Design of a Charge Measurement Device

DESIGN DOCUMENT

sdmay20-11
Honeywell
Long Que

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Executive Summary

Engineering Standards & Design Practices

Standards

IEEE 4-2013 (High Voltage Testing)

IEEE 1696-2013 (High Voltage Probe Measurement)

Design Practices/Constraints

No official design practices were applied to this project. The main design constraint this project dealt with was ensuring that all components and systems would safely operate under the high voltage range designated by Honeywell.

Summary of Requirements

Requirements:

- Measure the charge between 10 nano-Coulombs and 300 nano-Coulombs
- Operate in voltages between 250- and 750-volts DC
- Confirmation of accuracy

Recommendations:

- Small scale prototype circuit by the end of first semester
- Final design size approximately 3” by 6” PCB

Applicable Courses from Iowa State University Curriculum

- EE 201
- EE 230
- EE 303
- EE 311
- EE 333
- ENGL 314

New Skills/Knowledge acquired that was not taught in courses

- High Voltage Safety
- Larger team professional interactions
- Working with a client
- Following a budget

Table of Contents

List of figures/tables/symbols/definitions

1 Introduction

1.1 Acknowledgement

The company we received both technical advice and financial aid from was Honeywell. Jacob Starr and Nathan Orton were the project design contacts throughout the year. Another source of technical advice was Long Que, our group's advisor through Iowa State University (ISU). Our equipment came Electronics Technology Group (ETG) and Honeywell.

1.2 Problem and Project Statement

Problem statement.

Honeywell needs a way to accurately measure the accumulation of charge on electronic devices. The device should be reasonably sized and capable of handling any conditions or operating specified per requirements. The application of this device is important for extending Honeywell's ability to confidently test and understand the behavior of the electronics their electronics.

Solution approach.

Our team developed an approach from research and prior course material. We created a process flow that was referenced throughout the duration of the project. This kept everyone to stay organized and in sync with the current state of the design. An Agile-based process was also used to our team for organization and execution of all tasks.

1.3 Operational Environment

The device will be used in a lab/test environment. We found it unnecessary to spend extensive time on an enclosure because the device will not be exposed to irregular or uncontrolled conditions However, in a lab setting there are still potential hazards such as dropping the device, unintentional use outside of its capabilities, and high voltage contact. The final product's enclosure will ideally be a solid, well fitted casing that will primarily protect users from high voltage contact while protecting the device from small daily wear and tear events. The enclosure will remain simple, economic, and easily duplicatable.

1.4 Requirements

- Capable of operating at 250-750 V
- Accurately measure charge accumulation from 10-300 nC
- Only DC operation
- Connect to a computer UI
- Easily duplicated/simple design
- Relatively small PCB (around 3"x6") and final product enclosure
- Enclosure should protect the user from the high voltage
- Remain within budget restrictions ($2500 per semester)

1.5 Intended Users and Uses

This design is purposed for company use. The user is expected to be experienced or knowledgeable regarding the functionality and application. The intended application for this device is to measure the accumulation of charge in a testing environment. The information Honeywell could share is limited due to sensitivity of their work. We anticipate that the device will be used on a regular basis, so the end-product should be durable, reliable, and safe.

1.6 Assumptions and Limitations

Assumptions-

- The end-product is only intended for company use at Honeywell
- Honeywell plans to duplicate the design and create more units
- Only intended for DC operation
- Device will only measure the charge one node at a time

Limitations-

- PCB should be small (around 3”x6”)
- $2500 budget per semester
- System must be capable of operating safely between 250-750 VDC
- Accessibility to a high voltage power supply for testing

1.7 Expected End Product and Deliverables

In the project proposal form, there were a few examples of expected deliverables listed. We were expected to deliver a final presentation, final report, and any prototypes. This device will not be commercialized. The final presentation will be an outline of the design process used throughout the course of the project. This includes a timeline of events, difficulties faced in the design and testing processes, methods we to overcome obstacles, and a summary on the general success of the project. The presentation will occur at the end of the second semester.

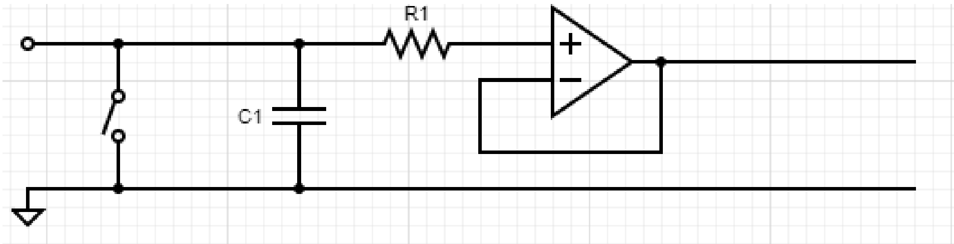
A final report will be included to document functionality of the final product, components used in the design, a list of costs accumulated through developing prototypes, etc. This will also be near the end of the second semester. The final product or prototype is expected to be a functional charge measurement device. A prototype will be developed by the end of the first semester.

2. Specifications and Analysis

2.1 Proposed Design

The design implementation for our charge measurement circuit is simple. The input voltage is taken from the shell of the connector. This circuit gives charge accumulation from the shell by generating voltage across the capacitor. The charge is equal to this voltage multiplied by a known capacitance. To manage the high voltages for measuring, a voltage divider is used. The lowered voltage goes into a buffer to isolate the system. The output of the buffer will go to into an ADC to be read digitally. The switch allows discharging between measurements. The accuracy of the charge will correspond directly with the value of C1.

Figure 1: Example Charge Measurement Circuitry



2.2 Design Analysis

The difficulty with this product is working in a high voltage system. We needed to find components that are tolerant of voltages above 750 volts. Another difficulty we faced was choosing our capacitor. The tolerances of the capacitor need to be minimal ensure accurate measurement. Our design simplicity allowed us freedom of part selection and minimal construction.

2.3 Development Process

We followed the Agile process for this project. We used this style because it encouraged communication between the team members. We believe that to get the best product we all needed to contribute and voice our opinions. Agile allowed everyone to be a part of every step in the process and encourages discussion between everyone.

2.4 Design Plan

Our design plan started with researching different charge measurement methods. After weighing the characteristics of the different circuits, we began testing with lower voltages. We would transition this design to the voltages per the requirements. This transition meant developing a PCB and using SHV connectors capable for high voltages.

3. Statement of Work

3.1 Previous Work and Literature

Electrometers have been used since the 18th century but could only handle nanovolts. Modern day electrometers can handle much larger voltages. For DC, a vibrating reed electrometer is used to measure charge. These can handle much larger DC voltages and the output will supply a constant current to keep the capacitance constant. Value electrometers use vacuum tubes with a very high gain and input resistance. The value model has a very small leakage making it less accurate than most others designs.

3.2 Technology Considerations

The vibrating reed electrometer is the only electrometer that can used for DC voltage. The issues with this design are the size and cost of the capacitors. It also is not as accurate as other designs but those are for AC only.

3.3 Task Decomposition

- Charge Measurement Research
- Low voltage testing
- Part research
- High voltage testing
- Pin expansion (optional)
- Computer UI
- PCB design
- Enclosure Design

3.4 Possible Risks and Risk Management

This project involved working with high DC voltages. This presented serious harm to team members and equipment. We needed to create safety procedures and redundancy to protect ourselves and the project. This included arc flash training, lock out tag out, and ground safety procedures.

3.5 Project Proposed Milestones and Evaluation Criteria

Milestones for this project were the first circuit design, ordering parts for the prototypes, functioning prototypes, and finalization of the product.

3.6 Project Tracking Procedures

A shared calendar and planner was used in Microsoft Teams.

3.7 Expected Results and Validation

A PCB that can measure the charge given the requirements of the client. The PCB should be easy and safe to use. Accuracy of the design will be determined while prototyping.

4. Project Timeline, Estimated Resources, and Challenges

4.1 Project Timeline

Figure 2: Timeline chart

Project Step	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Charge Measure ment Research							
Low voltage model							
Part research							
PCB design							
High voltage model							
Pin expansion (optional)							
Computer UI							
Enclosure Design							

Blue – Research and Design

Green – Construction and Testing

Purple – Finalization

This timeline was proposed as we did not currently have a lot of experience with the concept with charge measurement, searching for appropriate parts, and using high voltage. A lot of time would be spent researching the principles of charge measurement. We would use a low voltage model to safely develop testing and usage procedures. During that time, appropriate parts would be selected for the high voltage model.

After understanding how charge measurement works, we would scale up the voltage to meet the requirements of the project. After a few months with that model and the accuracy and safety have been thoroughly verified, the team will break up into subgroups to finalize the product. A lot of time to finalize was desired so changes may still be made if necessary.

Due to COVID-19, the timeline has undergone some considerable revisions. PCB design, which was started weeks before spring break, now has ceased, since Honeywell no longer wants a PCB. Because there is currently no hardware-related deliverable, there has is need for a GUI or enclosure design. The time since spring break has been spent building our circuit in PSPICE and gathering data.

4.2 Feasibility Assessment

The final product will be a finished PCB with optional enclosure. The PCB will, regardless of enclosure, have all high voltage circuitry protected for safety reasons. A jack will be mounted to the board for connecting to a computer. The PCB will be able to measure charge and store little if any charge. If the PCB does store charge, it shall be measurable.

4.3 Personnel Effort Requirements

Table 1: Timeline Descriptions

Task	Personnel Effort
Charge Measurement Research	Continuous Research on charge measurement until low-voltage model has been developed. All members are expected to understand the principles of how charge can be measured and weigh the advantages and disadvantages of different methods. This will be done on an individual basis with the preliminary design chosen as a group.
Low Voltage Model	As a team, the preliminary design will be tested on a breadboard prototype. This can be accomplished by just a few individuals, but testing will require the group's effort. Half of the group will focus primarily on this model and the whole group will work on testing.
Part Research	The other half of the group as described above will start investigating parts for the high voltage model. This group will give input for both models but will have more focus on selecting and ordering parts as necessary. This will be continuous until a working prototype for the high voltage model is developed.
PCB Design	Members of the team not working on part research will work on designing a PCB for the high voltage model.
High Voltage Model	After the low voltage model is developed and testing has shown good indications, work on

	the high voltage model will begin. There will still be ongoing research for parts as this task is being handled. Testing will also require the group's effort. This will be held back slightly by the PCB design group initially.
Pin Expansion (Optional)	A small amount of time will be dedicated to expanding to the other pins of a SHV connector. Two personnel will be dedicated, but time spent should be minimal.
Computer UI	At this point, the design has entered the finalization stage. One person will be solely dedicated to this one aspect for the time specified in the Gantt chart.
Enclosure Design	This team will be formed after the PCB team is approaching their final design. Enclosure design members will work intermittently with the PCB design team.

4.4 Other Resource Requirements

- Breadboards
- High power rated resistors
- High voltage rated capacitors
- Low tolerance ICs
- Access to PCB design software
- Access to electrical simulation software
- Access to 3D modeling design software
- High voltage power supply
- Equipment capable of measuring high voltages
- Wires and connectors
- Soldering irons
- Solder
- Heat-shrink

4.5 Financial Requirements

We were given $2500 for each semester to work on this project. For the entire duration of the project, we received $5000.

5. Testing and Implementation

5.1 Interface Specifications

The circuit was tested on a small scale during the first semester using a breadboard. An oscilloscope and multimeter provided us the readings to verify that the concept was correct. During the second semester, the testing moved into the large-scale model. The GUI would need to be perfected so testing can be safe and as hands-off as possible.

5.2 Hardware and Software

First Semester (small scale prototype testing)

- Multimeter
- Oscilloscope
- DC power supply
- JUnit testing

Second Semester (large scale prototype testing)

- High voltage DC power supply
- GUI
- Oscilloscope
- Multimeter

High voltage DC power supply – We were given access to this by Honeywell. Using this supply is mandatory for making sure our high voltage prototype is functioning properly.

Multimeter/Oscilloscope – This will give us the voltage readings necessary to validate the concept.

JUnit testing – This will test the computer GUI. This will help making sure that the correct value of the voltage is being displayed.

GUI – Software that will enable the user to read the charge measurements. This will allow users to understand the measurements.

5.3 Functional Testing

Each unit of the system will be tested individually prior to the integration of the circuit – the ADC, the GUI, etc.

5.4 Non-Functional Testing

With non-functional testing, the quality of our system is the main concern. The user should be able to apply voltages in the range specified with little change in performance.

5.5 Process

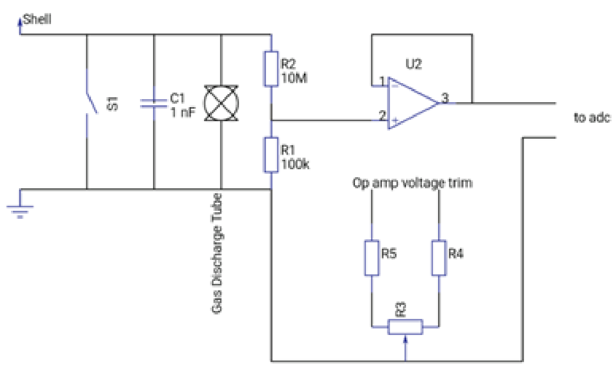
Low Voltage Model

This model followed the schematic of **Figure 3**, shown below, although it will likely not include the gas discharge tube. All the components in this model were through hole components used on a breadboard.

The voltage range for testing was restricted by the power supplies available to us in lab. Two power supplies were needed to be used: One for powering the op, the other acting as the input shell.

The test voltage range was 5 – 15 VDC. The oscilloscope and multimeters were used to confirm our voltages, and the charge was be calculated. The switch will be used to discharge the capacitor after each test. This will be reiterated for each increment.

Figure 3: Charge Measurement Circuit.



High Voltage Model

The testing for this model followed a similar process as the low voltage model. Now, however, the voltage test range is 250 – 750 VDC, so we will implement a gas discharge tube to provide surge protection.

The difference between this model's testing plan and the low voltage testing plan is the use of a GUI. Ultimately, the user should not be interacting directly with this circuit, so the charge measurements need to be displayed for the user.

The software will undergo separate tests prior to being integrated into the rest of the system.

5.6 Results

With the advent of COVID-19, the deliverables required for this project have been dramatically altered. Honeywell stated that they will have no need for a PCB layout file or any physical prototype. And due to labs being closed, there was no physical testing on the high voltage model. Rather, it was done via simulation in PSPICE. Honeywell now only wants a proof of concept that the charge measurement works for the voltages and charge levels that they had specified.

These testing results will cover the low voltage model, which was tested physically, and the high voltage model, which was tested through PSPICE.

Table 2: Low voltage model test data.

"Shell" voltage (VDC)		Vo(t1) - Vo(t0)	Ideal Q	Measured Q	C
5		0.05625	5E-11	5.625E-11	0.000000001
6		0.05975	6E-11	5.975E-11	
7		0.07	7E-11	7E-11	
8		0.07875	8E-11	7.875E-11	
9		0.0875	9E-11	8.75E-11	
10		0.0975	1E-10	9.75E-11	
11	11.03	0.1075	1.1E-10	1.075E-10	
12	12.01	0.11875	1.2E-10	1.1875E-10	
13	13.01	0.1275	1.3E-10	1.275E-10	
14	13.97	0.1375	1.4E-10	1.375E-10	
15	14.99	0.15	1.5E-10	1.5E-10	

The data in Table 2 shows the voltage levels from the shell in the first column. Using the DC power supplies in lab, we were able to test the circuit's functionality. Knowing the capacitance for our reference capacitor, we can use the equation C = Q/V to find charge.

The ideal charge, Q, is simply the capacitance, 1 nF, multiplied by the supplied DC voltage. For each voltage input, we observed the transient on the capacitor and took the difference between the maximum and minimum, $V_o(t_1) - V_o(t_o)$, and multiplied by the capacitance. This yielded the measured charge.

Figure 4: Measured charge compared to ideal calculated charge.

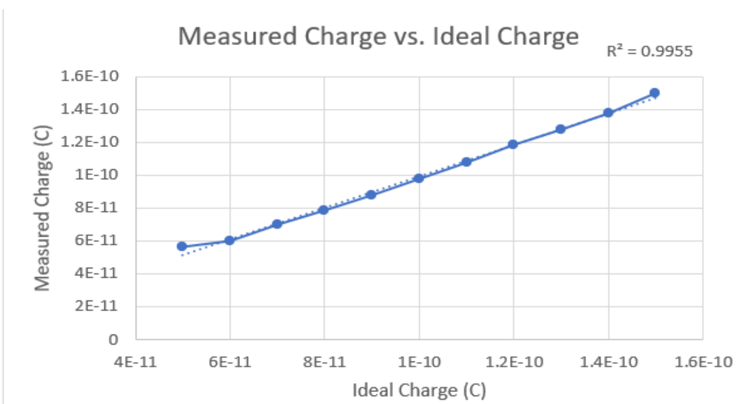


Figure 5 shows almost no deviation, with an R^2 value of 0.9955. Using this capacitor and applying these voltages showed that measuring charge by a capacitor is a working concept.

Figure 5: High voltage PSPICE simulation.

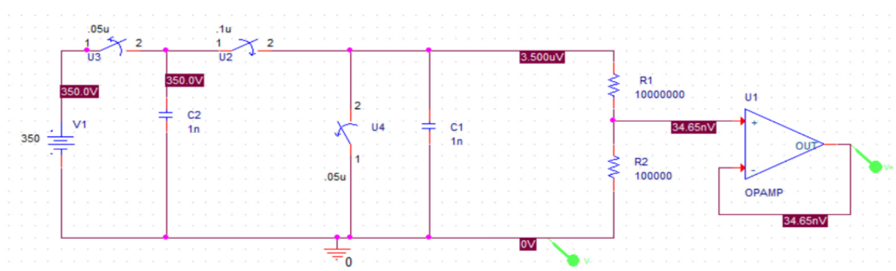


Figure 6: PSPICE transients for high voltage simulations.

6. Closing Material

6.1 Conclusion

From the physical low voltage model testing and the high voltage PSPICE testing, we can say that our results show a proof of concept. This circuit can be used to measure charge of a node operating at voltages between 250 to 750 VDC, provided the components are properly rated.

Prior to COVID-19, the circuit was designed such that the charge measurement would be sampled with an ADC and written to a GUI. This circuit was to be condensed into a small PCB and serve as a modular intermediary that would connect to power and the desired DUT. The goal was to give Honeywell the option to replicate this to multiple pins and devices.

We have sent Honeywell our test data and our PSPICE file. We will also send them a theoretical accuracy statement.

6.2 References

S. Buchman, et al. "Charge Measurement," *The Measurement, Instrumentation, and Sensors Handbook*, 1999. [Online]. Available: http://einstein.stanford.edu/content/sci_papers/papers/BuchmanS_1995_47.pdf. [Accessed Oct. 15, 2019].

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