253	1.2
Voltage Swell 2 Seconds	230	30
	253	2

The voltages of 207 V and 253 V are 10% above and below the nominal voltage, 230 V.

Each emulation will show to what extent the PQ Monitor can capture events such as a dip and sag.

The first test was to emulate a voltage dip of 10% below the nominal voltage for 0.5 cycles. The results in Fig. 6 show that the PQ Monitor was not able to record this event.

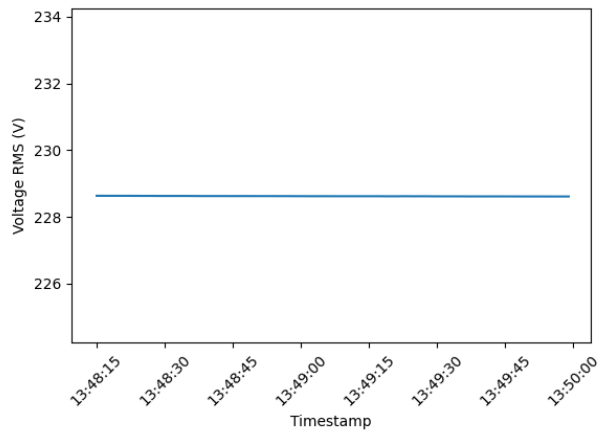

Fig. 6. 0.5 Cycle Voltage Dip Emulation

Following this, the 60-cycle or 1.2-second voltage dip was emulated. This emulation showed better performance in being recorded as dips are shown in the data, but are not always as large as they should be. The first dip in Fig. 7 is shallower than it should be, however, the device can accurately record the second dip. This is likely due to where the dip occurs in the RMS averaging period, for example, if the dip solely occurs in one two-second RMS calculation or gets split up into two. Therefore, it is possible that dips or swells can be missed, however, this means it is also important to pay attention to shallower dips or swells.

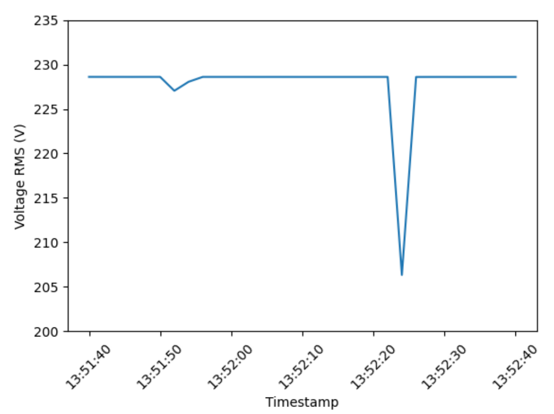

Fig. 7. 60 Cycle Voltage Dip Emulation

Finally, the voltage dip was emulated for two seconds which is the sample rate of the device. At this duration, the device was consistently able to record the event as seen in Fig. 8.

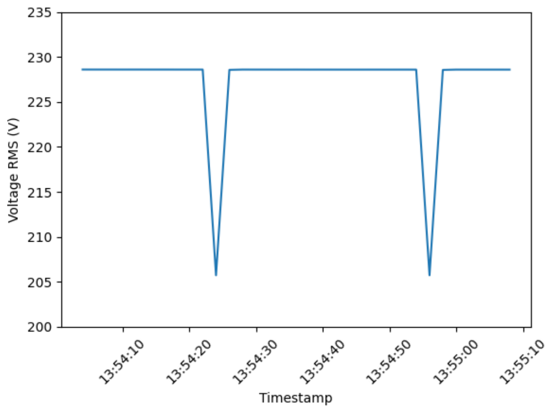

Fig. 8. 2 Second Voltage Dip Emulation

The next event that was simulated was the Voltage Swell or Surge. This experiment was also repeated three times for 0.5 cycles, 60 cycles, and 2 seconds. The first emulation was also not visible to the PQ Monitor similar to the voltage dip. This can be seen in Fig. 9.

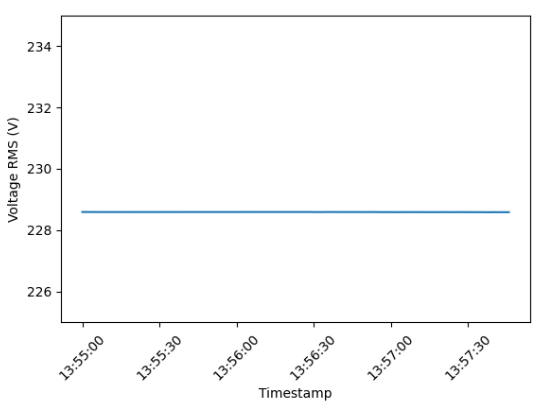

Fig. 9. 0.5 Cycle Voltage Swell Emulation

The 60-cycle emulation for the voltage swell also had similar results as the voltage dip emulation. The first peak in Fig. 10 was recorded however it did not capture the whole event and was shorter than it should have been, however, the next peak was recorded correctly.

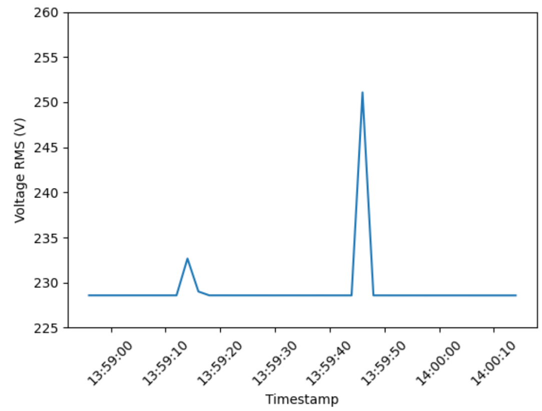

Fig. 10. 60 Cycle Voltage Swell Emulation

The last experiment in this section was the Voltage Swell for two seconds. The device was again able to record these events and showed peaks at the correct voltage in Fig. 11 just like the voltage dip emulations.

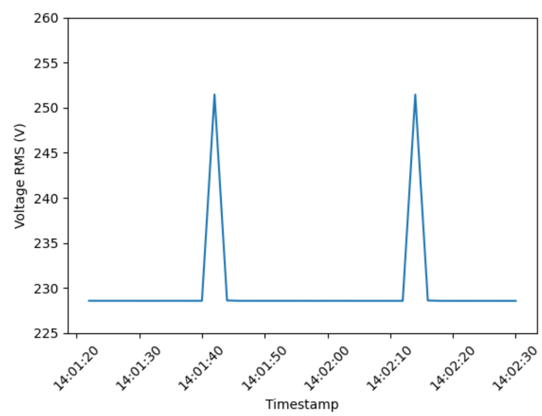

Fig. 11. 2 Second Voltage Swell Emulation

After discussing the results of the emulations conducted it is clear that the device can only reliably record EMI events with a duration of two seconds or longer. This means that most voltage dips as mentioned in [6] would not be detectable, however, it is still possible for these events to occur at longer durations, and at slightly shorter durations there may still be indications of an event occurring as in the first peaks in Fig. 7 and Fig. 10.

V. MRI Data Collection

The PQ Monitors were used to collect data to try to observe any effects from EMI events in other sections of a building's grid. Two PQ Monitors were installed at the Techmed Building at the University of Twente. The university has two MRIs in this lab with magnetic strengths of 0.25T and 1.5T [14]. The first PQ Monitor was installed as close as possible to the control room of an MRI system. The second PQ Monitor was installed across the hall on a different circuit group to test if there are any power quality phenomena to investigate if this also propagates further in the building. Both PQ Monitors were connected to the internet using a TP-Link M7200 Mifi Router and are shown in Fig. 12 and Fig. 13.

Fig. 12. Power Quality Monitor #1

Fig. 13. Power Quality Monitor #2 and TP-Link Mifi Router

The data was collected between May 16th and May 24th. A reservation schedule was also provided to help determine periods of time when the MRIs could be running. A 24-hour view of the data is shown in 14 and shows the voltage variations and deviations that occur over time and is useful to understand the overall health of the grid.

A. Results

After reviewing the data collected from the Techmed building no EMI events were occurring for two seconds or longer.

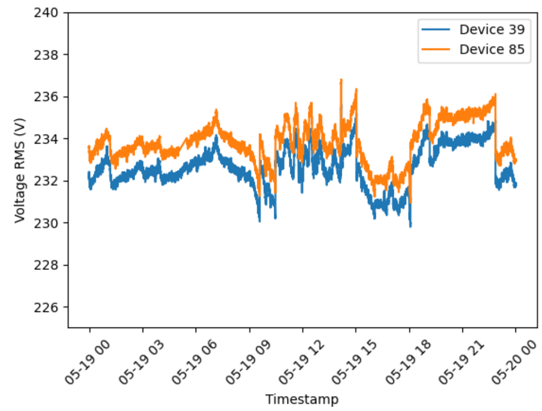

Fig. 14. 24-Hour MRI Data

This matters as events occurring for less than two seconds may not be visible in the data that was collected. Therefore, it cannot be stated that no events occurred at all. The CSV file collected from the PQ Monitor was processed and visualized with a graph with a program made with Python. The events considered were those covered under the IEC 61000-2-2 and IEC 61000-3-3 standards [15], [16]. It would not be possible to determine if any EMI events occurred within the two-second window due to the sample rate of the device. There were however several patterns that occurred consistently throughout the measurements which caused the voltage level to deviate from its desired level. These events are not considered dangerous but will be highlighted. Additionally, since these patterns are only slight deviations from the desired voltage they are referred to as variations instead of events in power quality [7].

Four events are created to define the recurring patterns in the data. These events are as follows, Sharp or Sudden Drop, Sharp or Sudden Increase, Sharp drop with recovery, Sharp increase with recovery. These events do not meet the commonly used standards and definitions but do have similar characteristics as other EMI events such as Voltage Drop, Voltage Swell, and Rapid Voltage Change.

The first two events that appear repeatedly in the data could resemble a voltage dip in Fig. 15 and voltage swell in Fig. 16, however, there is no recovery back to the normal level, at least until much later.

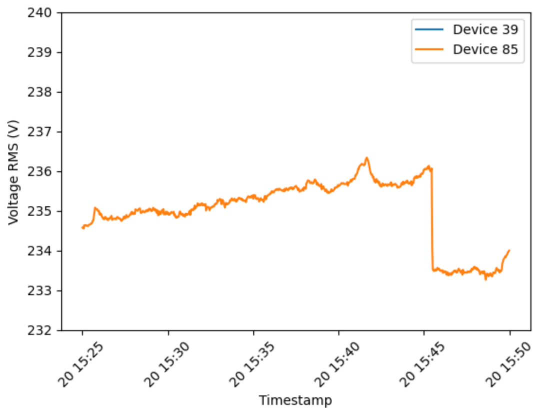

Fig. 15. Sharp or Sudden Drop

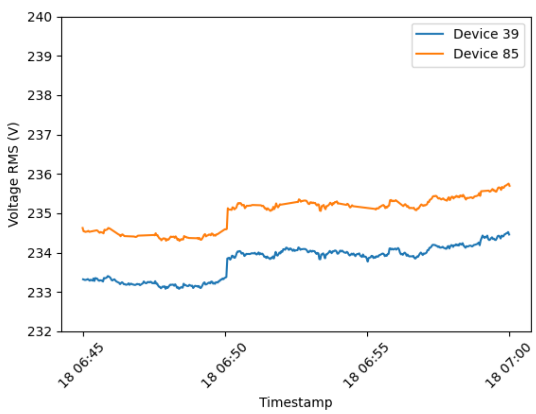

Fig. 16. Sharp or Sudden Increase

The last two events are similar, however, do return to the previous voltage level much faster, Fig. 17 resembles a voltage dip and Fig. 18 resembles a voltage swell.

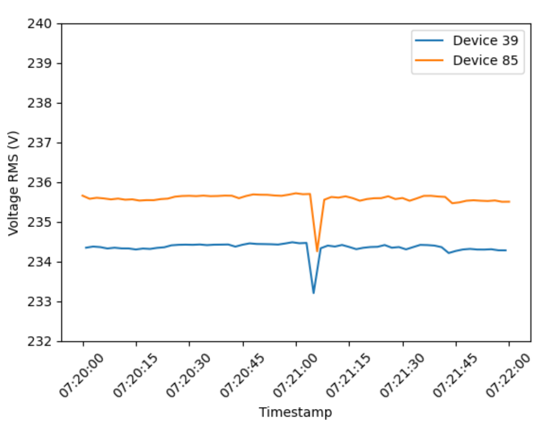

Fig. 17. Sharp drop with recovery

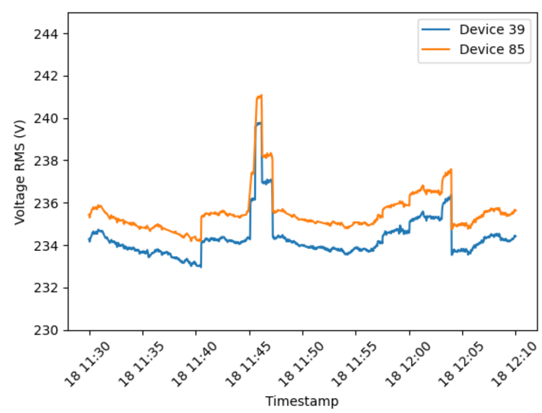

Fig. 18. Sharp increase with recovery

Additionally, the defined events do not indicate if an MRI scan occurred or not as the events occur outside of the reservation times as well as within.

The potential causes of these events which cause the voltage to deviate from the desired level could be due to loads being connected and disconnected from the grid [6]. Different loads will cause the grid's voltage level to drop or alternatively rise. This is also why the devices differ in their voltage level as one device had no load attached and the other had a charger for the Wi-Fi router plugged in. There is also a current visible when a load is attached and otherwise the current remains zero as there is no load, this can be seen in Fig. 19.

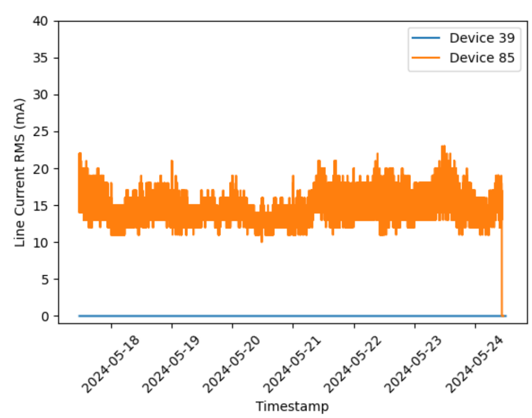

Fig. 19. Current RMS of Both Devices

VI. Future Research

In the future, several improvements can be made to the design of the PQ Monitor and the execution of the experiments to achieve better data and discover more insights into power quality affecting grids in medical environments or grids in the vicinity of MRI machines. The first recommendation is to increase the sample rate of the PQ Monitor. This is because the most common EMI events are occurring with a duration of less than two seconds. It is important to be able to see these occurring and be able to analyze them, this also helps immensely with identifying potential causes by being able to track where an event started and how it propagates to other measurement points in the grid. In combination with this, the local storage of the device may need to be increased since more data will be collected. A compression algorithm should also be created for the data to increase upload rates. Each device may need its own router as well. The make uploading from the device more efficient an algorithm could be created as well to make improvements from the side of the PQ monitor. The second recommendation is to monitor and test grids that are known to be weak, this could include hospitals or medical clinics in third-world countries where the electrical infrastructure is lacking.

VII. Conclusion

This thesis tested and validated the accuracy of the University of Twente's Power Quality Monitor and found that it is accurate for taking voltage and current measurements within 2%. Additionally, the ability of the device to detect certain EMI and power quality events such as voltage dips and swells was evaluated. The results showed that the device can be used to detect events that occur for two seconds or longer due to the limited sample rate. An interface was also created to visualize the data collected from the power quality monitor. Data collection was also conducted at the university's medical building and it was determined that no EMI events of voltage drops or swells occurred for two seconds or longer and that it was not possible to predict or pinpoint MRI scans based on the voltage data. Over a 24-hour period, many voltage deviations can be observed and several self-defined events were labeled. These events were not severe and show that the grid of the university if strong. However, these events occurred within and outside of the possible time periods when an MRI scan could be done and therefore any influence of the MRI on the grid could not be confirmed.

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Appendix

A. AI Statement

During the preparation of this work, the author used Gemini in order to create code to make graphs. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work. During the preparation of this work, the author used Consensus in order to search for academic papers. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work. During the preparation of this work, the author used Grammarly in order to check spelling and grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.