# Embedded Acquisition Device for the Sonification of AC Mains Parameters

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# Abstract

This thesis presents the development of an embedded acquisition device and its use for the real-time sonification of Alternating Current (AC) power system parameter variations. Specifically, a fully custom Printed Circuit Board (PCB) was designed and manufactured. The electronics/ firmware design, development and manufacturing of the embedded system are outlined in detail. The designed system measures the voltage waveform from a North American household AC outlet (120 V/60 Hz) along with the current waveform flowing through any configurable AC devices/appliances with a maximum current rating of 15 A. From the measured current and voltage waveforms further AC mains parameters are extracted which are discussed in detail within the thesis. Using the measured parameters, various sonification methods were developed and are computed by the designed embedded system. The measured parameters are mapped to (Musical Instrument Digital Interface (MIDI) signals which are played through MIDI instruments. Multi-channel MIDI is presented with various AC parameters controlling multiple different instruments in parallel including software synthesizers and drum kit samplers. Sonification examples are presented displaying the various introduced sonification methods. Finally, an exploratory evaluation of the full system was made where electrical engineers evaluated several sonification strategies, providing feedback on the initial research and suggestions for future applications.

# Résumé

Cette thèse présente le développement d'un dispositif d'acquisition embarqué et son utilisation pour la sonification en temps réel des variations des paramètres d'un système électrique à courant alternatif (CA). Plus précisément, une carte de circuit imprimé (PCB) entièrement personnalisée a été conçue et fabriquée. La conception, le développement et la fabrication de l'électronique/micro-logiciel du système embarqué sont décrits en détail. Le système conçu mesure la forme d'onde de tension d'une prise de courant domestique nord-américaine (120 V/60 Hz) ainsi que la forme d'onde de courant traversant tous les appareils/appareils CA configurables avec un courant nominal maximum de 15 A. À partir des formes d'onde de courant et de tension mesurées, d'autres paramètres du secteur CA sont extraits, qui sont discutés en détail dans la thèse. En utilisant les paramètres mesurés, diverses méthodes de sonification ont été développées et sont calculées par le système embarqué conçu. Les paramètres mesurés sont transformés en signaux MIDI (Musical Instrument Digital Interface) qui sont joués via des instruments MIDI. Le MIDI multicanal est présenté avec divers paramètres CA contrôlant plusieurs instruments en parallèle, y compris des synthétiseurs logiciels et des échantillonneurs de sons de batterie. Des exemples de sonification sont présentés affichant les différentes méthodes de sonification introduites. Finalement, une évaluation exploratoire du système complet a été réalisée au cours de laquelle des ingénieurs électriciens ont évalué plusieurs stratégies de sonification, fournissant des commentaires sur la recherche initiale et des suggestions pour des applications futures.

# Acknowledgements

This project could not have been completed without the support of colleagues, friends, and family. Many thanks to my co-supervisor Marcelo M. Wanderley for his guidance and expertise in parameter mapping and sonification. Additionally many thanks to my co-supervisor Luke Dosiek of Union College, for continuing to work with me on power systems sonification. The concept for this research originally started as a brief idea proposed by Luke, which eventually became my undergraduate electrical engineering thesis when I was a student at Union College in 2017. Since then, the research has grown immensely. Also many thanks to Dave Durfee of Brown University and Bay Computer Associates Inc., who gave excellent, experienced mentorship and guidance in the electronics design, PCB layout, and firmware design of the embedded system. Finally, I would like to thank my friends and family who have provided moral support and love throughout my journey to complete this master's degree.

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# List of Acronyms

**AC** Alternating Current
**ADC** Analog-to-Digital Converter
**AFE** Analog Front End
**ANSI** American National Standards Institute
**BPM** Beats Per Minute
**CMSIS** Common Microcontroller Software Interface Standard
**DAW** Digital Audio Workstation
**DC** Direct Current
**DR** Data Ready
**DSP** Digital Signal Processing
**EMI** Electromagnetic Interference
**FFT** Fast Fourier Transform
**FR4** Flame Retardant 4
**GPIO** General Purpose Input/Output
**HAL** Hardware Abstraction Library
**IAM** Individual Appliance Monitor
**IC** Integrated Circuit
**IEC** International Electrotechnical Commission
**ISR** Interrupt Service Routine
**LDO** Linear Drop Out
**LEDs** Light Emitting Diodes
**LI-PO** Lithium Polymer
**MCU** Microcontroller Unit
**MIDI** Musical Instrument Digital Interface
**PC** Personal Computer
**PCB** Printed Circuit Board
**PMU** Phasor Measurement Unit

**POC** Proof of Concept

**RGB** Red/Green/Blue

**RMS** Root Mean Square

**SPI** Serial Peripheral Interface

**THD** Total Harmonic Distortion

**UART** Universal Asynchronous Receiver-Transmitter

**UL** Underwriters Laboratories

**USB** Universal Serial Bus

**WAV** Waveform Audio File Format

# Chapter 1

# Introduction

It is known that countries have different AC electrical characteristics. From 120 V/60 Hz in North America to 220 V/50 Hz in continental Europe, one tends to think of these features as static. It is less known that AC mains parameters are constantly changing due to the misalignment of synchronous power generators at power stations and local changes in system *electrical load*, a component that consumes energy from a power source. Power grids are tightly controlled and the voltage AC waveform appears to be constant and unchanging. Before the development of Phasor Measurement Unit (PMU), power flow measurements were used to infer the state of a power system. These estimates did not allow for direct measurement of the state of a power system and observation would reveal that a system was static and unchanging [1]. In reality, small variations in *distribution frequency* and *magnitude* can be observed in the power grid mains voltage signal. These small variations occur when the system is in normal *ambient* conditions [2]. Additionally, rare system events like a power line or equipment failure can cause *transient ring-down* and *forced oscillation* responses to occur which have much larger variations in power line voltage and distribution frequency [3], [4]. Power distribution quality to electrical loads can also be observed in the current waveform, which is the power flowing and consumed by the load. Depending on its properties, the power drawn by the load can cause vast variations in the voltage and current waveforms, e.g. in voltage magnitude. An electrical load can also cause delays between the times at which the voltage and current waveforms peak, which determines the *power factor*, an important parameter used for monitoring the efficiency of power distribution systems. Furthermore, non-linearities in electrical loads can cause *harmonic distortion*, i.e. integer multiples of the AC mains frequency, as well as high frequencies associated with switch-mode power supplies. Understanding such factors is an essential asset for engineers working with distribution systems, and is typically done using plots, graphs, or other visual aids. I hypothesize that with sonification, specifically parameter mapping sonification, auditory aids can simplify the process of understanding the significance of data variations in power distribution systems and convey information on the state of the system. The following sections provide a background overview of power systems theory and separately sonification.

## 1.1 Power Systems Theory

With the use of PMUs and signal processing, various information can be extracted from an AC mains voltage and current waveform. Once voltage or current data is measured with a PMU system, parameters can be extracted using a Fast Fourier Transform (FFT) of the measured waveform data.

As discussed in [2], the instantaneous 60 Hz distributed AC mains voltage is a two-element complex number:

$$\bar{V}(t) = V(t)e^{j\theta(t)} = V(t)\angle V_{\theta(t)} \tag{1.1}$$

where $j$ is the imaginary number, $V(t)$ is the voltage Root Mean Square (RMS) magnitude, and $\angle V_{\theta(t)}$ is the complex voltage number phase. This equation can also be used for the representation of the current phasor:

$$\bar{I}(t) = I(t)e^{j\theta(t)} = I(t)\angle I_{\theta(t)} \tag{1.2}$$

where $j$ is the imaginary number, $I(t)$ is the current RMS magnitude, and $\angle I_{\theta(t)}$ is the current complex number phase.

Additionally, this phasor representation can be expanded for each voltage and current harmonic off of the 60 Hz fundamental, therefore creating the following:

$$\bar{V_n}(t) = V_n(t)e^{j\theta_n(t)} = V_n(t)\angle V_{\theta_n(t)} \tag{1.3}$$

$$\bar{I_n}(t) = I_n(t)e^{j\theta_n(t)} = I_n(t)\angle I_{\theta_n(t)} \tag{1.4}$$

where n is the harmonic number.

### Harmonic RMS Magnitude

For both voltage and current, the RMS magnitude, $V_n(t)$ and $I_n(t)$ are calculated using the following equation:

$$K_n(t) = 2 * \frac{\sqrt{(Re(z_n))^2 + (Im(z_n))^2}}{N} \tag{1.5}$$

where $K_n(t)$ is the phasor RMS magnitude of $n^{th}$ harmonic frequency bin, $K$ represents either voltage $V$ or current $I$, $z$ is the FFT bin output complex number, and N is the FFT Size.

### Harmonic Phase

Additionally, the voltage and current bin phases are calculated using the following:

$$K_{\theta_n}(t) = atan2\left(\frac{Im(z_n)}{Re(z_n))}\right) \tag{1.6}$$

where $K_{\theta_n}$ is the, V or I, phase of the $n^{th}$ harmonic frequency bin and $z$ is the same as used in equation 1.5.

### Fundamental Distribution Frequency

The phase of the 60 Hz bin can be used with the equations discussed in [2], to calculate the fundamental distribution frequency through phase differentiation. The initial phase before the first data acquisition is set to 0. After each data acquisition and FFT computation, the current fundamental 60 Hz bin phase is subtracted from the previous data period 60 Hz bin phase to create a $dV_\theta$ value which is equivalent to the following operation:

$$dV_\theta = V_{\theta_1}(t) - V_{\theta_1}(t-1). \tag{1.7}$$

Then, from [2]:

$$f(t) = \frac{1}{2\pi}\frac{d}{dt}(2\pi f_1 t + \theta(t)) = f_0 + \Delta f(t) \tag{1.8}$$

can be further simplified to:

$$f(t) = f_1 + \frac{f_1 * dV_\theta}{2\pi} \tag{1.9}$$

where $f_1$ is the fundamental frequency, 60 Hz.

### Power Triangle

For AC systems, the distributed power can be analyzed using the power triangle shown in figure 1.1.

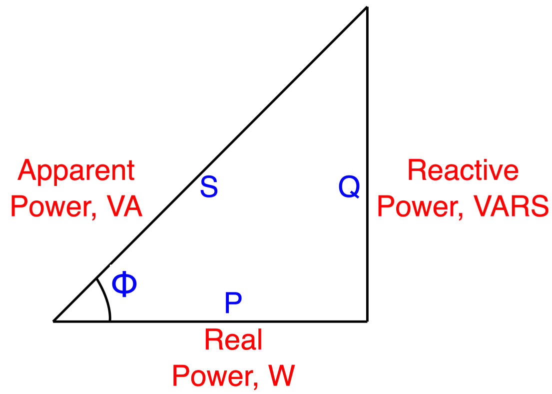


**Fig. 1.1** AC Power Triangle

In the figure, P is the *real power* used for useful real work such as heat, light, and motion. Q is the *reactive power* "wasted" on the support of electromagnetic fields with some being useful and some parasitic. S is the *apparent power* which is the total power in an AC system, therefore the combination of the real and reactive power [5]. Φ is the phase difference between the voltage and current waveform which for the fundamental can be calculated as

$$\Phi_1(t) = V_{\theta_1}(t) - I_{\theta_1}(t). \tag{1.10}$$

The real, reactive, and apparent power can then be calculated for the 60 Hz fundamental power signal, using the following equations:

$$P_1(t) = I^2R = V_1(t) * I_1(t) * cos(\Phi_1(t)) \tag{1.11}$$

$$Q_1(t) = I^2X = V_1(t) * I_1(t) * sin(\Phi_1(t)) \tag{1.12}$$

$$S_1(t) = V_1(t) * I_1(t) \tag{1.13}$$

### Power Factor

Power factor represents the ratio of real power and the total apparent power. It can be used as a metric for power distribution efficiency. Using the phase difference equation 1.10, the power factor of the signal can be calculated as:

$$pf(t) = P/S = Cos(\Phi_1(t)). \tag{1.14}$$

### Harmonic Distortion

Harmonic distortion is calculated on both the voltage and current harmonics. As discussed in [6], there are two equations used to calculate Total Harmonic Distortion (THD) of a signal:

$$THD_{K_f}(t) = \frac{\sqrt{(h_2(t))^2 + (h_3(t))^2 + ...(h_n(t))^2}}{h_1(t)} \tag{1.15}$$

$$THD_{K_r}(t) = \frac{\sqrt{(h_2(t))^2 + (h_3(t))^2 + ...(h_n(t))^2}}{\sqrt{(h_1(t))^2 + (h_(t)2)^2 + (h_3(t))^2 + ...(h_n(t))^2}} \tag{1.16}$$

where $h_1, h_2, ..., h_n$ represents the harmonic RMS value for harmonics 1, 2, ..., n [6]. Equation 1.16 represents THD of the entire AC signal, while equation 1.15 represents the THD relative to the fundamental harmonic. $K$ represents either voltage, $V$, or current, $I$, as above in 1.5.

### Non-linear Load Power Factor

As described in [7], the harmonic distortion from any non-linearity in a load should be considered for calculating "true" power factor. When calculating power factor for any non-linear load, you must consider the contribution from the harmonics using the below equation.

$$pf_{true}(t) = pf_{disp} * pf_{dist} = \frac{P_1(t)}{S_1(t)} * \frac{1}{\sqrt{1 + (THD_{I_f}/100)^2}} \tag{1.17}$$

## 1.2 Sonification

Sonification is a research method that uses sound to convey information [8]. The International Community For Auditory Display, founded in 1992, is the main research community for the discussion and publication of works in sonification. The community hosts a conference every year for the introduction and discussion of new sonification techniques/works, called the International Conference on Auditory Display. The community is described as being "a forum for presenting research on the use of sound to display data, monitor systems, and provide enhanced user interfaces for computers and virtual reality systems. It is unique in its singular focus on auditory displays and the array of perception, technology, and application areas that this encompasses" [9]. Although developed before the establishment of the term sonification, a well-known effective sonification application includes the Geiger counter for measuring ionizing radiation [10].

One of the main sonification methods is parameter mapping sonification. Parameter mapping sonification, involves mapping data parameters to auditory parameters, i.e. amplitude, pitch, etc. of sound [8]. An issue with sonification and parameter mapping sonification is that the sonification of data can be unpleasing and does not necessarily produce meaningful results as these types of sonifications can lead people to switch sonifications off. It is important to include the user when designing an effective sonification [11]. Quinton et. al mention that "sound is a temporal phenomenon and sonification can be effective at representing time-based data [11]. With variations in AC electrical waveforms being time-varying, sonification is a very interesting method to use for the analysis of such data. Additionally, few works of sonification focused on power systems exist, other than examples listed in **Chapter 2**, which primarily focus on bringing awareness of power consumed in buildings and households.

In the first part of the thesis, I designed a device for the acquisition of local power grid AC mains data in collaboration with Union College, NY. Specifically, a custom electronic circuit board was created that allows for local AC mains power signal voltage and current, to be measured from which various parameters are extracted. In the second part, I used the embedded system to create examples of parameter mapping sonifications to sound synthesis parameters for auditory analysis. The main intent of this research is not to create "effective" or "meaningful" sonifications but to provide the framework for users to easily create sonifications of power system parameter variations.

## 1.3 Outline of Thesis

This thesis has six chapters. **Chapter 1** concludes in this section and introduces the project and relevant background information. **Chapter 2** provides a literature review of existing power system data acquisition systems and power system sonification systems and introduces a set of design requirements for the embedded acquisition device. **Chapter 3** presents the electrical design processes and assembly of the embedded acquisition device while **Chapter 4** presents the firmware design processes for the data measurement and AC parameter extraction. The sonification methods designed and used by the acquisition device are explained in **Chapter 5** with included examples and a small-size electrical engineer evaluation of initial results. The thesis concludes with **Chapter 6** which includes a discussion of the project's impact and future work needed to expand on the research.

# Chapter 2

# Power System Data Acquisition & Sonification Systems

This chapter presents a literature review of existing power system data acquisition systems and, more specifically, works on power system sonification. It then introduces design requirements for a custom embedded acquisition device for the sonification of AC mains parameters, based on the literature review, which are listed in the last section of the chapter.

## 2.1 Power System Voltage & Current Data Acquisition Systems

Various dual-channel AC voltage/current Integrated Circuit (IC) chips exist with corresponding evaluation boards for power system monitoring[1]. Microchip Technology[2] produces the most relevant IC technology and corresponding evaluation boards.

Two of their most popular products are the MCP39f511N and the MCP3901 Analog Front End (AFE) ICs [12], [13], which each have corresponding evaluation boards [14], [15]. Both AFE IC and evaluation board systems are reviewed. In the following sections the IC MCP39F511N will be referenced as IC1 and the MCP3901 IC will be referenced as IC2.

[1] `https://www.digikey.com/en/products/filter/pmic-energy-metering/765`
[2] `https://www.microchip.com/`

### 2.1.1 MCP39F511N AFE Power Monitor Demonstration Board

The IC1 power monitor demonstration board is an energy metering board intended for use of 60/50 Hz and 120/240V system AC voltage and current measurement.

**Fig. 2.1** MCP39f511n Demonstration Board [14]

Specifically, the board measures voltage and current separately on two data acquisition channels. The mains voltage is measured via a resistor divider, while the load current is measured across a neutral-connected shunt resistor. For each channel, the system calculates "active power, reactive power, RMS current, RMS voltage, active energy, (both import and export), reactive energy and other typical power quantities" [14]. The device supports two separate loads for a total of 15 A current draw and has a user-isolated Universal Serial Bus (USB) interface. The demo board also allows for the mains voltage and device loads to be connected via typical International Electrotechnical Commission (IEC) input and output connectors.

The system monitors the current and voltage waveforms in the time domain. As a result, the device does not measure THD or voltage/current fundamental frequency, which are important parameters needed for power system analysis. The device requires a connection from the USB port to a separate Personal Computer (PC), for use with a corresponding power utility software provided with the device, to compute frequency domain analysis. Additionally, this board costs $252.99 USD per unit, which is considered expensive for our goals.

IC1 was considered for possible use in the design of a custom embedded system, but it has a complex IC footprint with an exposed metal pad on the bottom of the IC as shown in 2.2.

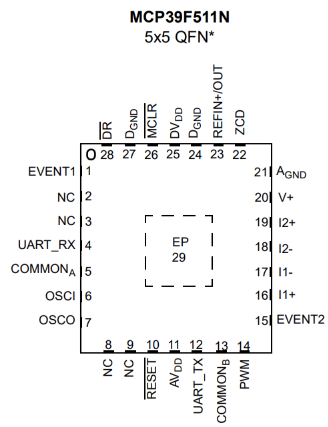


**Fig. 2.2** MCP39f511n IC Package Configuration [13]

This footprint configuration makes it difficult for manual soldering/assembly and an expensive automated pick and place machine and re-flow oven would need to be used for proper assembly on a custom Printed Circuit Board (PCB).

### 2.1.2 MCP3901 Evaluation Board

The MCP3901(IC2) evaluation board is a cheaper alternative to the IC1 at $130.89 USD per unit. The IC2 evaluation board measures the same parameters as the IC1 but also measures power factor [15]. Similar to the IC1 demonstration board, the IC2 evaluation board has an isolated USB interface, and requires a separate PC for frequency domain analysis, extraction of THD, and measurement of voltage/current fundamental frequency.

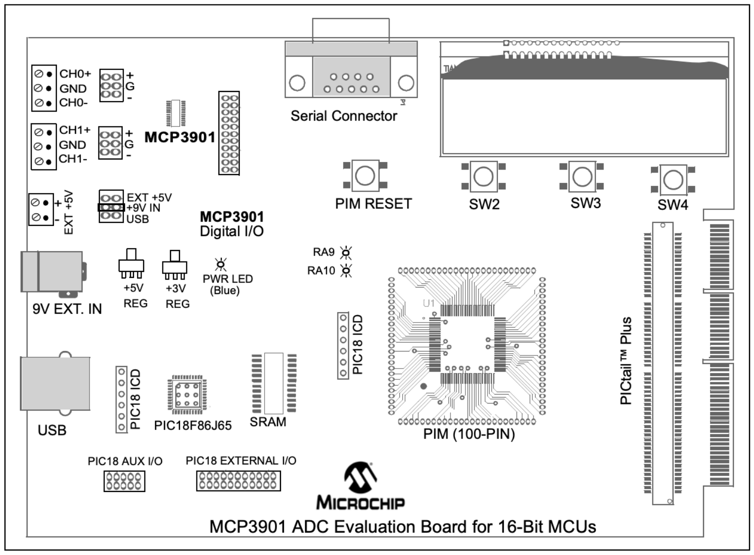


**Fig. 2.3** MCP3901 Evaluation Board [15]

One main difference in the IC2 evaluation board, is that the mains voltage and load current acquisition circuits require terminal clip connections for the input mains and the system electrical load. Therefore it does not support typical IEC outlet connections. This makes varying the load and disconnecting the system more complicated and therefore less of a "plug-and-play" device.

On the actual IC2 footprint level, unlike IC1, the IC is manufactured in various footprints, including a 20-SSOP, which is very simple for manual assembly.

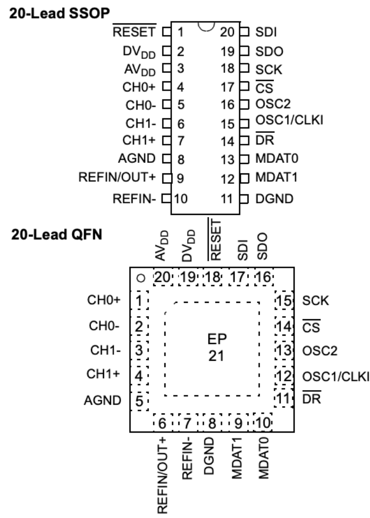


**Fig. 2.4** MCP3901 IC Package Configurations [12].

IC2 allows for differential measurement of two separate voltage channels with a maximum differential voltage of 500 mV per channel. Within the chip is a delta-sigma modulator with integrated decimation *sinc* filters. In short, the chip samples the input channels at very high sampling frequencies configured from the input master clock signal. Additionally, it is configured to decimate (down-sample) the incoming sampled data to a power of two divisor sampling rates. IC2 also has configurable channel gains and Analog-to-Digital Converter (ADC) resolution. IC2 outputs the acquired data and is controlled through the Serial Peripheral Interface (SPI) communication protocol [12].

As a result of the above evaluations, IC2 became the best IC candidate for measuring high voltage current and voltage waveforms. Due to the system limitations and cost of the IC2 evaluation system, the IC2 chip itself was ideal in use for the design of a custom embedded acquisition and sonification device. A custom embedded system allows for the AC parameter measurements/extraction and sonification parameter mapping to be completed in one stand-alone device.

## 2.2 Power System Data Sonification Works

The following sections review various published examples of power system data or related electromagnetic field sonifications.

### 2.2.1 Powerchord

Various authors have contributed and published works discussing a sonification system for analysis of power consumption in households called "Powerchord" [16]–[19]. Specifically, the created system uses Individual Appliance Monitor (IAM) units, which are wirelessly connected to a WiFi data processing and sonification Arduino-based module.

A diagram of the Powerchord system is shown in figure 2.5.

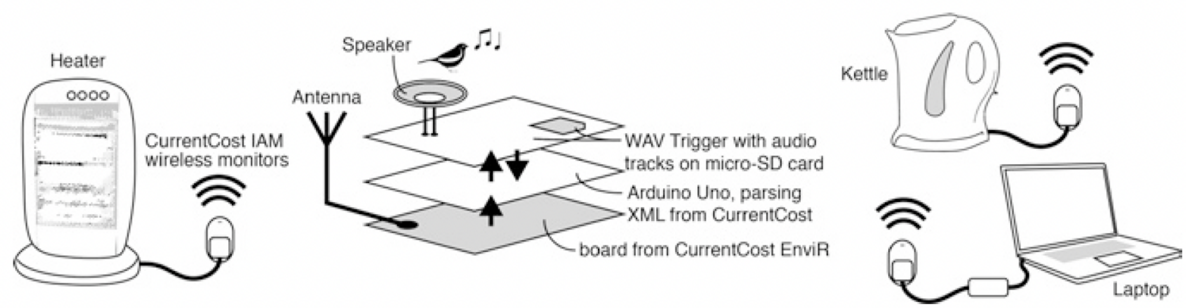


**Fig. 2.5** PowerChord System Diagram [18]. Image used with permission from the authors.

The Powerchord system allows for various household appliances to be plugged into the wireless IAMs. The IAMs measure the power consumption of the connected appliances, parsing the data every 6 seconds and sonifying it with bird sounds. Specifically, a polyphonic Waveform Audio File Format (WAV) trigger shield, with audio tracks on a microSD card, is used for sonification through WAV file triggering which is played back through a speaker.

For sonification, the device maps the number of birds and the bird agitation level in the auditory playback to the power consumption of the device. Additionally, each device is assigned a specific bird type [17]. The main concept behind their sonification is that for each appliance, as the power consumption increases, more birds will be heard, which will also proportionally sound louder and more agitated. The main focus of this research was to provide energy consumption awareness in households.

The Powerchord system did not look at any AC parameters from voltage/current other than consumed power and was not intended for monitoring the characteristics of a power system or the various effects that electrical loads can have on a power system.

### 2.2.2 Augmentation of An Institute's Kitchen

Another effort to awareness of energy consumption in households exists, focusing on the kitchen. This research consisted of creating an "augmented kitchen", 16-square meters in size, that monitored the power consumption of various kitchen appliances, including a dishwasher, a coffee maker, a water kettle, a microwave oven, and a fridge. Within the kitchen also was an omnidirectional microphone, used for recording the "environmental sound" of the kitchen [20].

The researchers created algorithms for sonifying the power consumption of the kitchen by applying reverb to the input recorded "environmental sound". Specifically, the recorded kitchen sounds were processed with various filters, that applied delay/reverb effects to the sound, and played back through a loudspeaker also within the kitchen in real-time. The sonification system had 3 different reverb presets all corresponding to different levels of power consumption. The greater the power consumption in the kitchen, the more reverb is applied to the input kitchen audio. Preset 0 corresponds to a kitchen with all appliances off, Preset 1 is representative of common kitchen power consumption use, and preset 2 is representative of high power consumption use. The levels which triggered these presets were based on a baseline proposed by the researchers.

Results from this research led to conclusions that the continuous power consumption to kitchen reverb mapping was not perceivable by evaluation audiences. The researchers believe this part to be since changes in reverb are most easily noticed when they are not continuous and instead are quick transient-based sounds.

Similar to the first example, the augmented kitchen sonification system did not look at any AC parameters from voltage/current other than consumed power and was not intended for monitoring the characteristics of a power system or the various effects that electrical loads can have on a power system.

### 2.2.3 Electrical Walks

Since 2003, a series of self-guided "electrical walks" tours have been developed. Every year new maps/tours in streets throughout the world are provided for participants to walk through. During these electrical walks, participants wear special electromagnetic induction headphones that amplify the electromagnetic fields produced by various electronics and appliances in the surrounding walk route environment. Users can walk through cities and hear the various effects of the electromagnetic radiation produced throughout the tour. Specifically, the creator notes that during the walks, there "are complex layers of high and low frequencies, loops of rhythmic sequences, groups of tiny signals, complex layers of pitches, long drones and many elements which change constantly and are hard to describe" [21]. The author also mentions that some of the sounds generated by the electromagnetic fields are similar from walk to walk and country to country but some sounds are completely independent of specific areas/countries.

This research provides a direct audification sonification routine of electromagnetic fields, but like the previous examples, it does not directly monitor many of the ongoing AC parameter variations within electrical power systems. Although some of these variations may be heard within the fluctuating electromagnetic fields, it is unlikely that a user could perceive changes in parameters like distribution frequency, power factor, and other relevant AC parameters, which are needed for this thesis sonification research.

### 2.2.4 SonEnvir

The SonEnvir[3] project focused on the development of a general sonification environment for connecting sound experts and scientists in the creation of sonifications of various types of scientific

[3] `https://sonenvir.at/`

data sets [22].

It has also been specifically used for the exploration of sonification of power systems data [23], when the authors discussed the use of sonification as a means for educating students on fluctuations in power systems. The article mentions an example of the oscillations caused by ground fault failure, though no specific example of sonification could be found. The authors also recommend the use of parameter mapping sonification for "making audible the 'character' of fluctuation behavior" [22].

Additionally, a workshop was held that combined audio design experts, sonification experts, and people who work with power data. The participants were split into groups and asked to create sonifications of power consumption data over one week for households, trade and industry, agriculture, heating, and warm water, and street lighting individually as well as a sum of all of the former. The groups all created various mapping strategies ranging from audification, and parameter mapping of consumption to amplitudes and separately frequencies. In my opinion, most of the frequency mapping and audification examples that were generated are not the most pleasing to listen to. They have the typical "droney" type of sounds of common sonifications and high-pitched sounds that can lead people to switch sonifications off [11]. There are a few amplitude mapping examples, where power was mapped to amplitudes of tones and in another example to filter frequencies. These sonifications are easier to listen to and more pleasing in my own opinion.

### 2.2.5 Sound For Energy Project

The Sound For Energy Project[4] focuses on "design, develop and evaluate real-time digital sonic interactions as augmentations of individual appliances and aggregated smart meters' outputs, which will promote energy efficiency in the household". Recently, two developments have come out of the project, which is discussed in the following sections.

[4] https://soundforenergy.net

### The Singing Shower

The singing shower is a sound-reactive shower that responds to the user's singing. The user's singing controls water flow in a binary manner: if the user is singing then the water will flow, and if the user is not singing then the water will not flow. The creators aimed "to reinforce the physical connection between the user and the water flow, with their voice providing the metaphorical 'power' required to shower" [24]. Therefore it was intended on giving a user a better understanding of the energy that is consumed by the shower.

### The Sonic Carpet

The sonic carpet is a sonic interaction device that allows a user to monitor local energy source emission, consumption, and grid-split [25], the amount/percentage of energy provided by an individual energy source. The carpet contains six force-sensitive resistors on the underside, with each resistor representing an energy source (wind, hydro, nuclear, geothermal, gas, solar). On the user-facing side, above each resistor, is a symbol displaying each energy source. This allows the user to step on the symbol, consequently pressing onto the force-sensitive resistor, and receive auditory feedback about that specific energy source. The system also allows the user to press on the symbols and receive auditory feedback for multiple energy sources. When stepping on an energy source symbol the user is provided with auditory feedback representing the emissions or consumption of the energy source as well as the grid split. For wind, hydro, and nuclear, feedback is provided about the power consumption of the power source. For geothermal, gas, and solar feedback about the emissions of the power source is provided. For the three types of parameters above, the researchers developed three individual, separate, mapping strategies.

First, for the consumption data, a Fourier Re-synthesis technique was used. "The amount of realtime energy consumption in kWh is mapped to the amount of frequency bands whose gain is not zero in the spectrum, after being properly scaled. The higher the consumption, the higher the number of high-pitched frequency bands activated" [25].

For the emissions data, frequency modulation with noise technique was used. The sound generated from the previous sonification is "frequency-modulated by low-pass filtered white noise. The amount of emission data influences the amplitude of the modulation noise, the cut-off frequency of the low-pass filter, and the amount of noise-modulated signal that is mixed with the original one" [25].

Finally, the grid-split data is sonified using bell sounds. Each power source is assigned a bell tone with a specific frequency. The percentage of energy produced by the energy source is directly mapped to the duration that the bell tone is played back, with a range of a minimum of 0.5 and a maximum of 3 seconds. Therefore the longer the duration of the bell tone, the more power the energy source.

The two prototypes discussed above, introduce very novel applications for user interaction with power systems. Specifically, these focus again on power and energy consumption and bringing awareness to average consumers. This is an ever-increasing important area of research and poses for further research and discussion. The idea of an interactive system for the user to process energy consumption entertainingly suggests strategies for improving a basic user's experience in understanding and processing ever-changing parameters in a power system.

The emissions sonification mapping, representing a metaphor for the cultural association of noise with pollution is extremely interesting though. One parallel that comes to mind for power signal quality sonification is examining if there could be a human association with audio distortion and distributed power THD. For example, the "dirtier" the distributed power(higher distortion), the more audio distortion can be heard by the listener. I explore these ideas in **Chapter 5**.

### 2.2.6 Auditory Displays of Electric Power Grids

Before coming to McGill, I created various preliminary algorithms for the sonification of both recorded and separately real-time, AC mains fundamental voltage magnitude and frequency [2].

The first, primary mapping technique for this research involved one-to-one mapping of power system voltage magnitude to Musical Instrument Digital Interface (MIDI) velocity and mapping power system voltage frequency to MIDI pitch. The algorithm allowed for the specification of sonified note length (corresponding to one data sample), in a user-specified key and tempo. Additionally, a mapping technique was created for mapping power system voltage frequency deviation from the nominal to quantized drum kit "hits" via MIDI sampler triggering. These algorithms were ported into a real-time version and a Proof of Concept (POC) Arduino zero[5] based prototype was introduced. The prototype allowed for real-time measurement and sonification of voltage magnitude and frequency using the above mapping techniques. Finally, this research introduced the concept of the multi-channel power systems sonification technique, where various pre-recorded data sets were each sonified into separate MIDI channels/instruments to create a music track. In the specific example shared within the paper, recorded data from 6 synchronized power stations was sonified to a kick drum, hi-hat, snare, crash, melody, and a "chords" channel. The "chords" channel used the one-to-one mapping technique to generate a MIDI note that was played through a MIDI chord effect to create background chords.

This research only examined voltage data and did not consider power system variations across electrical load through measurement of AC current. Therefore it did not examine parameters such as power factor, THD, and others extracted from both the voltage and current phasors.

The above algorithms, concepts, and POC prototype served as a basis for this research and the sonification methods used by the device. Detailed explanations of the chosen mapping techniques are discussed later in **Chapter 5**.

## 2.3 Design Requirements

The review provided a guide in determining the design requirements for a custom embedded acquisition device for the sonification of AC mains parameters used in this thesis research.

A custom embedded system PCB should be created that contains all of the data acquisition and sonification within one system. This eliminates the need for an external PC. Additionally, to protect the user from high-voltage shock, the system should be split into a high-voltage side and

[5] `https://store-usa.arduino.cc/products/arduino-zero`

an electrically isolated user side. The data acquisition should be on the high voltage side, while the data processing, sonification generation, and user interaction should be on the user side. The system can reference the evaluation board and demo boards developed by Microchip Technology Inc., for the design of the electronics [14], [15]. Specifically, as mentioned due to the various package footprint configurations, the MCP3901 IC should be the core data acquisition module on the mains high voltage acquisition side [12]. Also, the user side should be battery power-able so that the system can run without being plugged into a power supply.

The system should measure the voltage and current waveforms of any configurable electrical load up to 15A. From those waveforms, the waveform phasors should be converted into the frequency domain. From these phasors, power factor, fundamental magnitude, fundamental frequency, real power, reactive power, apparent power, and power factor should all be extracted for parameter mapping sonification. The system is intended to sonify using MIDI signals which will be sent to a MIDI instrument or interface. Finally, multi-channel MIDI signaling should be supported by the device, and allow for any user-configurable quantization and timing that is within the MIDI protocol bandwidth.

To summarize, the embedded acquisition and sonification device should:

- have a high voltage data acquisition side and an electrically isolated low voltage side for sonification and user interaction.
- contain the AC mains voltage/current data acquisition and sonification embedded within one PCB.
- should use the MCP3901 at the core of the mains voltage/current data acquisition.
- support any AC electrical load up to the typical household power socket rating of 15A.
- utilize the POC prototype, proposed concepts, and methods introduced in [2].
- measure voltage and current phasors of connected electrical loads in real-time.

- process the voltage/current phasors in real-time and extract relevant AC parameters from the voltage and current phasors including power factor, fundamental magnitude, fundamental frequency, harmonics up to the 13th multiple, THD, real power, reactive power, apparent power.
- sonify the various parameters using the MIDI protocol.
- support multi-channel MIDI signaling, and quantization at any user-configured rate.
- have MIDI IN/OUT ports for interfacing with a MIDI interface or MIDI synthesizer.
- contain a serial port for user control and measured parameter output.
- be battery power-able on the user isolated side.
- be self-powered by AC mains on the high voltage side.

# Chapter 3

# Electronics Design & PCB Manufacturing

This chapter describes the electronics design and manufacturing processes for the embedded sonification system. The first section discusses the initial electronic improvements to the sonification system discussed in [2] and its further limitations that led to the design of a new custom acquisition/sonification system. The second section introduces the electronics system architecture and subsystem design for the newly designed embedded system used for the power systems sonification research of this thesis. The third section describes the PCB layout design of the new embedded system. The fourth section discusses the system's board manufacturing and assembly processes. The chapter concludes with the initial bring-up and smoke testing of the assembled PCB.

## 3.1 Proof of Concept Prototype Updates

As mentioned in **Chapter 2**, an Arduino based AC to MIDI sonification system POC prototype was introduced in [2]. For the initial part of the thesis research, various hardware updates were made to this system to improve functionality and user interaction.

- The power supply electronics for the device were redesigned for improving the stability of the system.

- A current sensor was also added so that current could be measured in parallel with voltage.
- Rotary encoders were added to improve user control of the system.

The updated hardware of the system can be seen in figure 3.1.

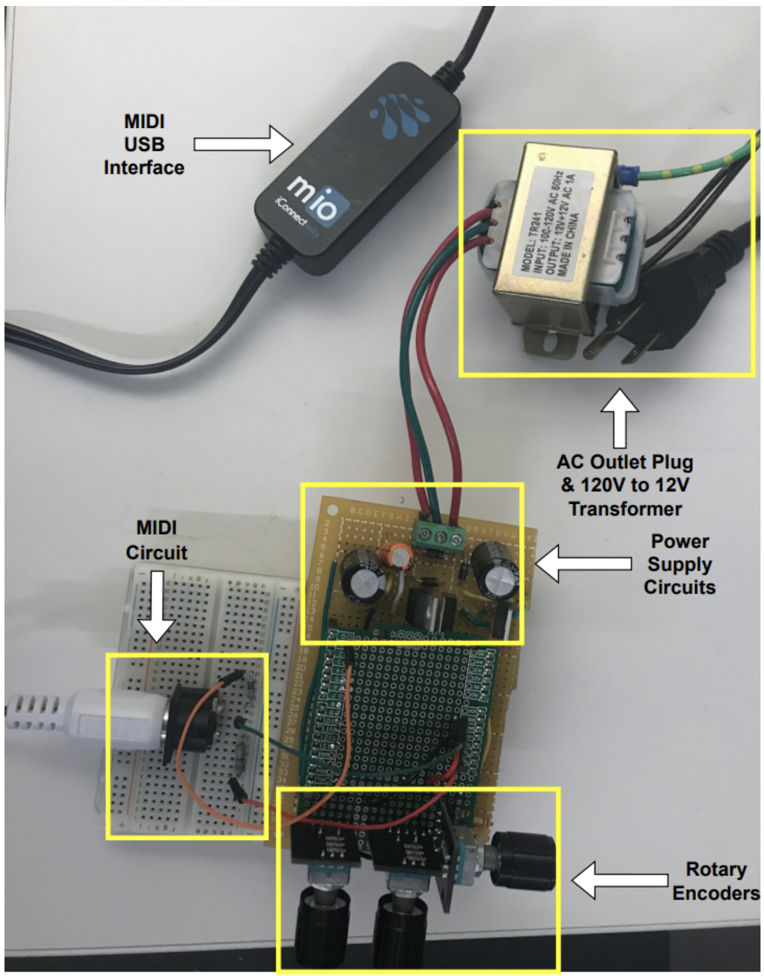


**Fig. 3.1** Updated POC Real-Time AC to MIDI Sonification Device Prototype. The data acquisition circuit and current sense module are not visible. Those circuits are soldered onto the tan perforated board below the green perforated board. Below the tan perforated board is the Arduino zero board.

### 3.1.1 Power Supply Electronics Improvements

The original system design used a center-tapped transformer to step down 120 V mains voltage down to 24 V. The center tap served as a ground reference and allowed for positive and negative power supplies to be generated using a voltage rectifier and positive/negative voltage regulators [2]. Unfortunately, the original design of the positive and negative power supplies did not follow the voltage regulator data sheets correctly. The data sheets suggested using bypass capacitors of specific value on the positive and negative voltage regulator inputs and outputs. On the original POC device design, this recommendation was accidentally overlooked. These bypass capacitors are recommended by the data sheets for filtering out noise on the regulator input and output power circuits [26], [27]. Following the data-sheet guidelines, the appropriate bypass capacitors were added to the system on the regulator input and outputs.

### 3.1.2 Current Sensor

A current sense module from SparkFun electronics was added to the system so that the AC signal current could be measured along with the AC voltage [28]. This module was added so that power factor, THD, and other parameters related to voltage/current phasors could be measured.

### 3.1.3 Rotary Encoders

Rotary Encoders were added to the system with the intent to improve user interaction with the device. Three rotary encoders were soldered onto a green perforated board. From the green perforated board, connections were made between the rotary encoders and Arduino zero digital pins. Ideally, the rotary encoders could be used for adjusting system and/or sonification parameters. Unfortunately, the software implementation of the encoders was never fully completed after the realization of various issues with the updated POC prototype.

### 3.1.4 Issues With Updated POC Prototype

Although the previous changes helped to improve the AC sonification POC prototype, there were various limitations to the system design, discussed in the following sections.

First, the initial current sensing circuit was designed to measure the mains current across a linear, resistive load. The current drawn by the load was not considered properly, as the magnitude of the current drawn was far too low for the current sensor module to measure. Therefore the update did not allow for accurate current measurement and the various parameters associated with the current phasor could not be obtained.

Second, the system used a step-down transformer for dropping down the mains voltage. Voltage transformers inherently have voltage losses across their cores and coils which can be even more significant with non-linear loads [29]. The load of the POC system was kept constant as a linear resistive load which also significantly limited possible sonification analyses. Since there are various types of electrical loads varying in linearity, power factor, and current draw, it is important to have a configurable load for sonification research. This aids in having diverse data sets for sonification.

Third, the POC prototype did not have strong physical integrity. As mentioned previously, the prototype consisted of various circuit boards connected along with an oversized transformer. Various connections within the system were not mechanically robust and the device was prone to open-circuit connections.

Finally, Arduino zero has a Cortex-M0+ core-based processor, which is designed for optimized power consumption but lacks processing power. M0 based processors are not intended for Digital Signal Processing (DSP) applications, especially for efficient FFT computation. In contrast the Cortex-M4 and Cortex-M7 arm based processors are recommended for such applications and are supported by Hardware Abstraction Library (HAL) Common Microcontroller Software Interface Standard (CMSIS) DSP libraries [30]. These libraries reduce firmware development and are significantly tested and updated. Therefore, the Arduino based prototype would not allow for efficient extraction of voltage and current phasors using FFTs.

## 3.2 Custom Embedded System Electronics Design Process High-Level Overview

Following the review of the POC issues and limitations, a custom embedded system with a significantly more powerful arm-core processor, accurate voltage/current hardware acquisition circuits, and proper high voltage isolation was designed. The following section discusses in detail the electrical system design process, manufacturing, and assembly of the custom-embedded system for sonification.

The custom embedded system electronics architecture section describes in detail the electrical design of the system including all relevant sub-circuits and sub-systems. Since the system contains the measurement of high voltage mains, proper voltage isolation is required to protect the user [31]. As a result, the system is split into two main sub-systems that are properly isolated from one another: the high voltage mains, signals, and circuits are isolated from the side that the user and user hardware interact with. The physical isolation between the systems is discussed in further detail in the PCB layout section.

Following this, the PCB layout process is discussed. This process is composed of creating a model of the printed circuit board and designating all electrical layers within the system and the voltage/ground *planes*. Additionally, the components for the electrical design are "placed" in a specific orientation following data-sheet guidelines and recommended PCB layout practices on the top side of the PCB layout model. All electrical traces are "routed" which creates all of the schematic connections.

Once the layout was complete, the board was fabricated at a manufacturing house. This fabrication creates the physical circuit board which was then assembled by hand using a solder stencil and a hot air machine. After the system was fully assembled it was turned on and smoke tested to make sure that there were no significant short or open circuit connections and that all generated power supplies were working correctly.

## 3.3 Custom Embedded System Electronics Architecture

A detailed diagram of the custom embedded system is shown in figure 3.2.

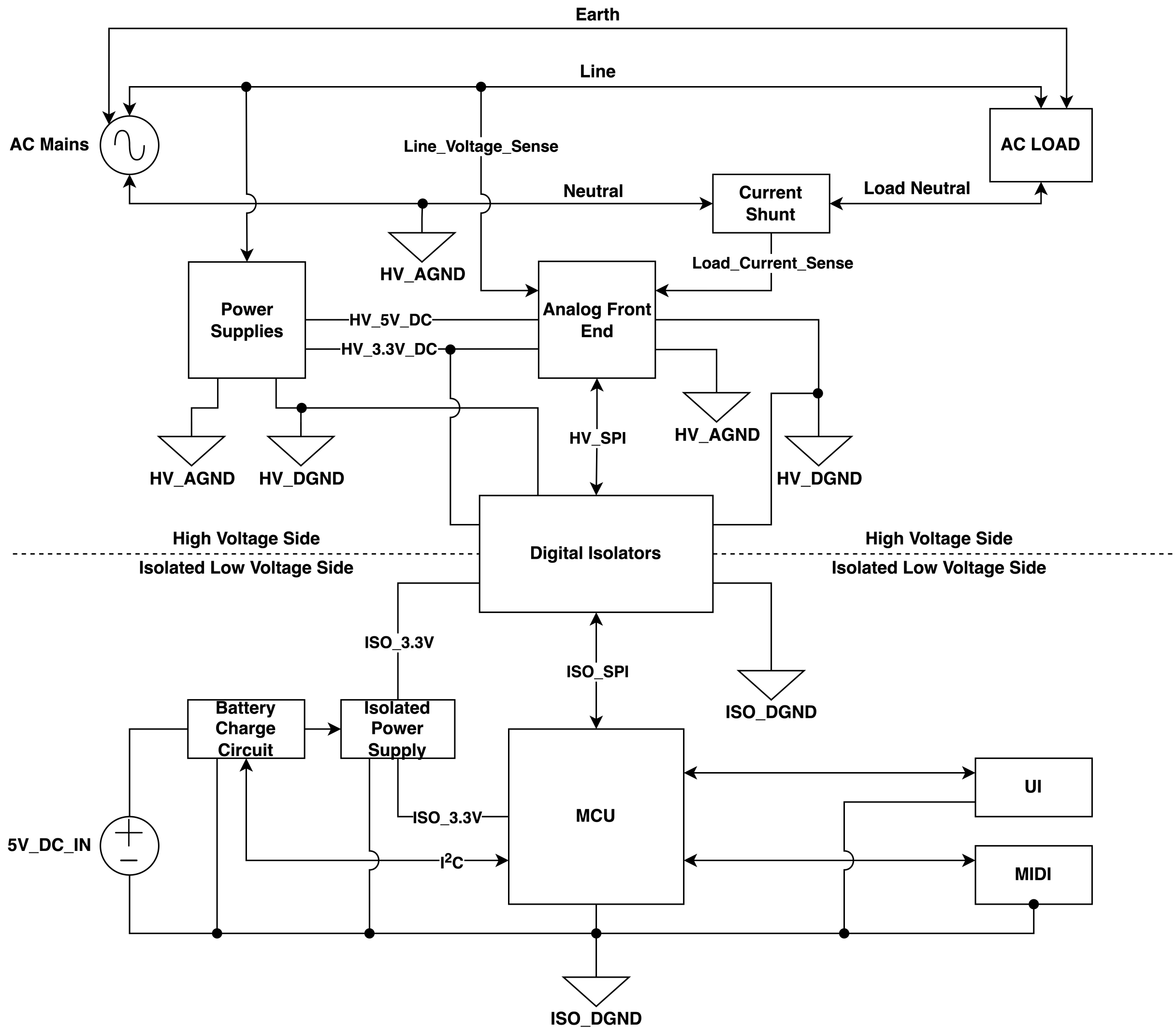


**Fig. 3.2** Electronics System Architecture Diagram

### 3.3.1 High Voltage Side

The high voltage side contains the acquisition circuits for measurement of the mains voltage and load current waveforms. At the core of the high voltage side is the microchip MCP3901 [12]. Reference designs provided by the manufacturer [32] were used as a guide for the development of the embedded system. The SPI bus of the MCP3901 is connected to digital isolators which allow for SPI communication between the low voltage and high voltage sides.

#### Analog and Voltage Power Supply Generation

The MCP3901 requires two power supplies to function. A power supply for analog data acquisition, and a supply for digital communication. Using the specifications listed in [12], the system analog voltage supply was chosen to be 5V and the digital supply was chosen to be 3.3V. To generate these power supplies, a transformer-less capacitive supply, as shown in the reference design [32] was used. This capacitive supply drops down the 120 VRMS line voltage to a nearly Direct Current (DC) 12-volt signal. The 12-volt signal is then inputted to two separate Linear Drop Out (LDO) voltage regulators which filter the 12-volt signal and drop it down to DC 5V and 3.3V power supplies. The 5V supply is referenced to the system analog ground while the 3.3V supply is referenced to the system digital ground.

#### Load Current Measurement

To measure the current of the AC mains input through an AC load, a measurement technique must be selected. The system designed for this thesis uses a current shunt resistor for measuring current similar to the reference design [32]. AC mains is inputted into the system through an IEC320-C14 input socket with connections to an AC socket line, neutral, and earth ground. On the output end of the system are connections to an AC load line, neutral, and earth ground through an output IEC320-C14 socket. The input line and earth ground are directly connected to the load line and earth ground while there is a very small $2 \pm .02$ m$\Omega$ resistance, high power resistor between the AC load neutral and the mains input neutral. This allows for the AC current drawn by the load to be measured. It is important to note that the AC mains input neutral is connected to the system analog ground so that the current signal can be measured as a voltage drop across the shunt resistor. The AC line flows through the device, and then back through the neutral connection across the shunt resistor. Depending on the properties of the load, the voltage across the neutral shunt can have waveform phase lead or lag in reference to the line voltage, which is directly representative of the current leading or lagging the line voltage. Using Ohm's law[1], the equivalent current drawn by the load can be acquired by

$$I = \frac{V}{R} \tag{3.1}$$

To measure the current waveform, the two terminals of the resistor are connected through passive anti-aliasing low-pass filters with the filter outputs connected to one differential channel set on the MCP3901. The MCP3901 acquires the voltage difference across the current shunt which is equivalent to the voltage drop across the current shunt. The system was designed to support the typical AC socket, 15A maximum current rating. Therefore the theoretical maximum voltage across the shunt can be calculated by

$$V_{max} = 15 * \sqrt{2} * 0.002 = 42.4mV \tag{3.2}$$

which is well below the maximum channel differential voltage of 500 mV.

### Line Voltage Measurement

Additionally, within the data acquisition, high voltage side is the line voltage measurement. A measurement connection is tapped off of the AC line voltage flowing through the device. Since this voltage is significantly higher than the rating for the MCP3901 differential channels, the line voltage needs to be dropped down using a voltage divider[2]. The line voltage inputted to the

[1] https://www.allaboutcircuits.com/textbook/direct-current/chpt-2/voltage-current-resistance-relate/
[2] https://www.allaboutcircuits.com/tools/voltage-divider-calculator/

system is dropped down using a voltage divider with an incorporated low pass filter. A voltage divider is defined by the equation

$$V_{out} = V_{in} * \frac{R_2}{R_1 + R_2} \tag{3.3}$$

For this system, the voltage divider consists of two 330kΩ resistors in series to create a $R_1$ resistance of 660kΩ. For $R_2$, a 1kΩ resistor was used. The American National Standards Institute (ANSI) specifies the nominal voltage in a North American 120 V system to have a maximum voltage of 127 VRMS [33]. Therefore using the voltage divider resistor values and equation 3.3, the theoretical maximum voltage inputted to the MCP3901 would be

$$V_{max} = 127 * \sqrt{2} * \frac{1}{661} = 272mV \tag{3.4}$$

This value is below the maximum channel differential voltage of 500 mV and leaves extra headroom for any voltage spikes within the local power grid that the device is connected to. The output of the voltage divider and low pass filter is connected to one terminal of the differential channel inputs on the MCP3901, while the second differential input is connected to analog ground.

### 3.3.2 Low Voltage User Side

The low voltage side is where the signal processing, sonification mapping layer, and user interface are located.

#### Input Power

The isolated side can be powered by either USB 5V or a rechargeable 3.7V Lithium Polymer (LI-PO) battery. If just the battery is connected, then the main system input power is provided by the battery. If a USB connection is also provided, the system switches the input power to the 5V DC. In parallel, the 5V DC power charges the battery using a LI-PO battery charge circuit. The input power signal is then sent to a 3.3V LDO which generates the isolated side 3.3V DC power signal. The entire low voltage side runs on 3.3V, with no other power supplies needed or generated.

### MCU

At the core of the low voltage, side is the Microcontroller Unit (MCU). A STM32F722RET6 processor was chosen for its fast processing speeds and internal floating point unit. It is a very high-performance MCU with intended uses for digital signal processing (DSP). Its core has a 32-bit Arm Cortex-M7 processor [34].

The MCU is powered by the 3.3V isolated power supply and runs at a digital logic level of 3.3V. Therefore all digital inputs and outputs of the system are configured to be at 3.3V logic high. The MCU completes all of the communication with the high voltage side to configure the MCP3901, and acquire the data through the SPI protocol. The MCU also completes all of the DSP and extraction of the various AC mains parameters in Firmware. Additionally, the MCU monitors the battery health from a gas-gauge circuit through the inter-integrated circuit ($I^2C$) protocol. The MCU also computes all of the parameter mapping sonifications and encodes the sonifications into MIDI output digital signals. Finally, the MCU operates with the user interface allowing for user control and feedback.

### MIDI Interface

The main parameter mapping sonifications are computed through the MIDI protocol. The system generates MIDI mappings within the MCU and then sends the encoded data out of a serial port which is configured to interface with a MIDI device. The system contains a MIDI In and a MIDI Out circuit following the electrical specifications for 3.3V signaling [35]. MIDI signals can be sent into the device through a MIDI In port, while MIDI signals can be sent out from the MCU to a synthesizer through a MIDI Out port. Currently, the MIDI In circuit is not used in the system and could be implemented at a later time.

### User Interface & Control

The last sub-system of the isolated low voltage side is the user interface and control. It is composed of various indicator Light Emitting Diodes (LEDs) and a control serial port. Three of the LEDs are indicators for the status of the battery charge circuit: the first one allows the user to determine if the USB power is sufficient/connected, while the other two indicate the status of the battery charging. These LEDs are controlled by the battery charge circuit and specific behavior is outlined in the functional description section for the battery circuit charge IC [36]. The system also contains two Red/Green/Blue (RGB) LEDs which are currently not used by the system. These LEDs could be used for user feedback to display errors or other types of feedback.

Additionally, two push buttons are connected to General Purpose Input/Output (GPIO) inputs on the MCU. These push buttons can be configured in firmware to allow the user to interact with the device and simulate system events to happen or to increment/adjust parameters but are not fully implemented in the existing system.

The final part of the user interface is the serial port Universal Asynchronous Receiver-Transmitter (UART) and USB interface. The MCU is configured to have a serial port UART which allows for data to be received and sent from the processor. A UART to USB dongle can be connected to the UART interface and any terminal console software can be used to interact with the system. This interface allows users to configure/adjust the configuration settings of the MCP3901 through simple command line commands sent from a PC. Though the system was designed to support USB 1.0 and therefore allow for USB MIDI, the USB firmware interface has not yet been configured. Eventually, to make the system fully stand-alone, a display screen and rotary encoders could be added onto a daughter board for the main user interface instead of using a PC. The system was designed with all extra processor pins routed to large through-hole test points for which rework wires could be soldered.

## 3.4 PCB Layout

After the electronics architecture was completed, the system schematics were ported over to a PCB layout. The layout was designed using the Siemens PADS Professional[3] software layout tool. The PCB layout process consisted of various steps which are detailed in the following sub-sections.

### 3.4.1 PCB Layer Stack-Up

Before completing the component placement, the PCB layer stack-up was configured. A PCB layer is an electrical layer of copper traces and or planes. In between each electrical layer is a small layer of a Flame Retardant 4 (FR4) that is often used in PCBs to provide layer-to-layer insulation.

This system was designed as a 4-layer board with the layer stack up shown in figure 3.3.

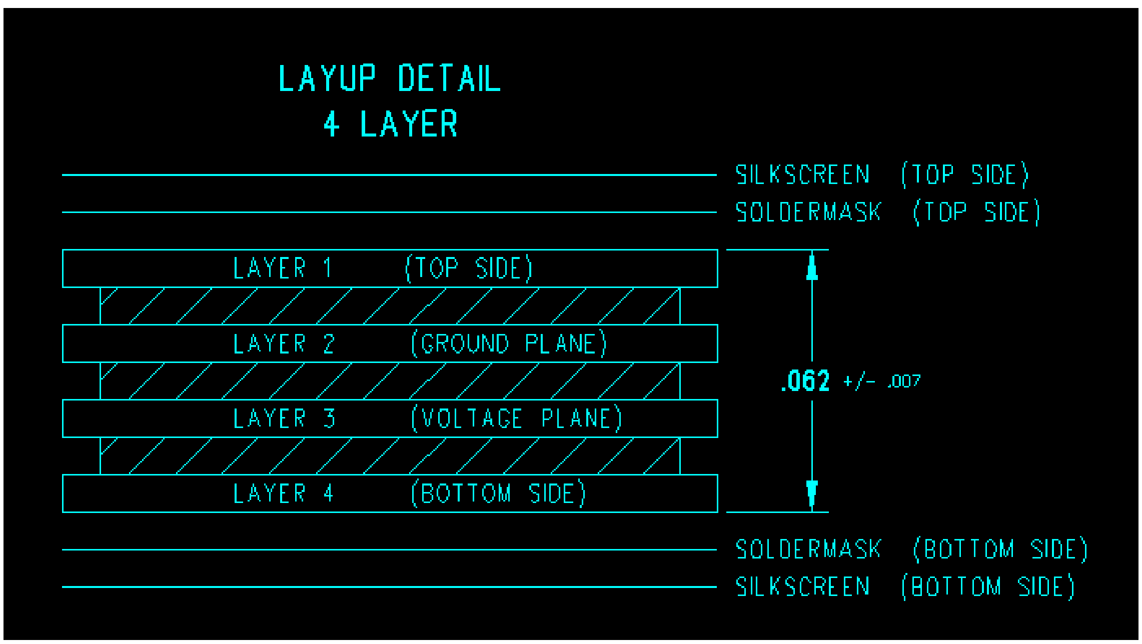


**Fig. 3.3** PCB Layer Stack-up. The PCB consists of two outer layers for signal routing and component placement: the top and bottom layer. The internal layers of the PCB include a ground plane layer for layer 2, and a voltage plane layer for layer 3.

[3] `https://eda.sw.siemens.com/en-US/pcb/pads/?cmpid=12938`

The design was configured to have all electrical components placed on the top layer. The second layer contains the ground planes, while the third layer contains the power planes[4]. For this design, all signal traces are routed on the top and bottom layers of the PCB. The ground and power planes create a plane-to-plane capacitance that helps improve Electromagnetic Interference (EMI) performance and signal integrity [37].

### Ground Plane Layer

The ground plane layer has four different ground planes. The high voltage side has analog, digital, and earth ground planes. These planes are separated from the isolated low-voltage ground using bare FR4 gaps within the layer. The FR4 gaps were designed to match the width of the digital isolator component specifications [38]. This plane separation, along with the SI8640BT-IS component specifications, creates voltage isolation of 5000 VRMS. Isolation voltage is "the highest voltage that can be applied across a device for one second without compromising the isolation in the device" [39].

This isolation design follows Underwriters Laboratories (UL) safety isolation requirements for high voltage embedded system design [31]. The planes and gaps are labeled in figure 3.4, where the isolation gaps are shown as the black spaces between the colored ground planes. The solid-colored shapes represent each copper plane area.

[4] A *plane* is an area of poured copper that lies within an electrical layer

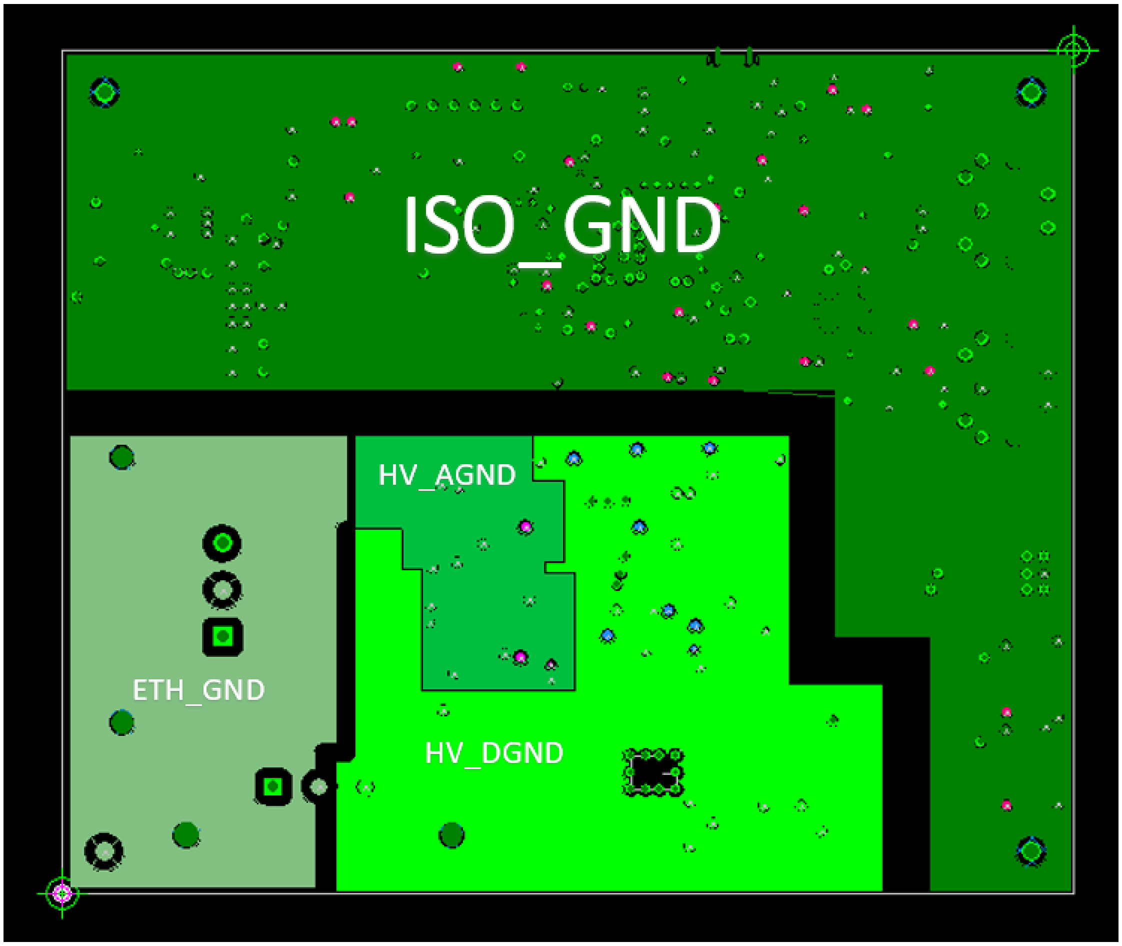


**Fig. 3.4** PCB Ground Planes Layout. The ground plane layer has a low voltage (isolated) ground plane (ISO_GND), high voltage analog ground (HV_AGND) plane, high voltage digital ground (HV_DGND) plane, and an earth ground (ETH_GND) plane.

### Power Plane Layer

The power plane layer contains 3 different power planes. Based on recommended guidelines for high voltage PCB designs, mains voltage should not connect through electrical layers or to a voltage plane [31]. Therefore the earth ground plane is duplicated on the mains voltage area of the PCB. This is also done to reduce bare FR4 space and improve EMI performance [37].

The high voltage side additionally has 3.3V and 5V power planes. These planes are separated from the isolated low voltage side 3.3V plane again using bare FR4 gaps within the layer. The planes and gaps are labeled in figure 3.5.

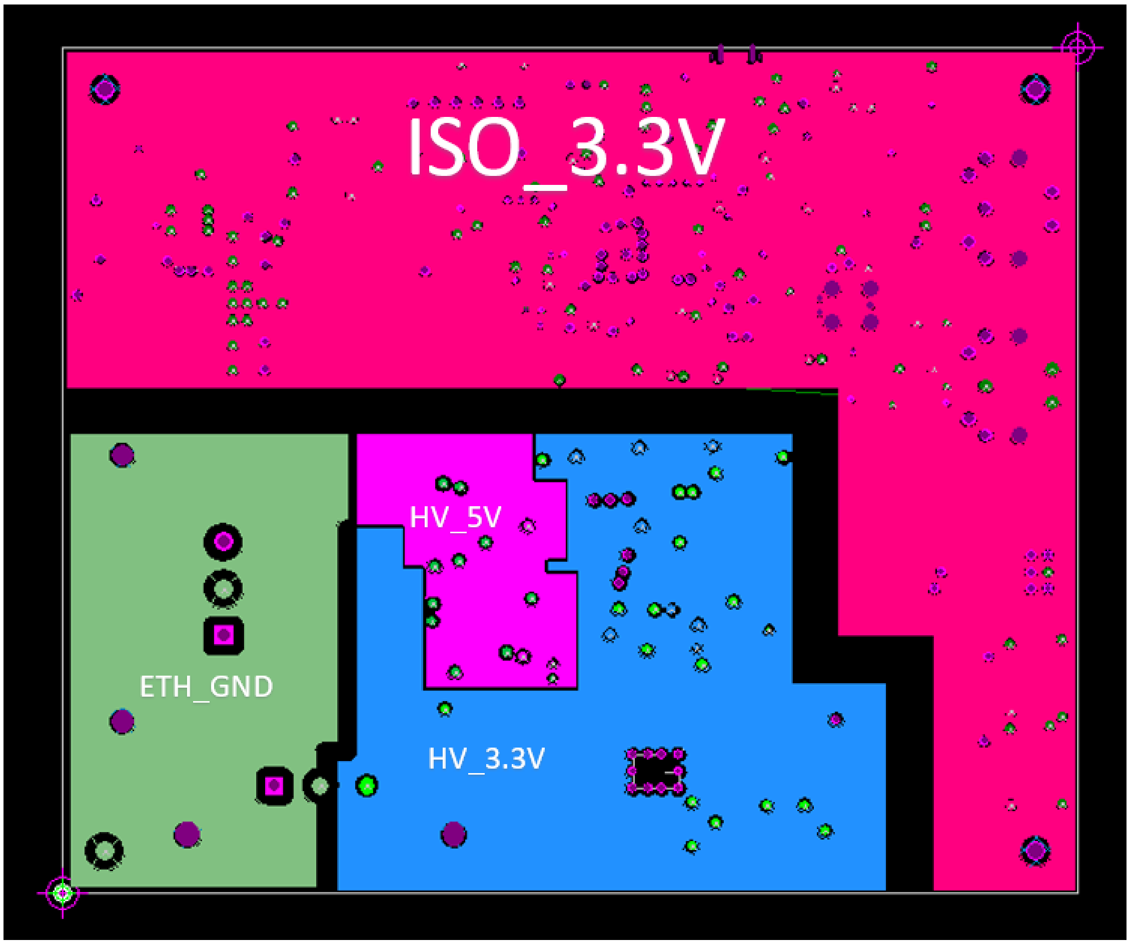


**Fig. 3.5** PCB Power Planes Layout.The power plane layer has a low voltage (isolated) 3.3V power plane(ISO_3.3V), high voltage 3.3V power plane (HV_3.3V), high voltage 5V power plane (HV_5V) and a duplicated ETH_GND plane.

As with the ground plane section, the isolation gaps are shown within the figure as the black spaces between the colored power planes. The solid colored shapes represent each power copper plane area.

### 3.4.2 Component Placement & Trace Routing

To complete the PCB design, all components were first placed onto the board in the PCB layout design tool. The high voltage side components were placed on the lower half of the PCB, above their respective HV_AGND and HV_DGND, while the low voltage side components were placed above the IS0_GND plane. The digital isolators were placed between the high voltage and low voltage side between the isolated and high voltage layer FR4 isolation.

Once the component placement was configured, the signal routing was completed. All electrical trace connections were routed on the top and bottom layer PCB. The final placement and routing can be seen in figure 3.6.

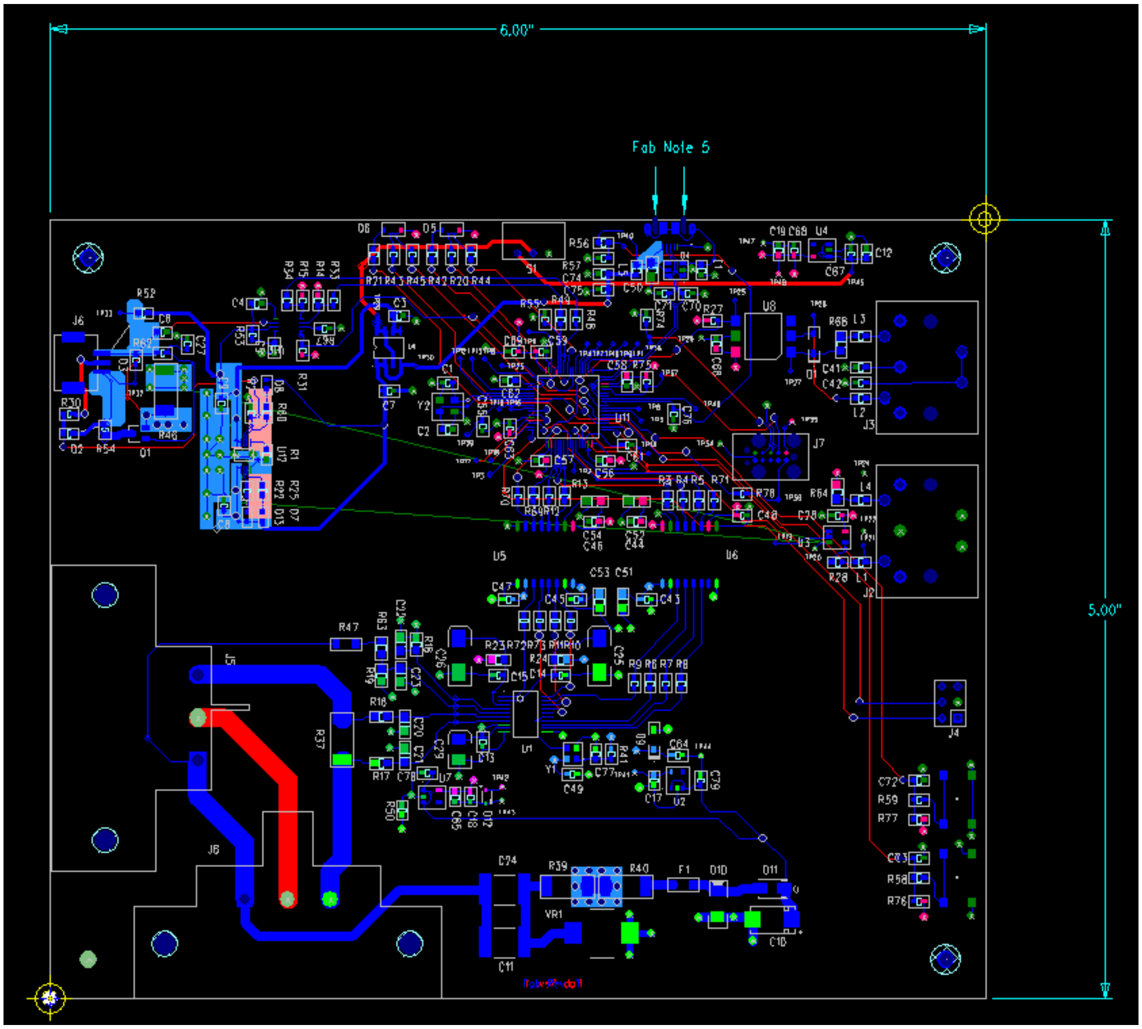


**Fig. 3.6** PCB Signal Routing & Traces. Signal Traces are labeled in blue (top layer) and red (bottom layer) while components on top layer are outlined within various grey shapes.

## 3.5 Board Fabrication & Assembly

The next process of the electronics design was to manufacture the physical PCBs. First, the PCB layout design files were sent to a fabrication house. A fabrication house fabricates the PCBs and provides a PCB for component assembly. The fabricated bare PCB can be seen in figure 3.7.

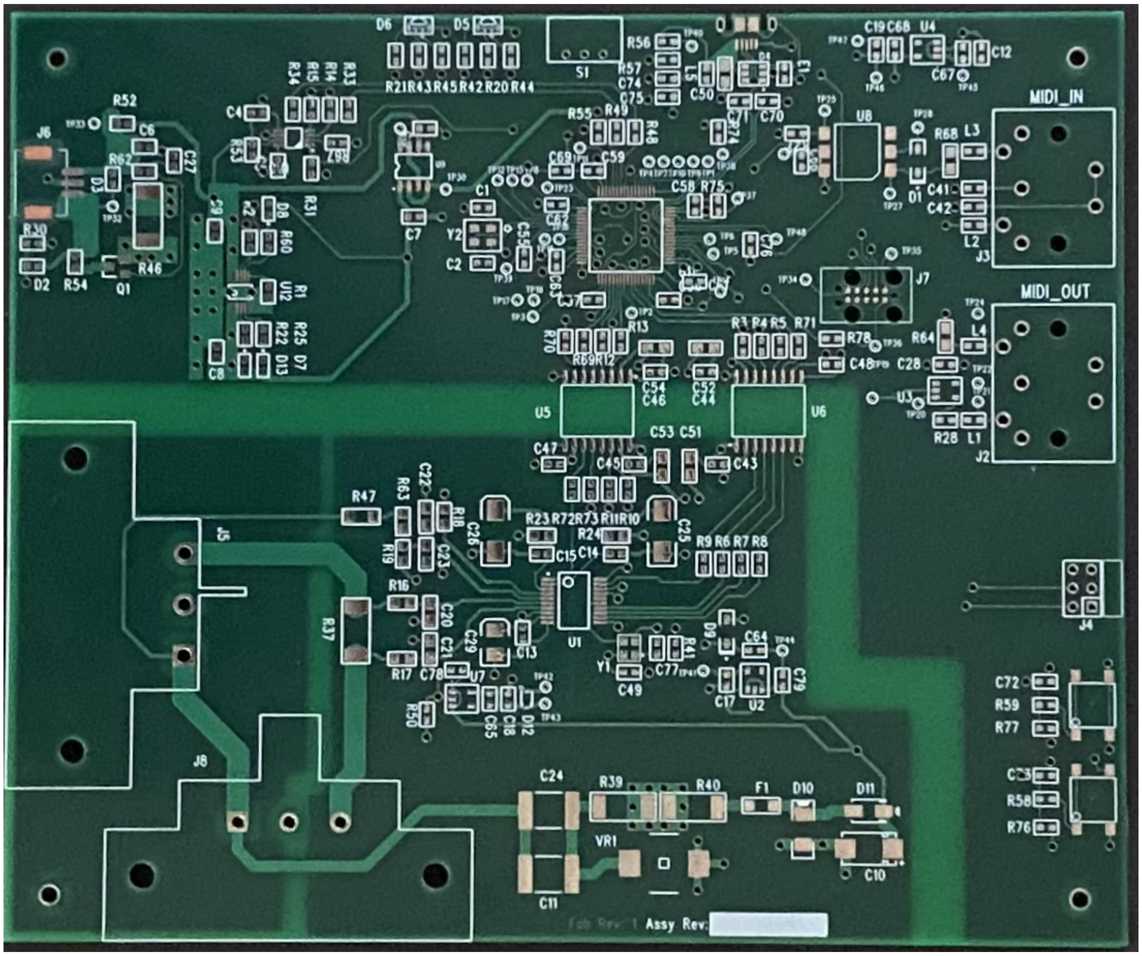


**Fig. 3.7** Embedded System Bare PCB. The component pads can be seen as exposed copper (silver-filled shapes).

Next, the electrical components were assembled onto the PCB. As paying for automated assembly processes can be expensive, especially for a board of this size, costing close to $1,000 USD, the board was assembled using a hot air rework station. A hot air rework station has a complex thermal control system that projects hot air out of a tube and regulates the PCB temperature to a user-set value. Thermo-couples are attached to the top and bottom layers of the PCB to guide the thermal control system board temperature regulation. The hot air is used to melt and reflow solder to the PCB pads [40].

First, a solder stencil was used to place solder paste onto the component pads. The solder stencil contains cutouts where the component pads are located. The stencil for this board can be seen in figure 3.8.

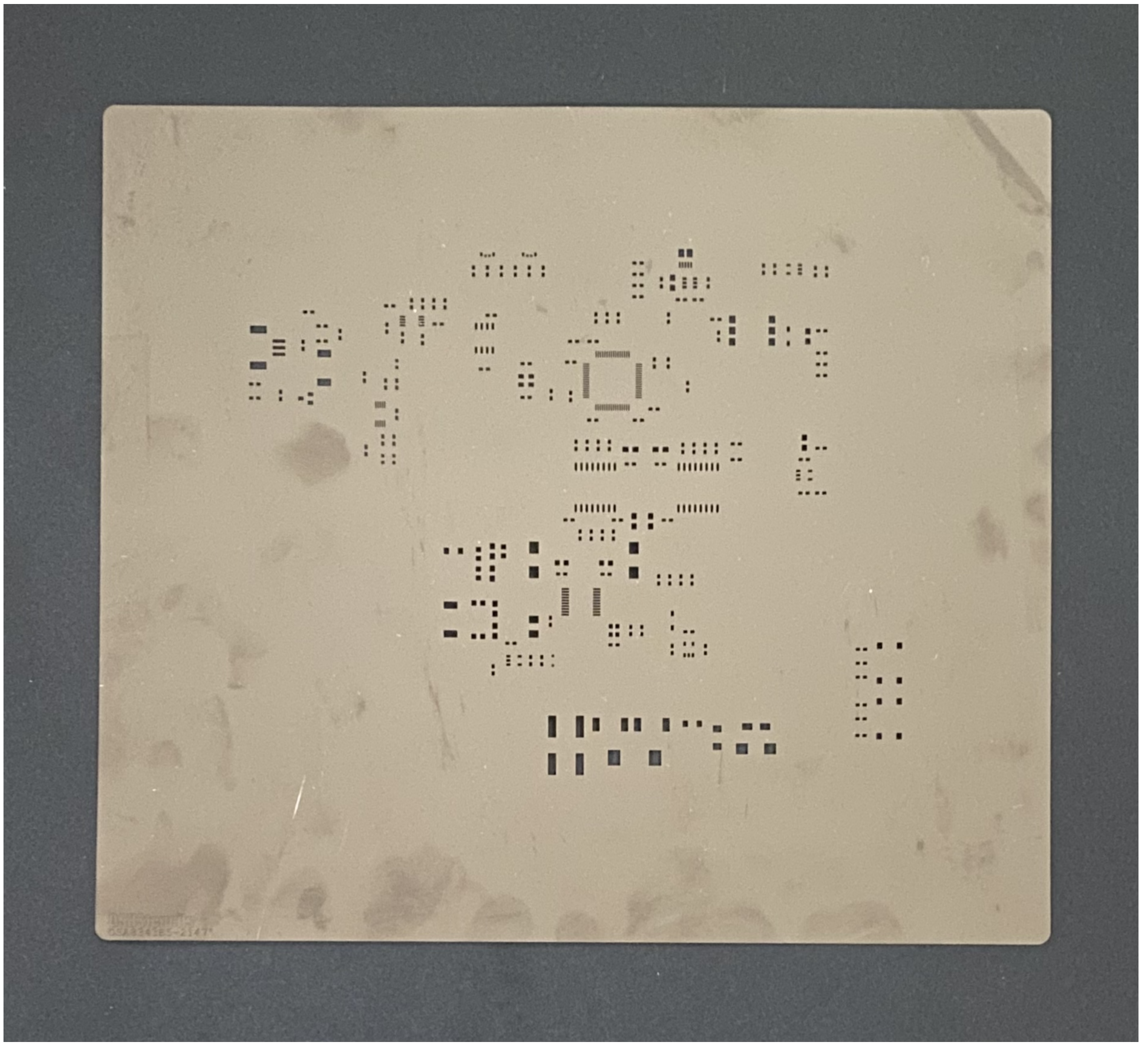

**Fig. 3.8** PCB Assembly Stencil

The holes in the stencil allow for solder paste to fill the component pad areas. The above stencil was placed on top of the bare PCB, and solder paste was applied across the entire stencil area. Next, the stencil was removed and each component was individually placed onto their PCB pads. Following this, the hot air machine was used to melt and flow the solder paste, creating a strong fixed connection between all of the components.

The final assembled PCB is shown in figure 3.9.

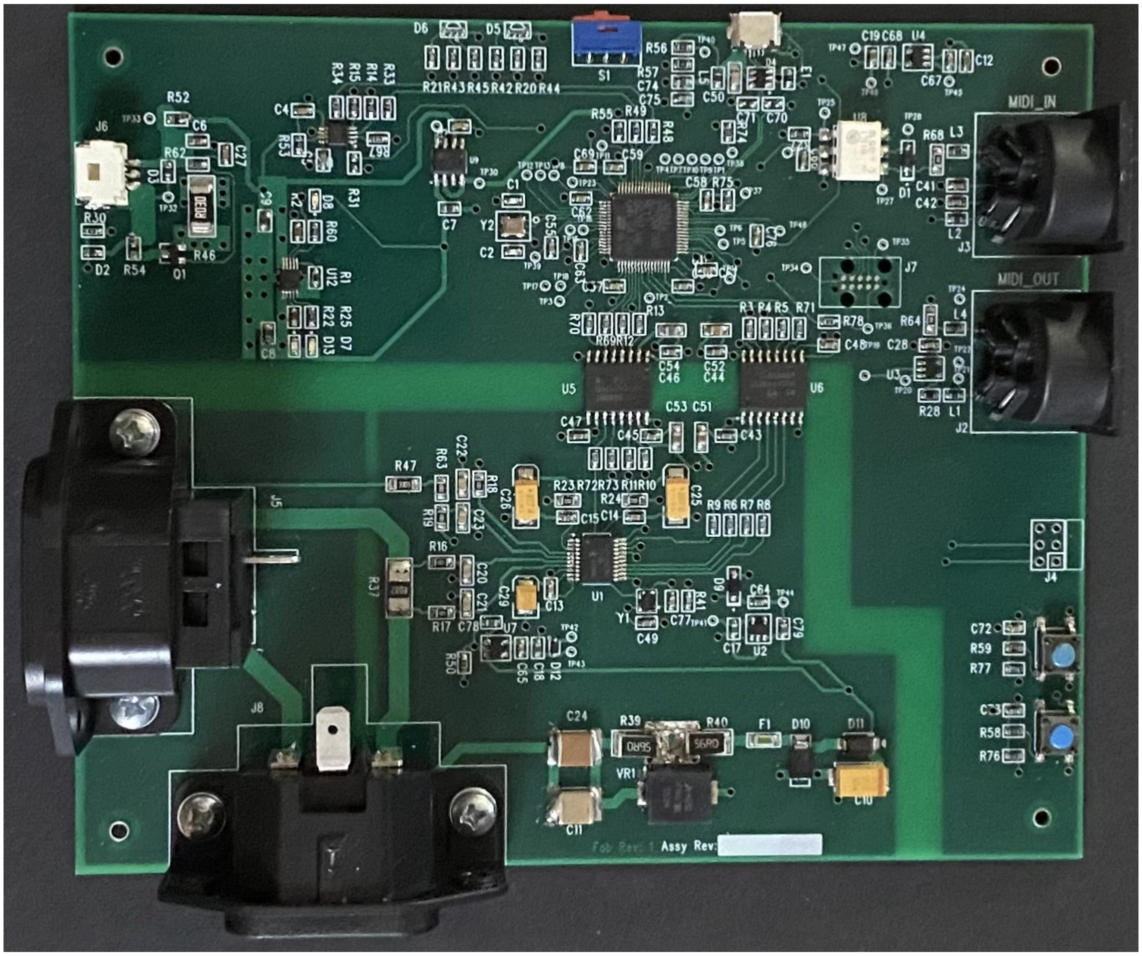


**Fig. 3.9** Fully Assembled PCB

## 3.6 PCB Smoke Testing

The final aspect of the PCB manufacturing process was to complete *smoke testing* on the assembled PCB. Smoke testing is a term used in embedded system manufacturing that refers to turning on an assembled PCB, measuring the system power supply voltages, and diagnosing any major short or open circuit connections. Before providing input power to the board, the USB positive power terminals, battery input power positive terminals, and power supply circuit output terminals were tested for any short circuit connections to one another or to any of the ground planes. Additionally, the ground planes were tested to verify that there were no short-circuit connections between any of the ground planes.

After verifying that there were no significant power/ground short circuit connections, the system was turned on and all the main power supply voltages were tested. The 3.3V and 5V power supplies on the high voltage side as well as the 3.3V power supply on the isolated side were measured to verify that their voltages met the expected voltage value. Once the power supply voltages were verified, the assembled PCB was ready for firmware development and testing.

## 3.7 Conclusions

This chapter describes the electronics design and manufacturing processes for the proposed embedded sonification system. Initial electronics improvements to the POC sonification system introduced in [2] and its further limitations were reviewed. The embedded sonification system electronics system architecture, subsystem design, PCB layout design, and manufacturing processes were all discussed in detail. These processes lead to the full assembly of a working PCB which was used for the sonification developments discussed throughout this thesis.

# Chapter 4

# System Firmware Design & Routines

This chapter describes the firmware design and architecture for the embedded sonification system. The first section discusses the system startup and module initialization processes. The second section describes the infinite main loop and its structure, including the digital signal processing of the sampled voltage and current data for AC parameter extraction. The third section describes interrupt-based data acquisition. Finally, the fourth section describes the timer overflow interrupt-based sonification routines that compute the data sonifications and create an output MIDI signal.

The sonification methods and routines are not discussed in this chapter. Instead, they are explained in detail in **Chapter 5**, which is dedicated to discussion of the system sonification procedures.

## 4.1 Firmware Architecture High-Level Overview

The firmware system architecture has a main infinite loop and uses Interrupt Service Routine (ISR)[1] for the time-sensitive operations.

For this design, a hardware pin interrupt is used for the Data Ready (DR) interrupt and corresponding data acquisition module. The MIDI note interrupt routine uses a hardware timer-

[1] An interrupt service routine is a firmware routine that is immediately computed when the corresponding routine interrupt is fired.

based interrupt, configured off of the internal MCU clock. These routines are discussed in further detail in the following sections.

In summary, the system completes a startup sequence every time the device is powered on which allows for all counters, timers, and variables to be initialized. After startup, the system enters the main infinite loop which contains the FFT, signal processing, and parameter extraction algorithms.

In parallel, the system continuously samples current and voltage data using a parallel DR ISR. Additionally, in parallel, is a MIDI note timer based ISR. This routine fires at the user-set rate, in music note length (eighth, sixteenth, etc.) at a specified user tempo.

When the timer is fired, the preset sonification methods will be computed and the resultant MIDI signals created. These MIDI signals are then output the UART transmit MIDI line, which is connected to a MIDI OUT connector. Therefore the resultant MIDI sonification can be played back in any MIDI-based instrument or Digital Audio Workstation (DAW).

A diagram of the custom embedded system firmware architecture is shown in figure 4.1.

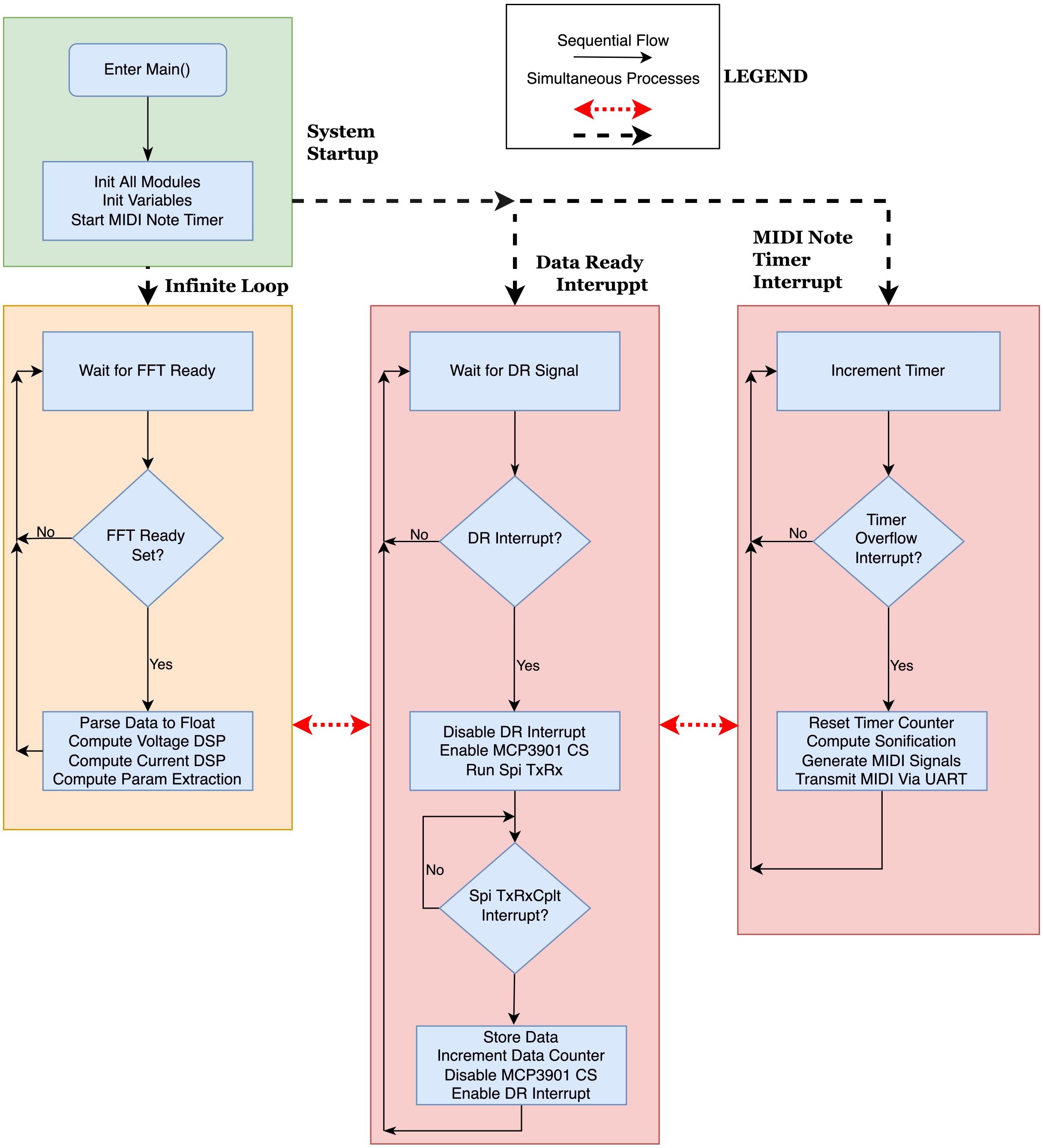


**Fig. 4.1** Embedded Sonification System Firmware Process Flow chart. The System startup sequence is highlighted in green, main infinite loop is highlighted in orange, and interrupt based processes are labeled in red.

## 4.2 System Startup

On startup, the system enters the "main" function and first initializes all peripherals. The GPIO, SPI, UART, and timer modules are all initialized, as are all system variables and the MCP3901 configurations.

The MCP3901 is configured first by resetting all parameter registers and then writing the user-set configuration parameters over the SPI communication line. The phase compensation is set to 0, ADC channel 1 & 2 gain is set to 1, data communication status is set to continuous read, and the two ADCs are set to 24-bit resolution with a 64 value oversampling ratio [12].

The resulting sampling frequency can be derived from the data-sheet DRCLK equation

$$DRCLK = \frac{MCLK}{4 * OSR * PRESCALE} \tag{4.1}$$

where $MCLK$ is the input master clock signal, $OSR$ is the oversampling ratio, and $PRESCALE$ is the user-set prescaler value. For the latest working embedded system, the $MCLK$ frequency is 2.048 MHZ, $OSR$ is 64, and the $PRESCALE$ is 1, resulting in a $DRCLK$ or sampling frequency of 8 kHz.

The original system was designed with a $MCLK$ of 1.966080 MHZ frequency, which would allow for a power of 2 bin/sampling buffer size that is divisible by 60 for the FFT computations. Due to the ongoing chip shortage, this clock frequency was not available from suppliers and was on backorder until late 2022. Instead, a 2.048 MHZ master clock was used. A simplified re-sampling process was used to adjust the sampling frequency to 1920 Hz. The 8 kHz incoming data is up-sampled to 48 kHz using linear interpolation-based up-sampling. Then the 48 kHz data is down-sampled to 1920 Hz by skipping every 25th sample. A simple algorithm was configured that efficiently computes these operations and only stores the re-sampled data samples in both of the data acquisition buffers.

## 4.3 Main() Infinite Loop

Within the main loop, a simplified process is executed continuously. If any interrupts are triggered, the system exits the main and computes the corresponding ISRs before executing any further code within main. Within main, the system waits for the FFT_Ready flag to be set. The FFT_Ready flag is set within the DR ISR when the user-defined FFT size number of data samples has been measured for the current and voltage channels. Once the flag is set the system enters a set of data signal processing routines. The data signal processing consists of three routines that result in the extraction of various power system parameters. The routines are outlined in detail.

### 4.3.1 ADC Reading to Corresponding Voltage/Current Conversion

Once the voltage and current data buffers are ready for FFT computation, they are converted from the ADC reading to their corresponding measurement values. Each voltage sample is converted using the following equation for every $n^{th}$ voltage sample:

$$V_n = \frac{V_{buff_n} * G * V_{Ref}}{ADC\_GAIN} \tag{4.2}$$

where $V_{buff_n}$ is the stored data buffer sample, G is the voltage acquisition circuit divisor and required gain, $V_{Ref}$ is the ADC reference voltage, and $ADC\_GAIN$ is the combined ADC gain outlined for 24-bit mode MCP3901 data acquisition in [12].

Additionally, the current data samples are converted using the following equation for every $n^{th}$ current sample:

$$I_n = \frac{I_{buff_n} * V_{Ref}}{R_{shunt} * ADC\_GAIN} \tag{4.3}$$

where $I_{buff_n}$ is the stored data buffer sample and $R_{shunt}$ is the current shunt resistance. $V_{Ref}$ and $ADC\_GAIN$ are the same as outlined in equation 4.2.

### 4.3.2 FFT Computation

Once the voltage and current data have been converted, they are ready for FFT computation. The system firmware uses the CMSIS DSP library[2] for fast and efficient FFT computation. Specifically, the Real 32bit FFT function from the library is used. This FFT operation processes the set of FFT data and returns the real and complex values for each FFT bin. The computation is computed for both the voltage and current data buffers separately. The resultant complex data from the FFTs are then used for further DSP and parameter extraction. For the latest implementation, the FFT size is set to be equal to one full cycle of 60 Hz sampled at 1920 Hz which is 32 total samples per FFT. This allows for the measurement of up to 16 harmonics of the fundamental 60 Hz, although only 13 are used for the parameter extraction procedures.

### 4.3.3 Parameter Extraction

Using the FFT voltage and current data, the various parameters discussed in **Chapter 1** are acquired and stored within memory to be later used by the sonification algorithms. The parameter extraction equations presented were ported to firmware code functions that are called to compute and store each parameter extraction in memory.

## 4.4 Data Ready Interrupt & Data Acquisition Routine

The main processor waits for the DR signal to be triggered from the MCP3901 for the processor DR interrupt to be initiated. The DR signal is an inverted output on the MCP3901, so when the data is ready, the MCP901 pulls the channel signal low. This DR signal is connected to a hardware interrupt pin on the main processor, so when the DR signal is triggered, the main processor initiates the data read ISR. The DR signal is signaled every time data samples have been measured by the MCP3901 and they are ready for processing. This interrupt has the highest priority, meaning that if any other interrupts are triggered in parallel, the DR ISR will be fully

[2] `https://www.keil.com/pack/doc/CMSIS/DSP/html/index.html`

executed until any other code is executed.

Before reading from the MCP3901, the DR hardware interrupt line is disabled to prevent the ISR to be re-executed part way through the routine has been completed. To read the measured data from the MCP3901 to the main processor, the processor transmits a data read byte and then immediately reads the data bytes from the MCP3901 via the SPI communication lines. The transaction consists of one-byte transmission followed by a 6-byte read. The processor SPI communication was configured in a non-blocking manner using an internal processor interrupt, TxRxCplt (TransmitRecieveComplete), so that other processes can occur in parallel while the processor completes the SPI transaction.

Once the SPI transaction is complete, the data bytes are processed and converted into a 32-bit signed integer which is then stored in the data buffers for the voltage and current channels. Within the data acquisition module, the data buffer indices are incremented and a data counter is incremented. Once the data counter reaches the user set FFT size, the FFT_Ready flag is set. The voltage and current channel buffers are circular, with a buffer size twice the FFT size. Therefore a full set of FFT data can be acquired while the previous FFT data within the buffer is used for the signal processing. At the end of the SPI ISR, the DR hardware interrupt is re-enabled, so that the next DR interrupt can be executed

## 4.5 MIDI Note Timer Interrupt & Sonification Routine

Additionally, the timing for the MIDI note generation is executed by a timer-based interrupt. When the timer counter reaches overflow, the set time period has elapsed. As a result, the data sonification methods will be completed and the corresponding MIDI signals will be created and sent through the isolated system MIDI out, UART transmit, line.

The MIDI timer is configured to be a 1 kHz timer, meaning that the timer ticks occur once every one-thousandth of a second. This timer is configured to have an overflow-triggered interrupt. Therefore when the timer ticks reach a specific value, the timer "overflows". When the timer overflows, the tick count is reset and a corresponding interrupt is triggered. This triggered interrupt will then cause the MIDI ISR to be executed. This allows for easy configuration of tempo. The user configures the tempo and the system calculates a timer overflow based on the tempo. The timer overflow can be set to occur once every quarter, eighth, sixteenth note, etc. for any user-defined tempo. The sonification is computed after this time period elapsed, which timer can be calculated from the following:

$$T_{overflow} = \frac{F_{timer}}{\frac{BPM}{60} * L} \tag{4.4}$$

where $T_{overflow}$ is the MIDI timer overflow period in the number of timer ticks, $F_{timer}$ is the timer frequency, $BPM$ (beats per minute) is the user-set tempo, and $L$ is the user set note length. For the $L$ parameter, a quarter note corresponds to a value of 1, eighth to a value of 2, sixteenth to 4, etc. These $L$ values can be derived from the fact that for 1 quarter note, there are 2 eighth notes, 4 sixteenth notes, and so on for other note divisions. As mentioned previously the detailed sonification methods and procedures are discussed in detail in the following chapter.

## 4.6 Conclusions

This chapter describes the firmware design and architecture for the embedded sonification system. The various firmware processes and ISRs used within the system to sample voltage and current data and the digital signal processing of the sampled data for AC parameter extraction are discussed. Additionally, the structure and process of generating MIDI signals are detailed.

# Chapter 5

# Sonification Methods & Results

This chapter discusses the various methods used for AC parameter mapping sonification. Included within the chapter are examples of four sonification methods that were created. Using the presented methods various types of electrical loads and analysis of their effects on power distribution quality using sonification are examined. Additionally, eight electrical engineers participated in a listening exercise and evaluation of three of the sonification examples. The results of this evaluation are discussed in the last section of this chapter.

## 5.1 Sonification Framework & Connectivity

The main sonification and connectivity framework used to create the sonification examples are shown below.

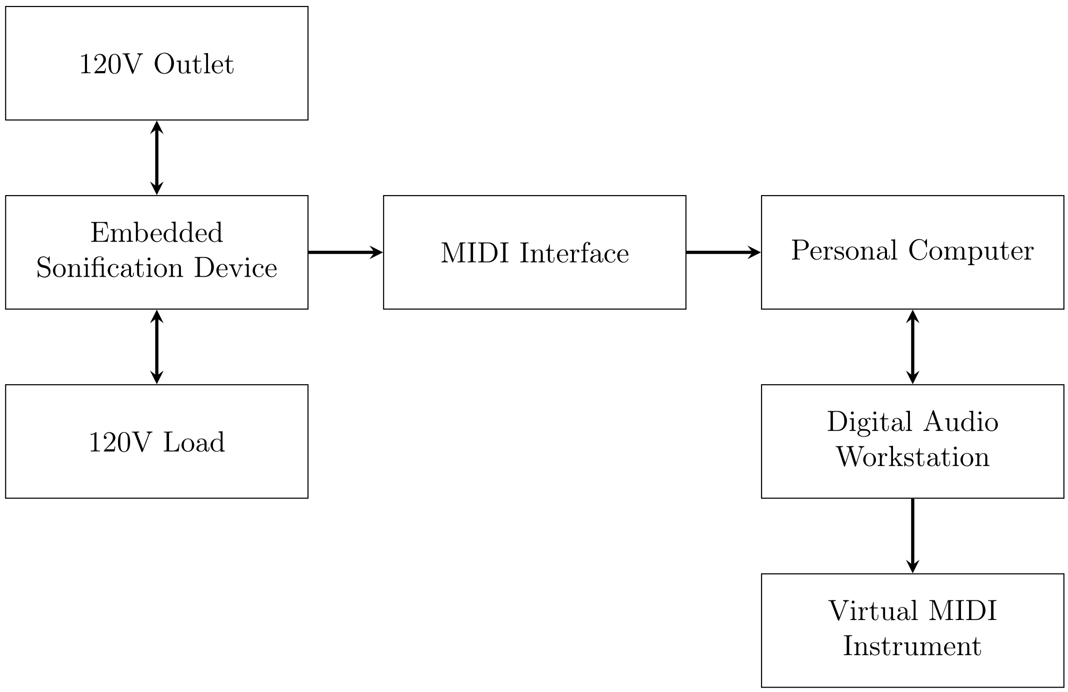


**Fig. 5.1** AC Mains Sonification Connectivity Diagram

The embedded sonification device is connected to an AC mains outlet and an AC appliance/load. Additionally, the MIDI Out from the device is connected to a MIDI-USB interface, which is used for converting the MIDI data into a USB signal. Finally, The MIDI-USB interface is connected to a PC USB port for use in a DAW. This connectivity allows for the generated MIDI data to be processed within the DAW and sent through a virtual MIDI instrument to control synthesizer parameters.

Specifically, for the sonifications discussed, *Ableton live*[1] was used as the main DAW, along with the iConnectivity *mio*[2]as the MIDI-USB interface. For the virtual MIDI instruments, the Lennar Digital *Sylenth1*[3] plug-in and the Ableton live internal MIDI drum rack sampler[4] were used.

[1] `https://www.ableton.com/en/`
[2] `https://www.iconnectivity.com/products/midi/mio`
[3] `https://www.lennardigital.com/sylenth1/`
[4] `https://www.ableton.com/en/manual/instrument-drum-and-effect-racks/`

## 5.2 Sonification Methods

Each sonification method involves using the various extracted AC parameter data and mapping them to MIDI parameters. A MIDI signal is constructed in each method, which is then sent through the MIDI out port of the embedded system device. This MIDI signal is intended to be connected to a MIDI instrument or MIDI interface. For the examples, the upper and lower bounds of voltage magnitude are set using the theoretical maximum/minimum values specified in [33]. The upper and lower bounds for the frequency deviation are set using historic average ambient deviations above nominal, measured by a PMU device continuously running at Union College. The various methods are discussed in detail in the following sections. Starting with direct one-to-one mappings, the most important AC voltage/current phasor parameters, magnitude and frequency, are sonified to MIDI pitch & velocity. The second method expands on this by using deviation steps for triggering chords and sequencing through arpeggiators. Third, a drum sampler triggering method is presented which allows for AC parameter sonification using drum kit samples. Finally, various parameters are normalized and directly mapped to MIDI control change values for direct control of synthesizer control parameters like dry/wet of an audio effect e.g. reverb, distortion, etc.

### 5.2.1 One-To-One Pitch & Velocity Mapping

The first method was first introduced as part of the POC prototype research in [2] but was optimized and improved as part of the initial POC prototype improvements discussed in **Chapter 3**. The voltage (or current) fundamental phasor sample is mapped directly (one-to-one) to MIDI velocity and pitch. Specifically, the RMS magnitude is mapped to MIDI velocity, and the fundamental frequency is mapped to pitch. A flow chart of this mapping process is shown below in the following figure.

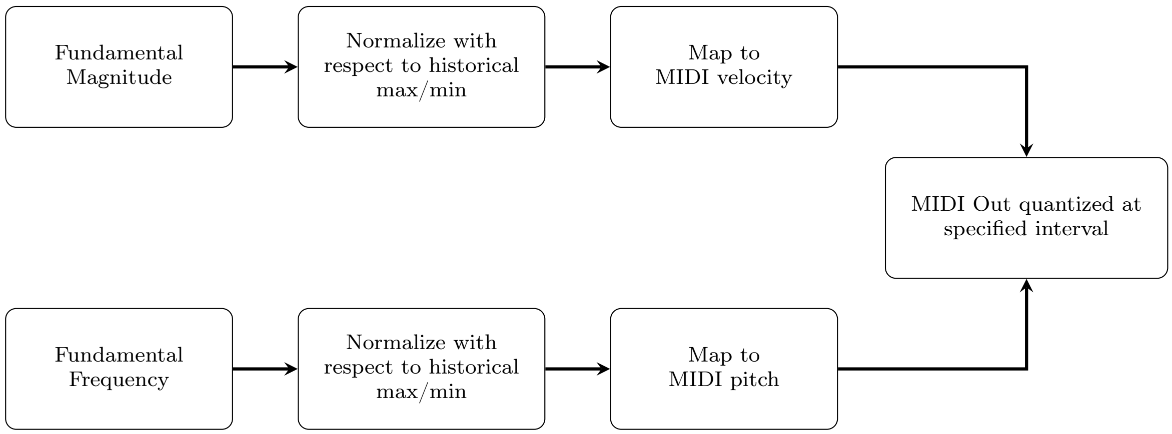


**Fig. 5.2** One-to-one mapping of Phasor to MIDI Pitch & Velocity

For this mapping, the fundamental phasor magnitude is normalized with respect to the set maximum and minimum values. The normalized value is then directly mapped to a MIDI velocity parameter in the range of 0 to 127 by mathematically multiplying the normalized value (0-1) by 127 and rounding to the nearest integer. Following this, the phasor sample fundamental frequency is mapped to a MIDI pitch parameter in a set musical key, over a user-set octave span. Before using this mapping, the user will select a specific musical major key, note length, and tempo. The note length and tempo affect the rate at which the sonification is computed. Using the hardware timers discussed in **Chapter 4**, this sonification method is completed at the user-specified rate (tempo/note length).

Additionally, the user will select a "number of octaves" parameter which corresponds to the number of octaves above and below the middle note. Using the user-set parameters, the algorithm generates an array of notes that span within the musical key, over the specified number of octaves. For example, if a user selected a key of C and one octave, the range of notes would include the scale notes one octave above and below middle C(C4). This would result in seven scale notes above and below middle C and therefore a total of 15 notes for the algorithm to choose from. The notes are stored in an array in value order. Similar to velocity mapping, the algorithm normalizes the phasor frequency value with respect to the historic minimum and maximum values. The value is then multiplied by the number of notes minus 1 since the programming language C starts with 0 as the first array index. So for the previous example, the normalized value would be multiplied by 14 and rounded to the nearest integer to find the pitch array index. The corresponding MIDI pitch is then extracted from the array using the index. For any key specified other than C, the extracted MIDI pitch value will be shifted. For example, C# would result in a MIDI pitch value shift of +1, D would result in a shift of +2, and so on for the other musical keys. Using the calculated MIDI velocity and pitch values, a MIDI signal is generated and sent through the embedded system MIDI out connector for MIDI instrument playback.

### 5.2.2 Chord Mapping

The second parameter mapping technique uses the voltage or current fundamental frequency deviation from the nominal 60 Hz. The absolute value of the deviation is normalized with respect to the historic maximum deviation. This normalized value is then mapped to the number of notes in a chord. The greater the absolute deviation, the more notes are played in a MIDI chord. A flow chart of this mapping process is shown below.

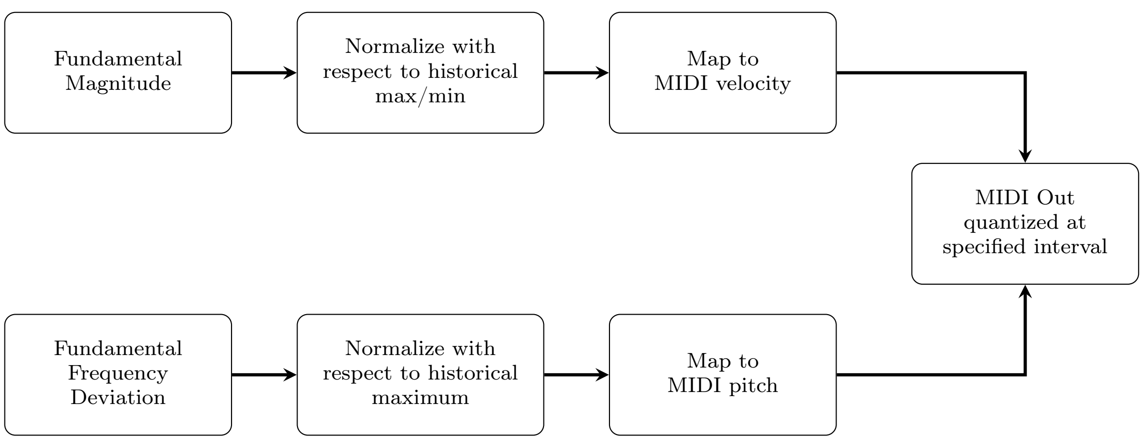


**Fig. 5.3** MIDI Chord Triggering

For this method, the user specifies the chord base note and the incremental semitone steps above the chord base. The total number of chord notes is used to generate thresholds for triggering each chord note. The first chord note is always played, while the other chord notes are added if the frequency deviation is equal to or greater than the generated note thresholds. An example of a C major 7 chord based at C4 is shown below.

| Chord Note | Semitone Increment | Trigger Deviation Threshold | Frequency Threshold(Hz) |
|---|---|---|---|
| C4 | 0 | 0 | 0 |
| E4 | 4 | 0.333 | 0.020 |
| G4 | 7 | 0.667 | 0.040 |
| B4 | 11 | 1 | 0.060 |

**Table 5.1** Chord Mapping for Middle C Based Major Chord

For the above example, the total number of chord notes is 4, so the chord note thresholds above the base note are split into steps of 0.33. Therefore, E4 will only be triggered if the frequency deviation is greater than or equal to 0.33, G4 will only be triggered if the deviation is greater than or equal to 0.667, and B4 will only be triggered if the frequency deviation reaches the maximum value.

Additionally, in this method, fundamental magnitude is mapped to MIDI velocity of the chord, and the resultant MIDI signal is output at a set quantized interval. The MIDI chord can optionally be sent through a MIDI arpeggiator to create interesting sequences.

### 5.2.3 Drum Rack Sampler Triggering

A third parameter mapping technique also uses the voltage or current phasor for sonification. A diagram of this method is shown below.

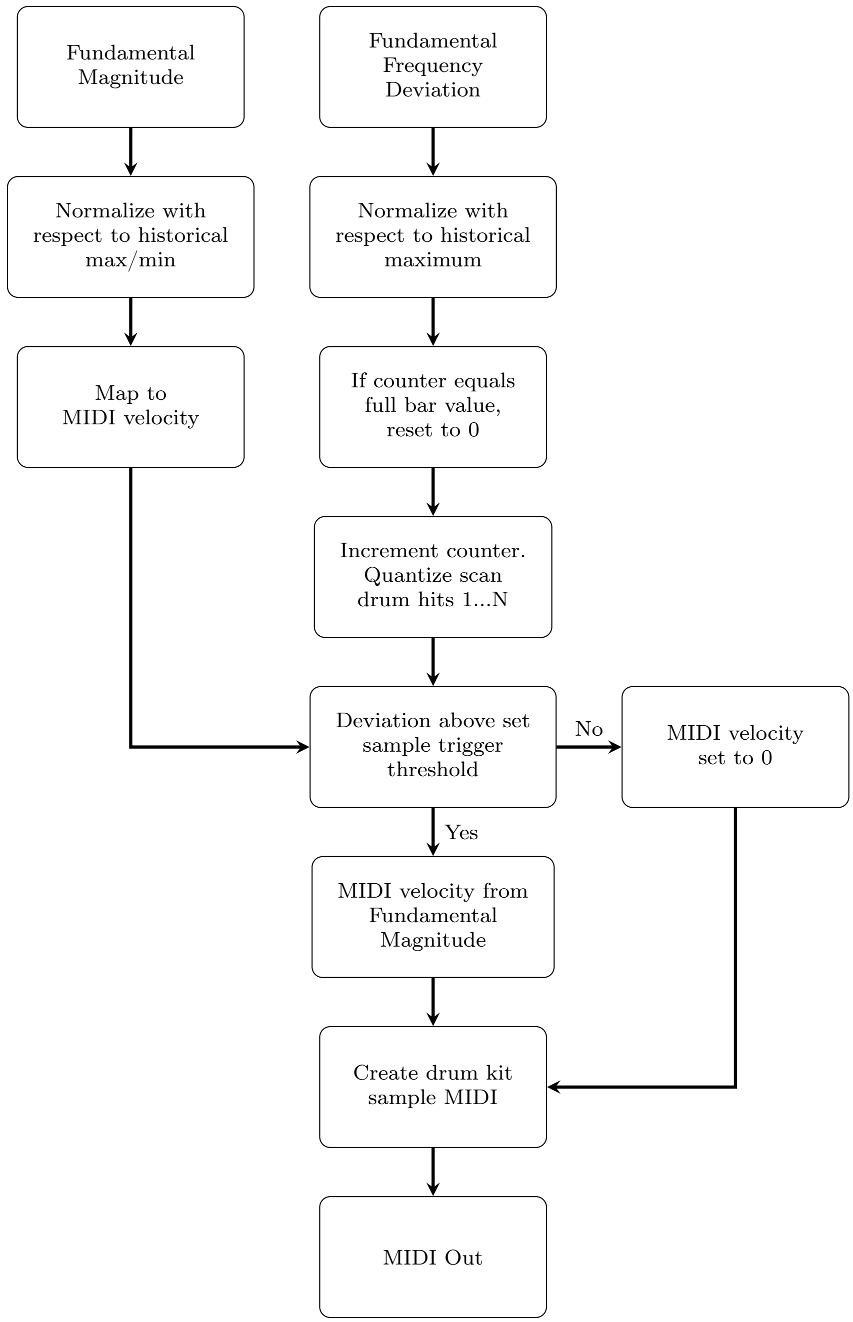


**Fig. 5.4** Drum Rack Mapping & Sequencing

The absolute frequency deviation, discussed in the previous section, is used for setting thresholds of drum rack sample triggering. Each drum kit audio sample is placed within a MIDI track drum rack sampler, like the drum rack instrument in Ableton shown below.

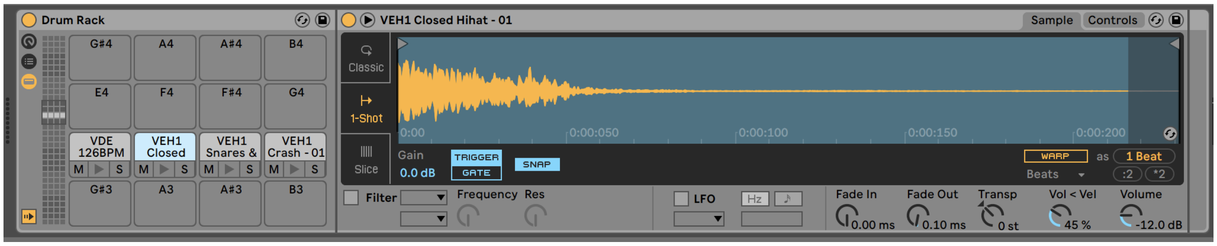


**Fig. 5.5** Ableton Drum Rack Sampler Example

This configuration allows for a MIDI pitch value to trigger a user-specified audio sample. For the above example, the kick sample corresponds to MIDI pitch 60, hi-hat pitch 61, snare pitch 62, and crash pitch 63. Therefore, a drum kit sample will be triggered if a MIDI signal with the corresponding sampler pitch value is sent through the MIDI track channel, with a velocity greater than 0.

For this parameter mapping method, if the deviation is greater than the specific drum rack threshold, the MIDI pitch corresponding to the drum hit is played through the MIDI drum rack sampler. Once again, the fundamental magnitude is also mapped to the drum rack sampler MIDI velocity. If the frequency deviation is below the specified threshold, the corresponding drum kit MIDI pitch signal will be sent with a velocity 0, so that the drum hit is not heard.

Each hit is quantized separately within the user-set tempo, to allow for rhythmic sequences to be generated. The sonification hardware timer triggers at the specified tempo, in eighth-note intervals. The algorithm keeps track of the eighth note sequence value for the quantization of the drum kit sampler. This count is reset after each musical bar or eight eighth notes, and the counting/scanning sequence repeats. An example of a common dance music-based drum kit sampler triggering sequence is shown below, where $\alpha$, $\beta$, $\gamma$, and $\delta$ are user-specified triggering thresholds.

| Sample | MIDI_Val | Trigger Deviation Threshold | Eighth Note Quantized Count Val |
|---|---|---|---|
| Kick | 60 | $\alpha$ | 1,3,5,7 |
| Hi-hat | 61 | $\beta$ | 2,4,6,8 |
| Snare | 62 | $\gamma$ | 3,7 |
| Crash | 63 | $\delta$ | 5 |

**Table 5.2** Drum Kit Sampler Triggering for Dance Music Quantized Sequence

### 5.2.4 MIDI Control Change Mapping

The final parameter sonification method involves mapping AC parameters to MIDI control changes, specifically for controlling audio effect control parameters. A flow chart displaying the mapping process can be seen in the following figure.

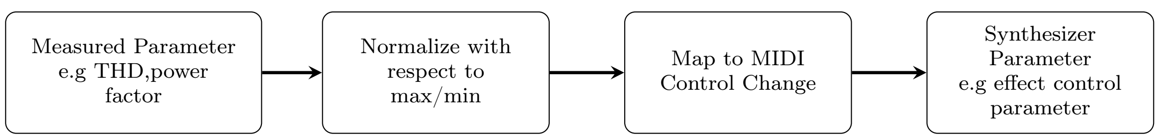


**Fig. 5.6** Parameter Mapping to MIDI Control Changes

A measured AC parameter is normalized with respect to its upper and lower bounds and is then directly mapped to a 0-127 MIDI control change signal. The signal is then sent through the MIDI out connector and intended to be sent to a MIDI control parameter like an effect dry/wet control parameter or other synthesizer parameter control parameter. For example, total harmonic distortion can be normalized and mapped directly to the dry/wet control parameter of a Sylenth1 synthesizer audio distortion effect.

## 5.3 Sonification Examples

Various sonification examples were created using the previously discussed connectivity framework. All of the examples discussed in this section and the following evaluation section are located at:

https://drive.google.com/drive/folders/1NjvDSu63YpzO_Ws3I5lZNSdvSPlbhf_7

The following sections outline the various sonifications that were created in detail.

### 5.3.1 Harmonic Distortion Sonified Using Audio Distortion

$THD_r$ or $THD_f$ is mapped directly to the dry/wet control parameter of an overdrive effect. The normalized value (0-1) is directly mapped to a MIDI control change signal. The resulting control change signal is sent to Sylenth1 dry/wet control parameter of an audio distortion effect. An example of this mapping is shown in the example called "Varying Loads".

### 5.3.2 Current/Voltage Phase Delay Sonified Using Reverb/Delay

Power factor, which is representative of the delay between the peaks of current and voltage, is mapped to the dry/wet control parameter of reverb and/or delay. The value (0-1) is inverted and directly mapped to a MIDI control change signal. Therefore a power factor value of 0, where current lags voltage 90 degrees out of phase, is equivalent to a MIDI control change value of 127. For a power factor value of 1, where current and voltage are in phase, the value is mapped to a control change value of 0. The resultant signal is then sent to the dry/wet control parameter of the Sylenth1 reverb or delay effect. An example of this mapping is shown in the following example called "Varying Loads".

### 5.3.3 Changing From No Load to Applied Load

A sonification was created in real-time that consists of changing the system load in a discrete manner (on/off). The tempo for this sonification is 120 Beats Per Minute (BPM). An air conditioner was connected to the AC load side of the embedded sonification system in the off configuration. A custom Sylenth1 "saw-tooth pluck" style synthesizer preset was initiated on one MIDI channel DAW track, while an Ableton sampler was configured on a separate MIDI channel DAW track.

This example can be heard within the file named **"Sonification_Air_Conditioner.wav"**.

For this example, the AC mains voltage phasor was sonified using the chord mapping sonification method, with an Ableton arpeggiator effect turned on within the first MIDI channel track. The voltage phasor sonification was computed every eighth note at the 120 BPM tempo or every 0.25 seconds. The chord mapping had a base note of C2 and was configured as shown below.

| Chord Note | Semitone Increment | Trigger Deviation Threshold | Frequency Threshold (Hz) |
|---|---|---|---|
| C2 | 0 | 0 | 0 |
| Eb2 | 3 | 0.5 | 0.030 |
| G2 | 5 | 1 | 0.060 |

**Table 5.3** Changing No Load to Applied Load Sonification Chord Mapping Configuration

Additionally, in parallel, the AC load current phasor was sonified using the sampler triggering method within the second MIDI channel track. For the sampler triggering, configuration shown in **table 5.2** was used. Specifically, the trigger deviation thresholds within the table were set to 0.1 for $\alpha$, 0.3 for $\beta$, 0.5 for $\gamma$, and 0.8 for $\delta$.

At the start of the sonification, there is no load applied to the system with the air conditioner turned off. Therefore, only the varying voltage phasor can be heard through synthesizer velocity for magnitude, and the number of arpeggiator notes for frequency deviation.

After about 12 seconds, the air conditioner load is turned on and applied to the system. The inrush current required to start the air conditioner causes the measured AC mains voltage to droop, which with careful listening can be heard as a drop in synthesizer volume. The droop can also be seen in the recorded synthesizer MIDI track shown below.

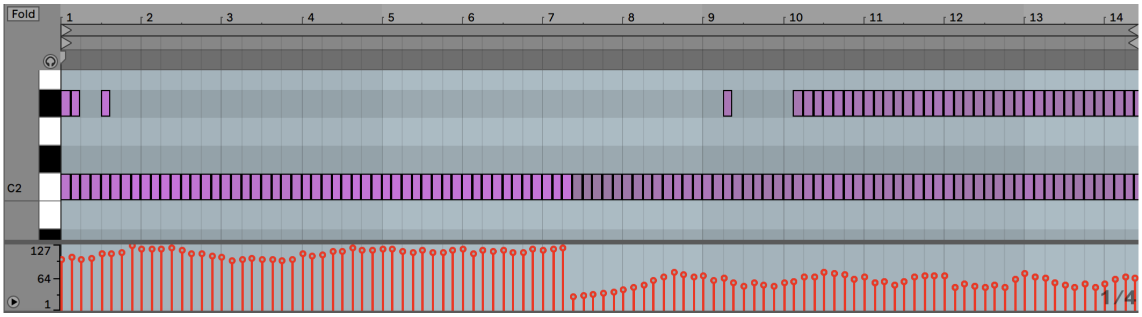

**Fig. 5.7** Voltage Sonification Synthesizer Channel MIDI. Each sonified MIDI note was quantized to eighth notes at 120 BPM

Based on the above figure, the voltage drop occurs at exactly 12.75 seconds. This is calculated from the fact that the drop occurs on the 51st eighth note, which at 120 BPM would be 12.75 seconds. This is also the exact time when the load was connected. At the 12.75 second point in time, there is a load connected and current is flowing through the data acquisition system (therefore current is no longer zero). As a result, the drum sampler triggering becomes audible. As the measured current phasor frequency deviation increases, more drum hits can be heard.

### 5.3.4 Incandescent Lamp & AC Fan Varied Parallel Load

An AC power strip was connected to the AC load side of the embedded sonification system so that multiple devices could be plugged in parallel. A sonification was created in real-time that consisted of adding and removing system loads for observation of the varying current consumption. The tempo for this sonification is the same as above at 120 BPM. An incandescent lamp and AC fan were connected to the AC strip on the load side of the embedded sonification system, both in the off configuration. The same Sylenth1 synthesizer preset used above was initiated on one MIDI channel DAW track, while an Ableton sampler was configured on a separate MIDI channel DAW track. This sonification sequence can be listened to within the file named **"Sonification_lamp_fan_parallel.wav"**

For this sonification example, the power factor was mapped to the dry/wet control parameter of the Sylenth1 synthesizer reverb effect. Additionally, the AC mains voltage phasor was sonified using the chord mapping sonification method within the first MIDI channel track. The voltage phasor sonification was computed every eighth note at the 120 BPM tempo or every 0.25 seconds. The chord mapping had a base note of C2 and was configured as shown below.

| Chord Note | Semitone Increment | Trigger Deviation Threshold | Frequency Threshold (Hz) |
|---|---|---|---|
| C2 | 0 | 0 | 0 |
| Eb2 | 3 | 0.167 | 0.01 |
| F2 | 5 | 0.333 | 0.02 |
| G2 | 7 | 0.5 | 0.03 |
| Bb2 | 10 | 0.667 | 0.04 |
| C3 | 12 | 0.833 | 0.05 |
| Eb3 | 15 | 1 | 0.06 |

**Table 5.4** Incandescent Lamp & AC Fan Voltage Sonification Chord Mapping Configuration

The AC load current phasor was also sonified, in parallel, using the same sampler triggering configuration as used in the above example. For the current sampler triggering, the maximum magnitude threshold used for normalization was set to 1A, since the fan and lamp have low current consumption. The fan used has a typical power consumption of 30W while the lamp had a 60W bulb, and therefore typical 60W Power consumption. Therefore the theoretical current consumption of each load can be calculated using the following equations.

$$I_{Fan} = \frac{P_{Fan}}{120V} = \frac{30W}{120V} = 0.25A \tag{5.1}$$

$$I_{Lamp} = \frac{P_{Lamp}}{120V} = \frac{60W}{120V} = 0.5A \tag{5.2}$$

The sonification example starts with just the lamp turned on. The voltage phasor can be heard through varying synthesizer velocity for magnitude, and the varying number of arpeggiator notes for frequency deviation. Since the lamp is a resistive load, there is no voltage/current phase delay and power factor is nearly 1. Therefore there is no apparent reverb effect.

The current phasor sonification can be heard through the drum kit sequencing. The higher the frequency deviation, the more drum kit hits are heard. Additionally, the current magnitude is heard as the drum kit triggered sample volumes.

At the 8-second time stamp, the fan load is turned on and applied to the system load. This causes the power factor to no longer be 1 due to the inductance of the fan. Therefore current and voltage are not in phase with a phase difference of about 52 degrees. This can be heard as the applied reverb effect. The drum kit volume also increases, since the current consumption also increased.

At the 16.75-second time stamp, the fan is turned off. Consequently, the reverb effect is no longer present and the drum kit sample volume decreases. The observed effects of the fan are then noticed again when the fan is turned back on at the 24.75-second time stamp. The varying current consumption mapping to drum kit MIDI velocities can be in the following figure 5.8.

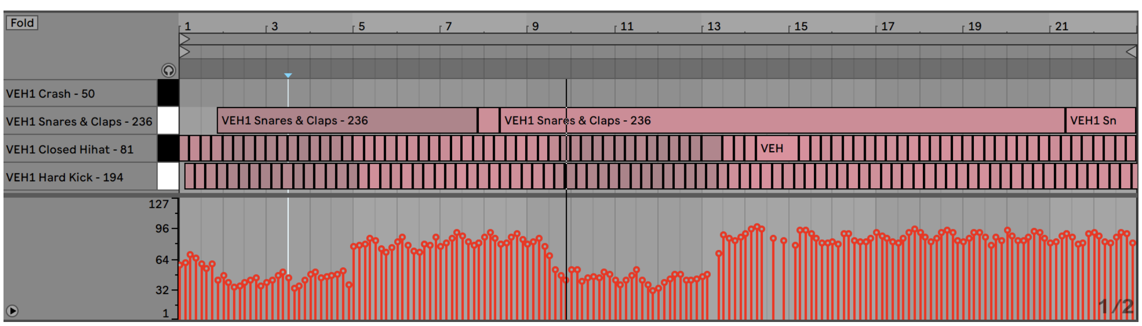


**Fig. 5.8** Incandescent Lamp & AC Fan Current Sonification Drum MIDI. Each sonified MIDI note was quantized to eighth notes at 120 BPM

Specifically, the above figure provides a visual display showing the addition and removal of the fan load, within the velocity magnitude mapping. When the fan load is added, a jump in magnitude can be seen at the fifth bar. When the fan load is removed, the drop in magnitude can be seen part way through the ninth bar. Finally, the second power consumption jump, for when the fan is added back as a load, can be seen part way through the 13th bar. With just the lamp plugged in, the MIDI velocities range from 31 to 69, which is equivalent to a range of 0.25 to 0.54 A. With the fan load added in parallel, the MIDI velocities range from 69 to 97 which is equivalent to 0.54 to 0.75A. These values are consistent with the theoretical current draw of each device load.

### 5.3.5 Varying Loads

A sonification sequence was created that consisted of changing the system load in real-time. An AC power strip was connected to the AC load side of the embedded sonification system, similarly as described in the above example. An incandescent lamp (resistive load), a fan (inductive load), and a PC (non-linear) load were all connected to the power strip in the off position. The same "saw-tooth pluck" synthesizer preset above was initiated, with audio distortion and reverb effects activated. A video displaying the changing loads, along with the corresponding voltage/current waveforms and current harmonics of the sonification sequence can be watched in the file labeled **"Sonification_Varying_Loads_Demo.mp4"**.

For this sonification sequence, $THD_f$, of the current was mapped to the dry/wet control parameter of the Sylenth1 synthesizer audio distortion. The power factor was mapped to the dry/wet control parameter of the Sylenth1 synthesizer reverb effect. Additionally, in parallel, the AC mains voltage phasor was sonified every eighth note using the same chord mapping sonification as the above examples, with an Ableton arpeggiator effect turned on. At the start of the sonification sequence, the lamp is turned on as the system load. Since the lamp is a resistive load, there is no harmonic distortion nor current/voltage phase delay. Therefore, only the varying voltage phasor can be heard through varying synthesizer velocity for magnitude, and the number of arpeggiator notes for frequency deviation.

Next, at the 13-second time stamp, the lamp is turned off and simultaneously the fan is turned on. This change causes the system to have an inductive load. Therefore, the voltage and current are out of phase with the current lagging the voltage and power factor becomes nearly 0. As a result, the Sylenth1 synthesizer reverb dry/wet control parameter increases to nearly full 127 value, and reverb can be heard within the sonification.

Following this, a PC load is switched on at the 26-second time stamp. This change causes the current to experience high amounts of harmonic distortion, due to the nonlinearity of the PC load switch-mode power supply. The measured THD is 40.36% and as a result, the Sylenth1 synthesizer audio distortion dry/wet control parameter increases to 40%, and audio distortion can be heard within the sonification. The PC load is then turned off at the 34-second time stamp and the audio distortion is no longer present. The sonification finishes after this load change with just the fan on. The same applied synthesizer reverb effect as discussed earlier can be observed along with the varying arpeggiator notes and synthesizer volume.

## 5.4 Sonification Evaluation With Electrical Engineers

A preliminary evaluation of the above sonification strategies was carried out with eight electrical engineers. The main goal of the evaluation was to assess the effectiveness of the proposed acquisition and sonification system as a tool to help identify AC parameter variations through listening to sound alone.

### Participants

The eight participants were colleagues from previous work and academic studies in electrical engineering, all with varying backgrounds and knowledge of music. The intent was to recruit electrical engineers who had a general familiarity with the parameters and electrical engineering concepts presented in the study. The recruitment was not focused on recruiting power systems experts but this could be expanded on in future evaluations. Each engineer was first informally contacted by phone to determine if they had an interest in possibly participating in an evaluation of this thesis research. Once they confirmed interest in the experiment, they were formally contacted with a recruitment email. Within the email was a brief introduction to the embedded system and a summary of its functionality. After accepting to participate in the evaluation, participants completed the procedures remotely and their answers were collected using an anonymous google form.

### Evaluation procedure

Participants were presented with three different sonification examples with increasing complexity, all generated from the acquisition device. Various questions were posed on the observation of parameter variations and divided into two sets.

For each of the three examples, participants listened to the given sonification and were asked the first set of questions focusing on the sound parameter changes they could perceive, before any explanations about the mapping chosen in the specific sonification. For instance, in example 1, after being informed that "The parameters sonified in this example include fundamental voltage magnitude and distribution frequency", participants listened to the sonification and were asked, "What auditory parameter changes can you perceive changing through the audio example?"

After answering this first set of questions, participants were provided with details on the different mappings. For instance, again in example 1, participants were told: "In this example voltage magnitude is mapped to MIDI note velocity/volume and distribution frequency is mapped to MIDI pitch." They were then asked to listen to the sonification a second time and asked: "Are the variations more easily perceived now that you know the mapping techniques? Can you hear the changes in volume and variations in pitch?".

Questions asked in sonification examples 2 and 3 went into further detail about the timing of parameter variations as well as about the qualities of these variations.

After the three sonification examples had been presented, a series of additional questions were asked to wrap up the study. These focused on the participant's experience with the evaluation, the potential of the system to be used in teaching electrical engineering as well as its musical potential. The results of the evaluation are discussed thoroughly in the following sections.

All of the sonification examples used in the evaluation can be found in the folder titled **"AC Sonification Device Observational Experiment Samples"** located in the google drive link shared at the beginning of **section 5.3**.

The procedures presented, along with the questions asked, are shown in **Appendix A**, and the ensemble of participants' responses are presented in **Appendix B**.

### 5.4.1 One-to-One Pitch & Velocity Mapping

The first portion of the evaluation had the participants listen to a sonification example, labeled "sample1", that used the "One-to-one pitch & velocity mapping" method for sonifying voltage magnitude and frequency outlined in **section 5.2.1**. As mentioned above, participants were first asked to listen to the example and comment on what auditory parameter variations they could hear without any knowledge of the sonification parameter mappings.

All participants successfully detected variations in pitch, with seven of them also detecting variations in volume. After being informed of the parameter mapping techniques that were used, all participants were able to successfully identify both parameter variations.

### 5.4.2 Varying Loads

For the second portion of the evaluation the audio from the "Varying Loads" example, presented in **section 5.3.5**, was used and was labeled as "sample2". The main intent of this section was to evaluate the participant's ability to detect load changes and comment on what types of load were present.

As in example 1, the participants were informed about the types of parameters that were sonified but were not told of the specific parameter mapping techniques. Additionally, an overview of the various types of loads present through the sample and their effects on the power distribution quality were provided. As mentioned in **section 5.3.5**, this example starts with a resistive load then changes to an inductive load at the 13-second time stamp, followed by a change to a non-linear load at the 26-second time stamp, and finally changes back to an inductive load at the 34-second time stamp. The participants were presented with the sonification example and asked to annotate when they perceived load changes and what type of load they thought was present.

All of the participants were able to detect the load changes at the 26 s and 34 s time stamps, with five of them also detecting all three load change time stamps correctly and three participants missing the load change at 13 seconds.

One participant correctly detected all time stamps and the types of loads for all three variations. Another one correctly identified only the last load (inductive). Six of the participants did not mention any load at all and only focused on the timestamps. This might have been an effect of a possibly poorly constructed question, which mixed the two aspects of the evaluation. It is then not possible to disentangle between those who did not detect the loads and those who simply skipped that part of the question.

The participants were then told the parameter mapping techniques used in the example and detailed explanations of how each parameter was sonified, though they were not informed of the load time stamps nor their corresponding load type. They were again asked to annotate when they perceived load changes and what type of load they thought was present. Responses remained mainly the same, with one engineer now detecting three additional load changes that did not occur.

### 5.4.3 Changing From No Load to Applied Load

For the third portion of the evaluation, a sonification with the identical configuration of the "Changing From No Load to Applied Loads" example presented in **section 5.3.3** was created. This sonification was labeled as "sample3". In this example, the air conditioner load was applied to the system at the 5-second time stamp.

Without knowledge of the specific mapping techniques, the users were presented with the example and asked to annotate when they perceived the load being applied. They were also asked if they could hear the variations in the drum kit triggering and what they thought was causing such variations.

Six of the participants were able to correctly detect that a load was applied to the system at the 5-second time stamp. Of these six participants, two participants thought there were two additional load changes, which might have been an artifact of the participants trying to listen to various load changes after completing the "varying loads" section.

For the drum kit triggering, all of the participants were able to detect that the drum kit sequencing was changing and believed it to be a result of variations in distributed power.

After being informed of the specific mapping techniques and listening to the example again, all of the participants commented that the frequency deviation of current was more apparent than before and that they could perceive the deviation varying.

### 5.4.4 Qualitative Evaluation

For the final part of the evaluation, the participants were asked questions regarding their experience with, and thoughts on, the intended use of the system.

All of the participants enjoyed listening to the sonifications with a strong agreement of using the tool for music creation. The majority of them also agreed that the system had potential use in power systems education and use for power systems operators.

Most participants found sample2 to be the most pleasing, with one participant enjoying sample3. Half of the participants found sample2 to be the easiest sonification example for comprehending data variations, with the other half evenly split between sample1 and sample3.

### 5.4.5 Discussion

The evaluation provided an initial review of the embedded system sonification results. Participants were able to perceive parameter variations in the sonifications even before information about the mapping used in each example was given, supporting the usefulness of the system. The results of the load detection section seem most promising, as participants were able to detect load changes accurately with a few correct estimates of the types of load. This accuracy may have been due to the discrete nature of the load changes causing changes in audio effects as sonifications. The application of reverb for an inductive load, and the application of distortion for a non-linear load are discrete changes that occur immediately after the change in load. These changes may be easily more perceptible to the participants versus the continuously varying note and volume/velocity changes present in the other mappings. Participants were also positive about the use of the proposed system in music creation and for teaching power systems analysis.

By allowing future participants to repeatedly listen to the examples and/or by providing training to help them identify the variations/loads in the sound signal, we expect that these results can be improved as mentioned by some of the participants.

A limitation of the study might be related to the fixed order of sections which may have caused issues with the results of the evaluation. For example, once users knew that pitch and volume variations occurred, they seemed to focus on these specific variations throughout the study. Similarly, an order effect might have been the reason for errors in the third sonification, when two users found in-existent load changes.

## 5.5 Conclusions

This chapter introduced four sonification methods used by the device: ranging from simple one-to-one MIDI parameter mapping to more complex MIDI chord and drum-kit sequencing, these methods explored sonification of various AC parameters. Using the designed methods, examples were created for analysis of electrical loads and their effects on the voltage and power distribution quality. A preliminary evaluation of the system was presented which showed promising results in the use of the system for musical creation and detection of AC parameter variations.

# Chapter 6

# Conclusions

This thesis described the development of an embedded acquisition device for the sonification of AC mains parameters for North American 120 V/60 Hz household power systems. The electronics architecture, development, and manufacturing of the embedded system were outlined in detail. Additionally, the firmware architecture and development of the device were discussed including a discussion of how the various AC parameters used for sonification are acquired by the system. Using the measured AC parameters various sonification methods were developed and computed by the embedded system. Examples were included demonstrating the sonification methods used for AC parameter analysis.

Using the created sonification examples, a preliminary evaluation was completed with eight electrical engineers. The results of this evaluation showed success in the detection of electrical load changes and parameter variations. The system allows for analysis of the effects on power distribution from various types of loads along with the natural ambient behavior of the distributed mains voltage variations. It provides a new way to analyze power systems data from traditional visual displays (graphs, plots, etc.). The system has the potential for use in households with possible use as an educational tool. It could be used for bringing awareness of the ever-changing nature of power systems to average consumers, musicians, and engineers. The results of this research warrant continuation of the project and areas of future work are presented below.

## 6.1 Future Work

### 6.1.1 Sonification Methods

With only four initial sonification methods introduced, there are nearly endless possibilities for sonification. Since the existing system provides the data acquisition and parameter extraction, the research could be completed entirely on the sonification procedure sub-functionality of the device and consequently, further sonification methods could be developed.

Not all of the AC parameter variations were used for sonification. Parameter mapping of real/apparent/reactive power and harmonic information(other than harmonic distortion) could also be explored. Additionally, other parameter mapping protocols and audio synthesis techniques could be examined outside of the use of MIDI.

Finally, the sonification methods presented could be further evaluated using various types of other appliances and also further examination of combining multiple loads in parallel.

### 6.1.2 Forced Oscillation and Transient Power System Response Sonification

The existing system focused entirely on the sonification of ambient power system conditions of a power system. As discussed in **Chapter 1**, forced oscillation and transient responses can occur which can cause large fluctuations in the distributed voltage magnitude and frequency. Initial developments were presented in [2], but these used simple one-to-one mapping of MIDI pitch/velocity and also were not computed in real-time. Further research on simulating these responses in real-time and creating relevant sonifications within the custom-embedded system is needed. Using the user push buttons, these events could be simulated and processed by the sonification algorithms while the system was running. Focus on sonifications to aid in the detection and differentiation of these events could be an important tool in power systems monitoring. This would further expand the possible use of the embedded system by power system engineers.

### 6.1.3 Further Evaluation With Electrical Engineers & Musicians

The presented evaluation results had a very small sample size of only eight engineers. The evaluation could be conducted further with more electrical engineers, specifically engineers working in power system design and/or monitoring. Additionally, the initial sonifications could be evaluated by musicians and other experts in sonification for feedback on the parameter mapping techniques that were chosen. This could be extended further into a workshop session including people with expertise in all of the above disciplines. An inter-disciplinary workshop discussing the AC parameters and mapping choices for their sonification could provide useful ideas for further sonification developments power system parameter sonification.

### 6.1.4 System Accessibility

The accessibility of the system could further be improved, specifically allowing easier use for visually impaired and general users. For general users, an improved, simple graphical user interface could allow general users to create their own custom mappings of parameters. In this interface, they could simply select an AC parameter and choose the type of mappings that they would like to use for sonification. For example, the data measured from the system could be sent out of the UART serial port and through to the Libmapper[1] framework. Combined with Libmapper, sonifications could be more easily created and experimented with by general users.

For visually impaired users, a speech recognition/processing system could be utilized. This type of application would allow visually impaired users to give vocal commands to the system specifying what AC parameters they want to be mapped, and to what type of auditory parameters. They could then give the system commands to play back their proposed parameter mappings and listen for feedback.

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# Appendix A

# Embedded Sonification System Observational Experiment Procedures

## I. First Prototype, One-to-One MIDI Parameter Mapping Sonification

The following example contains the sonification of AC socket mains voltage. The parameters sonified in this example include fundamental voltage magnitude and distribution frequency. Please answer questions in order since more information on the mappings are revealed as you go through the processes.

Listen to “sample1”.

1. **What auditory parameter changes can you perceive changing through the audio example?**

In this example **voltage magnitude** is mapped to MIDI note velocity/volume and **distribution frequency** is mapped to MIDI pitch. Listen to “sample1” again.

2. **Are the variations more easily perceived now that you know the mapping techniques?**
3. **Can you hear the changes in volume and variations in pitch?**

## II. Varying Loads In Real Time

The following example consists of a sonification of various different loads applied/adjusted at different points in time. The parameters sonified in this example include fundamental voltage magnitude, distribution frequency, load harmonic distortion, and current/voltage phase delay. The example starts with a single specific load type and then the load changes throughout the example.

The electrical loads used in this example include a purely inductive load which causes large delay between current/voltage(therefore affecting power factor), a purely resistive load(nearly no distortion nor current/voltage phase delay), and a highly non-linear load which causes harmonic distortion in the signal.

Please answer questions in order since more information on the mappings are revealed as you go through the processes.

Listen to "sample2".

1. **What auditory parameter changes or audio effects can you perceive changing through the audio example?**
2. **What are your estimated timestamps for the load changes(first load is at time 0), and what loads do you think are present at these timestamps. Note, that only a single load is present at a time. You will not be detecting multiple loads being applied to the system in parallel.**

Now we will share what specific sonification mappings have been implemented. We will have you listen to the sample again and answer further questions:

**Voltage distribution frequency deviation** is mapped to the number of notes in the synthesizer arpeggiator. The higher the frequency deviation from the 60 Hz norm, the more notes that are played through arpeggiator at a pre-set quantized rate. Additionally, **Voltage magnitude** is mapped to the synthesizer note velocities/volumes.

Load **harmonic distortion** is mapped to a dry/wet wheel for an audio distortion effect. 100% **harmonic distortion** results in full wet **distortion** effect while 0% results in zero distortion and "dry" **distortion** effect.

Load **current/voltage phase delay** is mapped to a dry/wet wheel for a reverb effect. 90 degree **phase delay(out of phase)** results in full "wet" **reverb** effect while 0 degree **phase delay** results in zero reverb effect.

Listen to the "sample2" again and annotate the time at which you believe the load changes occur.

3. **What are your estimated timestamps for the load changes(first load is at time 0), and what loads do you think are present at these timestamps.**
4. **Now that you are aware of the synthesizer mapping technique, is the varying number of arpeggiator notes (therefore frequency variations) more apparent?**

## III. Constant Load and No Load present

The following example consists of a sonification of one electrical load. The only parameters sonified in this example are the fundamental voltage magnitude, distribution frequency, and the load current magnitude and measured distribution frequency. As a reminder when there is no load applied to the system no current will be drawn and therefore current magnitude will be 0.

Listen to "sample3".

1. **Annotate the time stamp when you believe that the load has been applied to the system.**
2. **Do you notice any changes in velocity/volume throughout the sonification?**
3. **Do you notice any variations in the drum kit triggering? Comment on what you think might be controlling the variations?**

For this example , there is no load present at the start and at a certain point in time an Air conditioner is turned on. This causes a significant droop in the local mains voltage magnitude.

**Voltage distribution frequency deviation** is mapped to the number of notes in the synthesizer arpeggiator. The higher the frequency deviation from the 60 Hz norm, the more notes that are played through arpeggiator at a pre-set quantized rate. Additionally, **Voltage magnitude** is mapped to the synthesizer note velocities/volumes

**Current distribution frequency deviation** is mapped to thresholds for triggering quantized drum kit samples. The kick drum sample has the lowest threshold, followed by a hi-hat sample, snare sample, and the highest threshold for a crash cymbal sample. Therefore the higher the frequency deviation, the more drum kit samples.
**Current magnitude** is mapped to the synthesizer note velocities/volumes, therefore when no load is present there are no audible drum hits.

Listen to sample 3 again and pay close attention to the arpeggiator synthesizer velocity/volume.

4. **Do you notice any dramatic changes in synthesizer volume when the AC is turned on(roughly at 5 second mark)?**
5. **Is the current frequency deviation now more apparent in the drum kit sequencing?Add any additional comments.**

## IV. Qualitative Analysis

Additionally, I would like to qualitatively evaluate your overall experience with the embedded system sonification results. Please answer the following questions:

**I enjoyed the overall experience of listening to the Sonifications.**

Select an answer from 1 to 5.
Strongly disagree 1 2 3 4 5 Strongly agree ____________

**I believe that this system has potential to be used as an educational tool for power systems and electrical engineering studies.**

Select an answer from 1 to 5.
Strongly disagree 1 2 3 4 5 Strongly agree ____________

**I believe that this system has potential to be used as an analysis/monitoring tool for power systems operators.**

Select an answer from 1 to 5.
Strongly disagree 1 2 3 4 5 Strongly agree ____________

**I believe that this system has potential to be used as a tool for music creation.**

Select an answer from 1 to 5.
Strongly disagree 1 2 3 4 5 Strongly agree ____________

**Which Sonification Example Did you find the most Pleasing?**

Example 1 Example 2 Example 3

**Which sonification example did you find to be the easiest to comprehend data variations?**

Example 1 Example 2 Example 3 Same for all 3

Please give any feedback or other comments you may have about the experience and the various examples you listened to:

# Appendix B

# Observational Experiment Procedures Responses

# I. First Prototype, One-to-One MIDI Parameter Mapping Sonification

| What auditory parameter changes can you perceive changing through the audio example? |
|---|
| Volume, pitch, frequency |
| Loudness and pitch |
| A change in tone and volume. |
| The pitch and volume of each "note" vary. |
| Pitch, volume |
| Volume/amplitude, pitch |
| Noticed ascending and descending pitches throughout the audio |
| pitch, volume |

| Are the variations more easily perceived now that you know the mapping techniques? |
|---|
| Yes |
| Yes |
| Yes they are |
| I was able to recognize that both pitch and volume were changing when I first listened to Sample1. However, I was at first uncertain if the lower volume was intentional, or if I was just perceiving the volume to be lower because the pitch was low and my computer speakers were unable to effectively reproduce the pitch at the same volume as the higher pitch "notes". |
| I think I heard them pretty well to begin with. |
| No |
| A little |
| yes |

| Can you hear the changes in volume and variations in pitch? |
|---|
| Yes |
| Yes |
| Yes I can |
| Yes |
| Definitely, I can hear the direction of change but it's hard to tell what the magnitude is. |
| Yes |
| Yes |
| yes |

## II. Varying Loads In Real Time

| What auditory parameter changes or audio effects can you perceive changing through the audio example? |
| --- |
| Changes in volume and pitch |
| Duration, pitch, and loudness |
| change in note length, change in pitch , change in volume. |
| volume, pitch, frequency of "notes" being played, distortion, and a consistent background sound is heard at times...By the way, by "note" I mean the standout occurrence of a particular sound. |
| I hear a change in volume, pitch, and filter envelope modulation depth. |
| Volume, tone, frequency |
| Both note and volume changes |
| volume, pitch, reverberation, timbre |

| What are your estimated timestamps for the load changes(first load is at time 0), and what loads do you think are present at these timestamps. Note, that only a single load is present at a time. You will not be detecting multiple loads being applied to the system in parallel. |
| --- |
| 0:27 and 0.35 |
| 0:00 (highly non-linear), 0:26 (purely resistive), 0:35 (purely inductive) |
| A load change at 12 removal of load. A load change at 26 an increase in load. Decrease in load at 35. |
| high pitch notes begin at 3 seconds. Seem to be varying high pitch notes occurring throughout the Sample. a consistent background sound becomes audible at 13 seconds until 27 seconds. distortion and slight volume increase of the main/primary notes begins at 27 seconds. Distortion ends and volume of the main/primary notes decreases at 36 seconds. A consistent background sound, similar to the first, begins at 36 seconds. |
| First load change is 0:27, second is 0:35 |
| 0:14, 0:26, 0:36 |
| 0:14 the load is on (sounds sustain), 0:27 load is off (volume increase) and 0:35 load is on (sounds sustain) |
| 0s: resistive, 13s: inductive, 27s: non-linear, 35s: inductive |

| After knowing the mapping techniques and listening again. What are your estimated timestamps for the load changes(first load is at time 0), and what loads do you think are present at these timestamps. |
|---|
| 0:27 and 0.35. The different sections by load strength are 2, 3, 1 |
| 0:00 (highly non-linear), 0:14 (purely inductive), 0:26 (purely resistive), 0:34 (purely inductive) |
| 7sec higher voltage frequency. 15 seconds less voltage. 27 Harmonic distortion and higher voltage. 35 less voltage and phase delay. |
| same estimated time stamps as my previous response. After reading about the mapping technique, I believe the variation in pitch is related to the voltage, the background noise is reverb (generated by the phase delay), and the distortion of the audio signal is representative of the harmonic distortion. |
| I believe I'm hearing the load harmonic distortion changing, at 0:27 and 0:35 seconds. |
| 0:06, 0:09, 0:34 additionally |
| Yes |
| 0s: resistive, 13s: inductive, 27s: non-linear, 35s: inductive |

| Now that you are aware of the synthesizer mapping technique, is the varying number of arpeggiator notes (therefore frequency variations) more apparent than before? |
|---|
| Yes |
| Yes - I know what to (attempt) to listen for |
| Yes they are I was not sure if they were there or if I was hallucinating them due to the change in pitch. |
| Yes |
| I think it might be a bit subtle for me -- I only ever hear two notes in the arpeggiator, up-down, up-down. Perhaps there's another definitely of "number of arpeggiator notes" that's evading me. |
| Yes |
| Yes |
| yes |

## III. Constant Load and No Load present

| **Annotate the time stamp when you believe that the load has been applied to the system.** |
|---|
| 0:05 |
| 0:05 |
| 5 seconds |
| I believe around 13 seconds as this is when I believe the pitch of the arpeggiation changes. |
| 0:05, 0:08, 0:15, 0:23, 0:27, 0:30 |
| 0:05, 0:11, 0:18, |
| 0:11 |
| 5s |

| **Do you notice any changes in velocity/volume throughout the sonification**? |
|---|
| Yes |
| I believe I notice a volume change with a slight fade in or out |
| velocity may have changed and volume changed slightly. |
| No. |
| Not much. I was mostly focused on the crash cymbal. |
| No |
| Yes |
| yes |

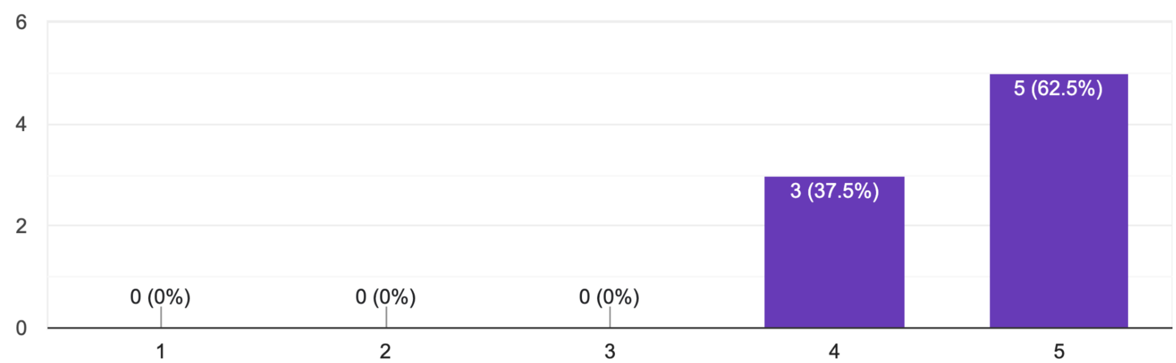
| Do you notice any variations in the drum kit triggering? Comment on what you think might be controlling the variations? |
|---|
| Yes, fluctuation in power usage |
| Yes - maybe current frequency changes beyond a certain setpoint? |
| Increase in volume and increase in velocity. |
| While the tempo of the drum kit doesn't seem to change, there is significant variation in which components of the drum kit are making sound throughout the sample. I'm really not sure what could be controlling these variations because the parameters being measured do not seem "instantaneous" to me similar to how hitting a drum is instantaneous. |
| I'm not sure what was triggering the variations, but I'm assuming it's some stepped thresholded value, and the higher it gets the more elements of the drum set are playing. Sounds very cool. |
| Yes, I noticed variation to the triggering, off tempo |
| Yes, pitch of the background beat |
| yes, the beat gets more energetic with deviations in pitch |

| After knowing the mapping techniques and listening again. Do you notice any dramatic changes in synthesizer volume when the AC is turned on(roughly at 5 second mark)? |
|---|
| No |
| Yes, slight decrease in volume when the AC is turned on |
| Yes the volume decreased. |
| I do not notice any change in synthesizer volume at the ~5 second mark. |
| I find this change is relatively subtle compared to the entrance of the drum kit, so I didn't notice it. Even on repeated careful listening I find it a bit difficult to pick out. |
| Yes |
| Yes |
| gets quieter |

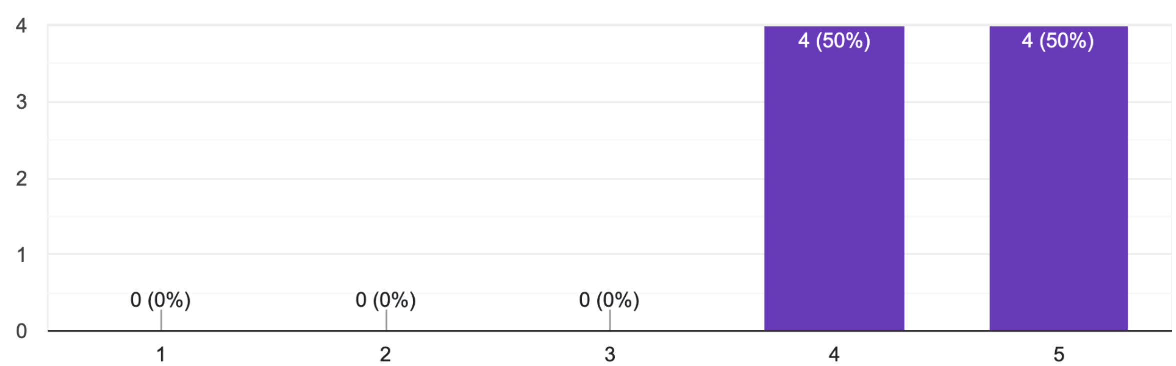
| **Is the current frequency deviation now more apparent in the drum kit sequencing? Add any additional comments.** |
|---|
| It's a bit harder to tell with the multiple instruments but it is apparent. |
| Yes definitely - Once you know mappings it is easier to notice changes |
| Yes it is more apparent because the sounds are distinct but I am not sure I would be able to recognize and associate them to the correct deviation without training. |
| Yes, it makes more sense now to understand that the different components of the drum kit are triggered by different thresholds of the current frequency deviation. |
| I find that the drum kit sequencing is a very clear indicator to follow. However, the relative levels of intensity are not always clear -- is a kick drum more weighted than a high hat? What is the significance of the crash? Etc. Though I can certainly tell that something is changing! |
| It is after a few listens |
| Yes |
| yes |

# IV. Qualitative Analysis

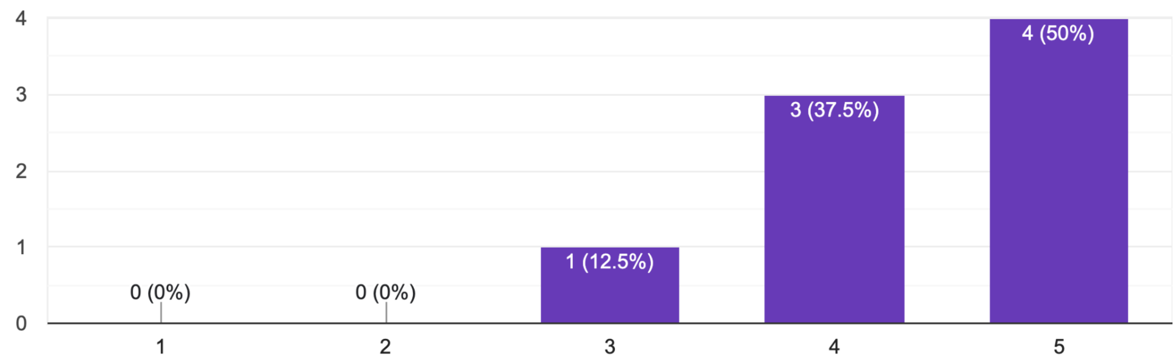
I enjoyed the overall experience of listening to the Sonifications.
8 responses



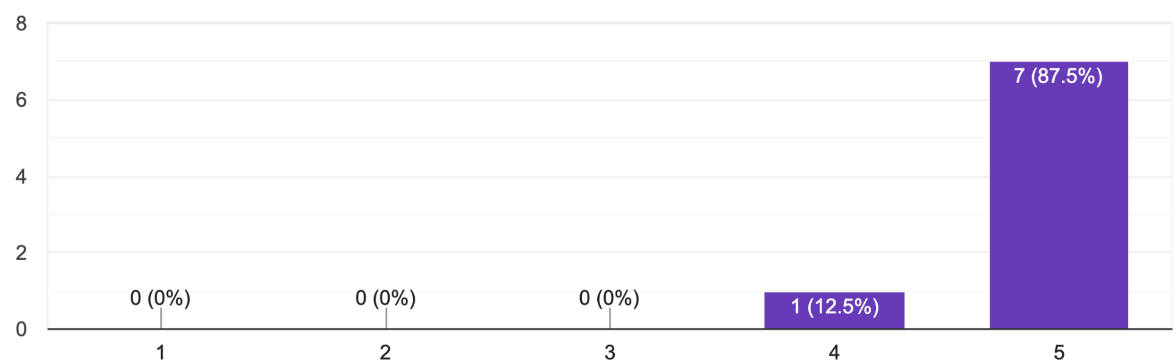

I believe that this system has potential to be used as an educational tool for power systems and electrical engineering studies.
8 responses



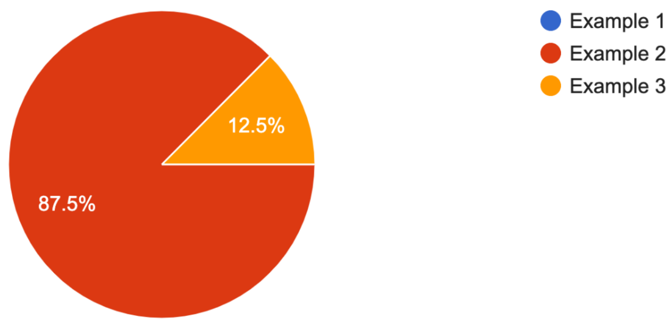
I believe that this system has potential to be used as an analysis/monitoring tool for power systems operators.
8 responses



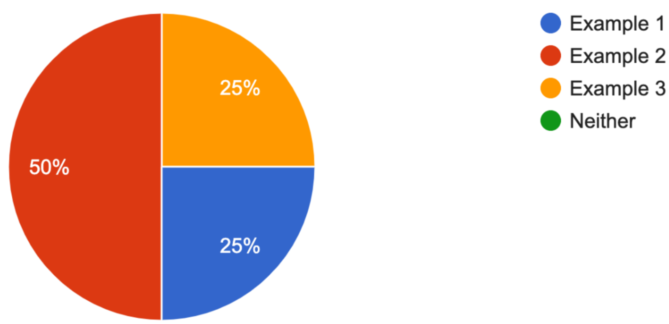

I believe that this system has potential to be used as a tool for music creation.
8 responses



Which Sonification Example Did you find the most Pleasing?
8 responses




Which sonification example did you find to be the easiest to comprehend data variations?
8 responses



**Please give any feedback or other comments you may have about the experience and the various examples you listened to. This is open for anything and can include ideas for future mapping techniques, criticisms or feedback on what has been done in these examples, etc.**

| |
|---|
| Could have used some more background info on what loads and data I was listening to. |
| I appreciate the progression of the study - going from simple to more complicated sonifications. I believe this has immense potential to be used for music creation and inspiration - a way to be more closely intertwined in the full experience of listening to music, connecting the listener directly to the physical/electrical world in a way that has not been done before. |
| I have less of a background in music so some of the terminology related to the music went over my head but was able to follow along through my knowledge of power systems. |
| I believe the various samples and corresponding questions were well put together and allowed me to quickly learn and identify events that occurred during the audio sample. I would be interested to see the real life steps to go from hearing a certain audio signal to then identifying and potentially resolving an issue in the power system that is causing that audio signal. |
| I think this is a really great idea. I particularly like the use of the arpeggiator, and think this could be both an expressive and meaningful way to communicate information. Thank you for the opportunity to take part! |
| Very cool experiment. For music creation, it will be interesting to hear how these sonifications of powerline data can be used to increase creative possibilities; however, strictly following these principles may not ultimately be the most pleasing to the ear. |
| Brief background about auditory parameters at the beginning would be helpful |
| I think with the frequency deviations from 60 Hz to pitch mapping the listener doesn't really need to think about the mapping and can rather just listen and understand what is happening. This is very nice. I'm unsure if you are trying to convey each characteristic of the signal with equal weight because they are equally important when determining power system health etc. If the pitch mapping is by far the most important characteristic, then I think that mapping is successful because it is the easiest to perceive. If the characteristics are equally important, I think the mapping could better reflect that (not sure how). Either way, awesome job and congrats! |