

# Battery Simulator for Microgrid Lab

Electrical Engineering  
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## Acknowledgment

This work was performed under the sponsorship of GridED Undergraduate Design Project of the Electric Power Research Institute.

## Abstract

The electrical engineering department at Cal Poly State University, San Luis Obispo is currently developing a new course that covers the broad topics of Microgrid. A laboratory component of the new course is also currently being developed that will serve as a demonstration tool to display to students the various components and technology utilized by a microgrid. This project aims to develop a battery hardware simulator that enables the students to construct a battery model and connect to a lab-scale microgrid. Additionally, the simulator provides students with the ability to create a simulation system that can emulate various battery technologies that are used in microgrids. Therefore, by utilizing this battery simulator, students can safely test the operation of various battery technologies without the inherent risks associated with real batteries. We implemented the design for the simulator with a 4-quadrant programmable power supply connected to an inverter. The power supply acts as the battery which can receive or supply power from or to the grid through the inverter. Results from the developed battery simulator show that the simulator can successfully generate battery profiles of lithium-ion and lead acid. Design and procedure on setting up the battery simulator will be included in this report along with data gathered from the experiment.

## Chapter 1: Introduction

Energy and its sources have always been a topical matter for electrical engineers. All modern devices including consumer electronics, housing appliances, and military apparatuses require power to operate. Currently, society runs off electricity sourced by the grid, which can be produced by fossil fuels, hydroelectric dams, wind, solar, and more. The source of energy and how it is converted to electricity has effects on how efficient energy transfer is from the generator (power plant) to the load (customer/consumer) and how sustainable the method of power generation is. Broadly speaking, the generation of electricity can be broken down into a few general steps.

All electricity found in homes and buildings begins from a generator at a local power plant. Regardless of where the energy is sourced from, it eventually is used to rotate a motor to convert mechanical energy into electrical energy. The generated electricity is mainly in the form of a sinusoidal voltage at a specific frequency (60 Hz in the United States). The electrical energy then must be delivered over a transmission line while minimizing losses, which are caused by the line's internal resistance. Losses are minimized by increasing the voltage amplitude through a transformer, which reduces the current and hence the losses by Ohm's Law. The stepped-up voltage is sent along a transmission line which then reaches another transformer that steps down the voltage so it can be distributed at lower voltage levels and used to power electrical devices.

There are many challenges involved in delivering power that electrical engineers must consider including losses incurred on the lines, designing efficient transformers, and generating the electricity itself. At present, new challenges in designing power electronics have also arisen due to the need to convert between different types of electrical energy. For example, renewable

energy sources like solar produce DC electricity which must be converted to AC to be compatible with the grid. This requires a power electronic circuit known as an inverter to convert a DC voltage into an AC voltage [1]. However, AC voltage must eventually be converted back to DC since most residential consumer electronics, appliances, and lightings operate on DC voltages [2]-[7]. Therefore, AC-to-DC converters, known as rectifiers, are needed to power phones, laptops, and other modern-day devices. With the rise of high-speed computing chips, ICs, and increasingly complicated digital systems DC-to-DC converter topologies are also needed to power different electronic systems at different DC voltages all from one source [8]. The same power electronic technology is also needed to improve energy consumption such as those found in smart load applications [9]-[11]. The combination of inverters, rectifiers, and DC-to-DC converters adds another challenge for energy generation and management for today's technology.

From how electricity is generated to the design of power electronics, there are numerous problems to consider when designing energy systems. Today's power engineers must deal with all phases of a power system all the way from generation to electronics stages.

## Chapter 2: Background

The power grid as we know it today sources its energy from a variety of sources including fossil fuels (coal, oil, and natural gas) and renewable energy such as wind and solar. Each source of electricity carries its own pros and cons as to how much power they can deliver and how sustainable they can be. However, with the rise of microgrids, more sustainable energy sources are needed to provide power to consumers in the event of a blackout or disconnection from the grid [12]. To meet this demand, growing research is being done on the use of chemically engineered battery technologies, such as lithium-ion and alkaline, for the generation of electricity in microgrids. With the demand for batteries to power microgrids comes the need for testing in a stable and controlled environment. Modern grid powering batteries are large, bulky, and carry high voltages making them dangerous to test in a laboratory setting. Additionally, it is difficult to transport these batteries and obtain them. A proposed solution is to develop a battery simulator that can closely emulate the characteristics of actual grid powering batteries to verify their ability to deliver and absorb power in the microgrid. The challenges involved in designing a battery simulator include developing the system level requirements to convert energy from the battery to useable electricity for the consumer, designing the software for the simulator to emulate various battery technologies, and safely connecting the simulator to the grid while maintaining high efficiency.

To design a battery simulator that closely emulates the characteristics of an actual microgrid battery, the charging and discharging effects of the desired battery technology must be programmed into a power supply. In a paper by Sergey V. Kuchak, et al, titled *Discharge*

*Characteristics of Lithium-Ion Accumulators under Different Currents*, the discharging effects of lithium-ion batteries at various temperatures are examined [13]. The authors provide the equivalent circuit of a lithium-ion battery which helps model the actual charging cycles of the voltage source. The circuit model (Figure 2-1) is very helpful because it provides an explanation of the discharging characteristics of the battery from a circuit analysis perspective.

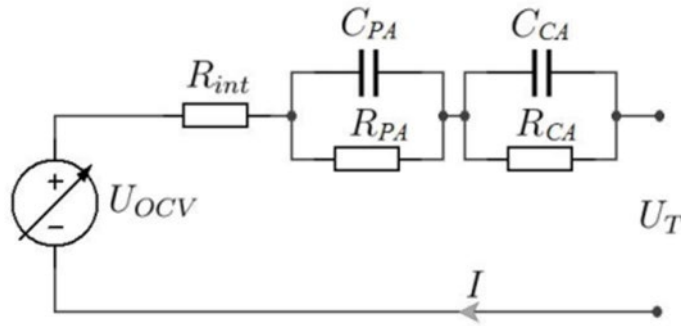


Figure 2-1. Lithium-Ion Battery Equivalent Circuit [13].

Additionally, the authors provide plots of the battery’s output voltage versus time at various temperatures. These plots, as depicted in Figure 2-1, are critical as they inform designers at what times the battery/battery simulator can provide power to the grid or receive power.

Another critical component in designing a battery simulator is the inverter, which is required to allow the battery to interface itself with the grid/microgrid, which is a 3-phase AC system. The inverter must be able to take in the DC voltage output of the battery/battery simulator and output a clean (low THD) 60Hz sinewave at the proper rms voltage (the frequency and voltage of the sinewave depends on the country). Juan F. Patarroyo-Montenegro, et. al., discuss a basic topology for connecting a 3-phase inverter to the microgrid in a paper titled *A Linear Quadratic Regulator With Optimal Reference Tracking for Three-Phase Inverter-Based Islanded Microgrids*



[14]. The inverter should be able to switch between powering the microgrid and receiving power from the grid. A diagram of this is shown in Figure 1-3.

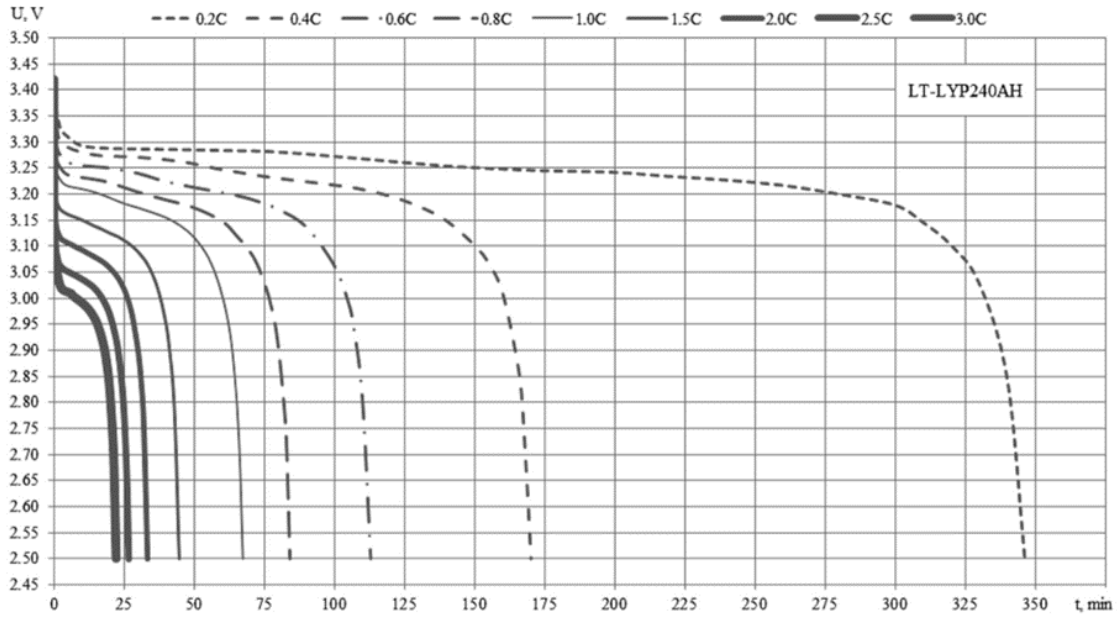


Figure 2-2. Lithium-Ion Discharging Characteristics (Output Voltage vs. Time Plots) for Various Temperatures [13].

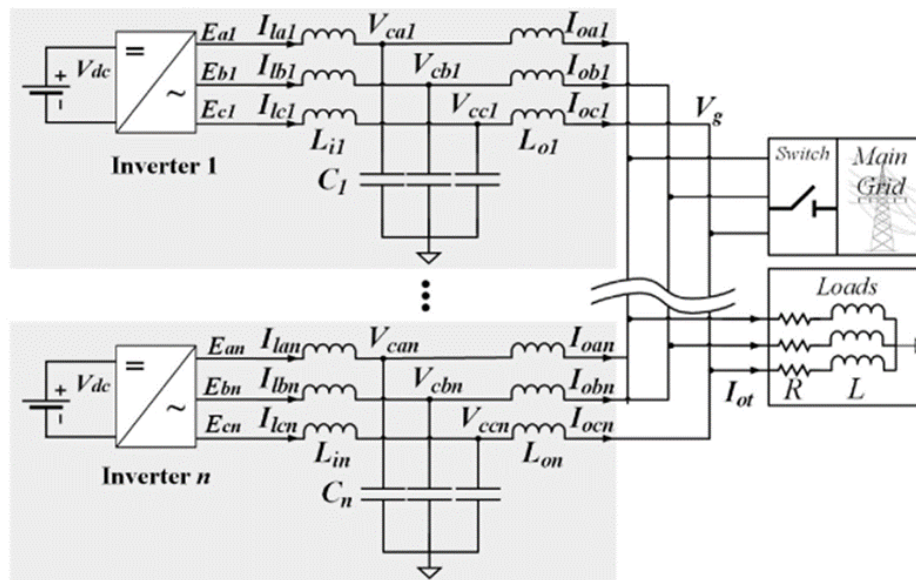


Figure 2-3. Circuit Diagram of Inverter Connected to Main Grid/Loads [14].

The motivation for implementing a system like what is described above is to provide clean, renewable energy to microgrids which can provide power to areas isolated from the grid. These isolations can be caused by natural disasters or malfunctions in the grid, leaving communities vulnerable to power outages. According to an article by Intel titled *Microgrids Promise to Transform Energy Grids*, “[the grid] has become greener, by connecting to more carbon-free energy sources. It also needs to be more reliable and resilient, able to provide power—especially to essential sites like hospitals and military facilities—during and after disruptions or disasters” [15]. There is a large demand for microgrid development which needs to be supplemented with renewable energy sources. Therefore, laboratory testing of microgrid energy technology is also needed to verify that these systems operate safely for the public. At Cal Poly, several projects have been done previously to address this issue [16]

Another interesting problem facing microgrid development is the threat of cyber-attacks. According to an article by the NIST called *Cybersecurity for Smart Grid Systems*, “smart grid cybersecurity must address both inadvertent compromises of the electric infrastructure, due to user errors, equipment failures, and natural disasters, and deliberate attacks, such as from disgruntled employees, industrial espionage, and terrorists” [16][17]. With the advancement of AI and other cyber technologies, the importance of cyber security grows and is also relevant in power grid systems. This provides another reason for microgrids, which can provide power in the event of an outage caused by a cyber-attack. The reliability of a microgrid depends on the quality of power delivered by its renewable source (wind, solar, etc.). Testing these microgrids with a battery simulator can allow the testing process of the power system to become easier.

A previous senior project group at Cal Poly began work on the use of a battery as the energy storage device for a microgrid. The group proposed using an ITECH programmable power supply to emulate the charging and discharging characteristics of different battery technologies. In their report they state that the ITECH power supply can “emulate a battery’s charge and discharge functions” as well as behave as an “electronic load to act as a sink for the battery” [18]. This makes ITECH an integral component of designing a battery simulator system that is connected to the microgrid.



Figure 2-4. ITECH Programmable Power Supply [18].

Continuing the work of the previous senior project group, this project proposes a design for a battery hardware simulator to simplify testing energy storage devices connected to the microgrid. The battery simulator design consists of three components: the ITECH programmable power supply to behave as a battery providing DC voltage, software to define the charging characteristics of the power supply, and a 3-phase grid tied inverter to interface with the grid/microgrid.

## Chapter 3: Design Requirements

### Block Diagrams

Prior to designing the proposed battery simulator, it will be useful to show a high-level view of the system. Level 0 block diagram of the proposed battery simulator is shown in Figure 3-1.

There are two inputs to the battery simulator which are then processed to yield one output in the form of AC power at 120 Vrms and frequency of 60 Hz.

Table 3-1 summarizes the descriptions of each of the inputs and the output.

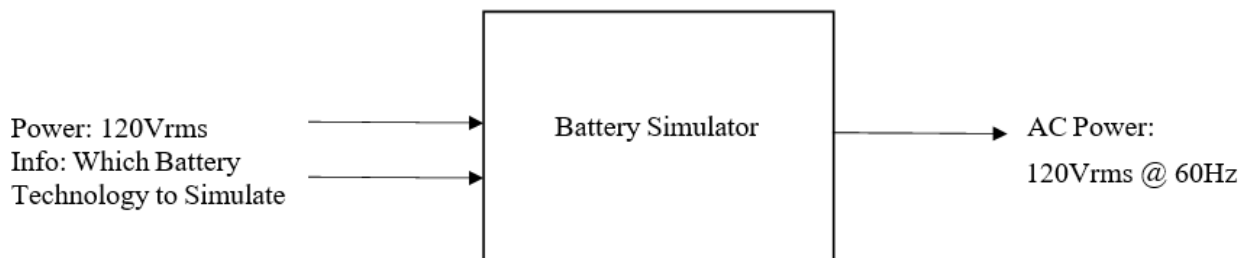


Figure 3-1. Battery Simulator Level 0 Block Diagram,

Table 3-1. Battery Simulator Level 0 Block Diagram Specifications.

<b>Level 0 Block Diagram</b>	
Level 0	Battery Hardware Simulator
Inputs	<ul style="list-style-type: none"> <li>• Electric energy (wall outlet)</li> <li>• Information (which battery type to emulate, i.e., Lithium-ion, alkaline, etc.)</li> </ul>
Output	<ul style="list-style-type: none"> <li>• Electric energy (AC 120 Vrms; used to power the microgrid)</li> </ul>
Functionality	<ul style="list-style-type: none"> <li>• Simulates various battery technologies used to power the microgrid</li> <li>• Provides safe and simple method for testing different battery technologies without the need to test actual batteries</li> <li>• Educates engineering students about how microgrid energy storage systems work</li> </ul>

Looking into more detailed components of the system, Level 1 block diagram depicted in Figure 3-2 shows the hardware components needed for the system. The programmable power supply takes in the input power and the info on the battery data to simulate. The battery info contains the battery's charging and discharging profile which will depend on the type of the battery. Based on this information, the power supply outputs the appropriate DC voltage that feeds into to a 3-phase grid-tied inverter. The inverter connects to the grid via three-phase output voltage. In the actual system, the three-phase output voltage will be connected to a lab bench to allow the three-phase power to flow back to the utility grid.

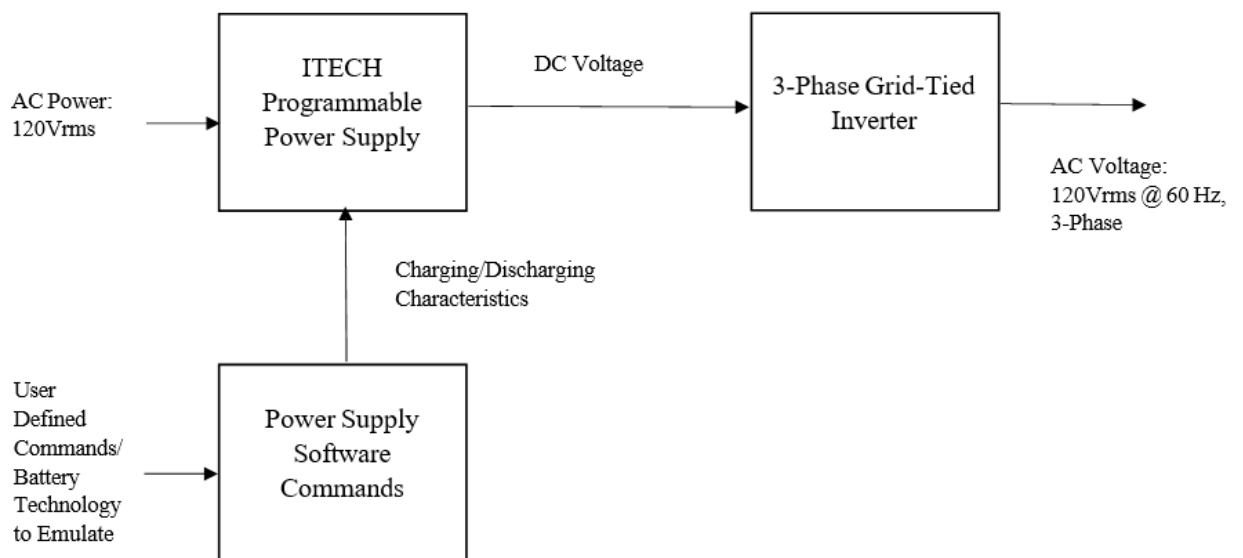


Figure 3-2. Battery Simulator Level 1 Block Diagram.

Tables 3-2 and 3-3 summarize the descriptions of each component in the Level 1 block diagram. The functionalities of each block in the block diagram are also explained in the tables.

Table 3-2. Battery Simulator Level 1 (Module 1-1) Block Diagram Specifications.

<b>Module 1-1</b>	
Level 1	4-Quadrant Power Supply
Inputs	<ul style="list-style-type: none"> <li>• Electric energy (wall outlet)</li> <li>• Information (how much voltage and current to output; desired direction of current and polarity of voltage)</li> </ul>
Output	Electric energy (variable DC voltage and current)
Functionality	<ul style="list-style-type: none"> <li>• Can output DC voltage and current in four quadrants, allowing flexibility in emulating different charging characteristics of various batteries</li> <li>• Programmable voltage and current; can be used to emulate batteries provided suitable software</li> <li>• Easy to transport</li> </ul>

Table 3-3. Battery Simulator Level 1 (Module 1-2) Block Diagram Specifications.

<b>Module 1-2</b>	
Level 1	Inverter
Inputs	Electric energy (DC output of 4- quadrant power supply)
Output	Electric energy (AC 120 Vrms; used to power the microgrid)
Functionality	<ul style="list-style-type: none"> <li>• Converts DC power output of power supply into AC power which can be used for the microgrid</li> <li>• Follows US power rating</li> <li>• Can be purchased commercially rather than needing to be built</li> </ul>

Table 3-4. Battery Simulator Level 1 (Module 1-3) Block Diagram Specifications.

<b>Module 1-3</b>	
Level 1	Software
Inputs	Information (which battery type to emulate)
Output	DC charging and discharging characteristics of power supply needed to emulate a specific battery type

Functionality	<ul style="list-style-type: none"> <li>• Allows users to select battery type to emulate</li> <li>• Open source and reprogrammable – can add new battery charging characteristics or edit current ones.</li> </ul>
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The design of this battery hardware simulator comprises of multiple blocks that each need to meet design specifications. All design specifications for each level of the design have been stated in the above figures and tables within chapter 3 of this report. To summarize, the core of the battery simulator is the ITECH programmable 4-quadrant power supply. Using software protocols supplied by the manufacturer, the supply’s charging and discharging characteristics can be modified to emulate the effects of an actual battery used in microgrid systems. The power supply must be powered via the wall outlet (120Vrms @ 60Hz in the US) and outputs a fluctuating DC voltage. The DC output of the power supply is fed into a 3-phase grid tied inverter which allows power transfer from the battery simulator to the grid. Furthermore, the inverter is bidirectional allowing power transfer from the battery to the microgrid or from the grid to the battery. This way, the microgrid can gain power from the grid when it is not isolated.

With all components connected, the battery hardware simulator can act as a tool for engineers and students to use when studying the microgrid. In particular, the energy storage branch of a microgrid can be analyzed without testing actual physical batteries that are difficult to transport and potentially hazardous.

## Chapter 4: Design

### **Solution Statement**

The proposed solution to designing a battery hardware simulator that can be used to emulate the results of microgrid energy sources involves connecting the ITECH programmable power supply to a grid-tied inverter outputting 60 Hz.

The ITECH will act as the DC power source for the microgrid (emulating batteries like lithium-ion). This power supply is a good choice since its voltage charging characteristics can be programmed. Depending on the charging and discharging characteristics of any battery, they can be programmed into the ITECH power supply. Furthermore, the ITECH has the added benefit of saving programs as files so that it is easy to switch between battery emulator settings.

For the inverter, the AP Systems QT2 PV microinverter was chosen to convert the ITECH's DC voltage to a grid tied three-phase AC voltage. The inverter is the link between the battery and the grid/microgrid allowing for power flow from the battery to the load and the grid. The inverter chosen also supports bidirectional power flow. This is to accommodate the two states the system can be in: power flow from the battery to the inverter to the grid and power flow from the grid to the inverter to the battery.

The general setup for the design is inspired by Cal Poly Alum Do Vo's thesis on *Microgrid Renewable Energy Integration* [20]. The setup involves a DC power source (in this case the ITECH power supply), a grid-tied microinverter, and 3-phase electricity generated by the grid. The block diagram is shown in Figure 4-1.



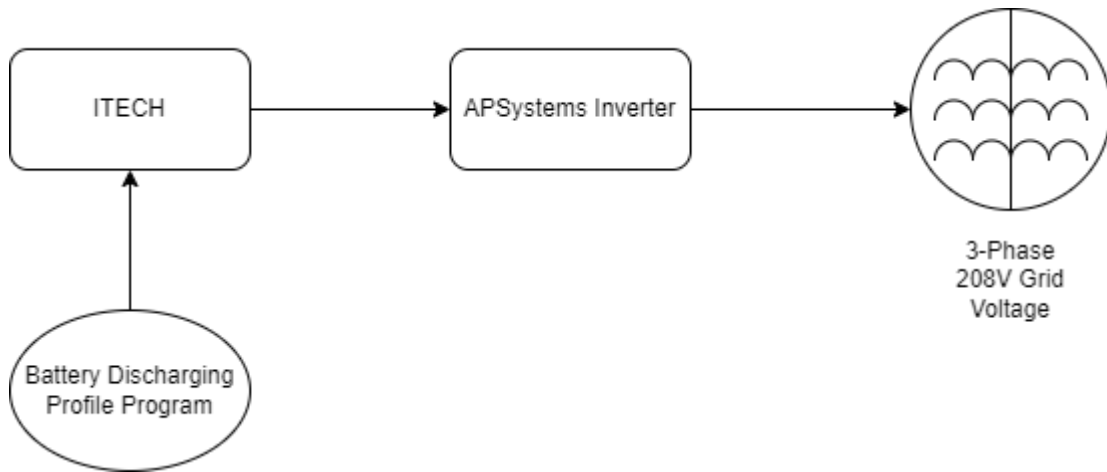


Figure 4-1. Battery Hardware Simulator Design Block Diagram.

The block diagram shown in Figure 4-1 outlines the general functionality of the battery hardware simulator. The input to the system is DC voltage from the programmable 4-quadrant ITECH power supply which is fed into a 3-phase grid tie inverter. The power supply's output voltage is programmed to emulate a battery's discharge profile. It can store up to 10 programs at a time allowing the user to store different battery discharge profiles at a time.

The ITECH power supply was selected for this design because it can be programmed to output a battery discharge profile and can push and pull power. The AP Systems QT2 microinverter was chosen as it can push and pull power to and from the grid while being connected to the 3-phase voltage source.

### **Selected Components**

1. ITECH four-quadrant programmable power supply
2. AP Systems QT2 208V 60 Hz grid-tied microinverter

Lab Setup

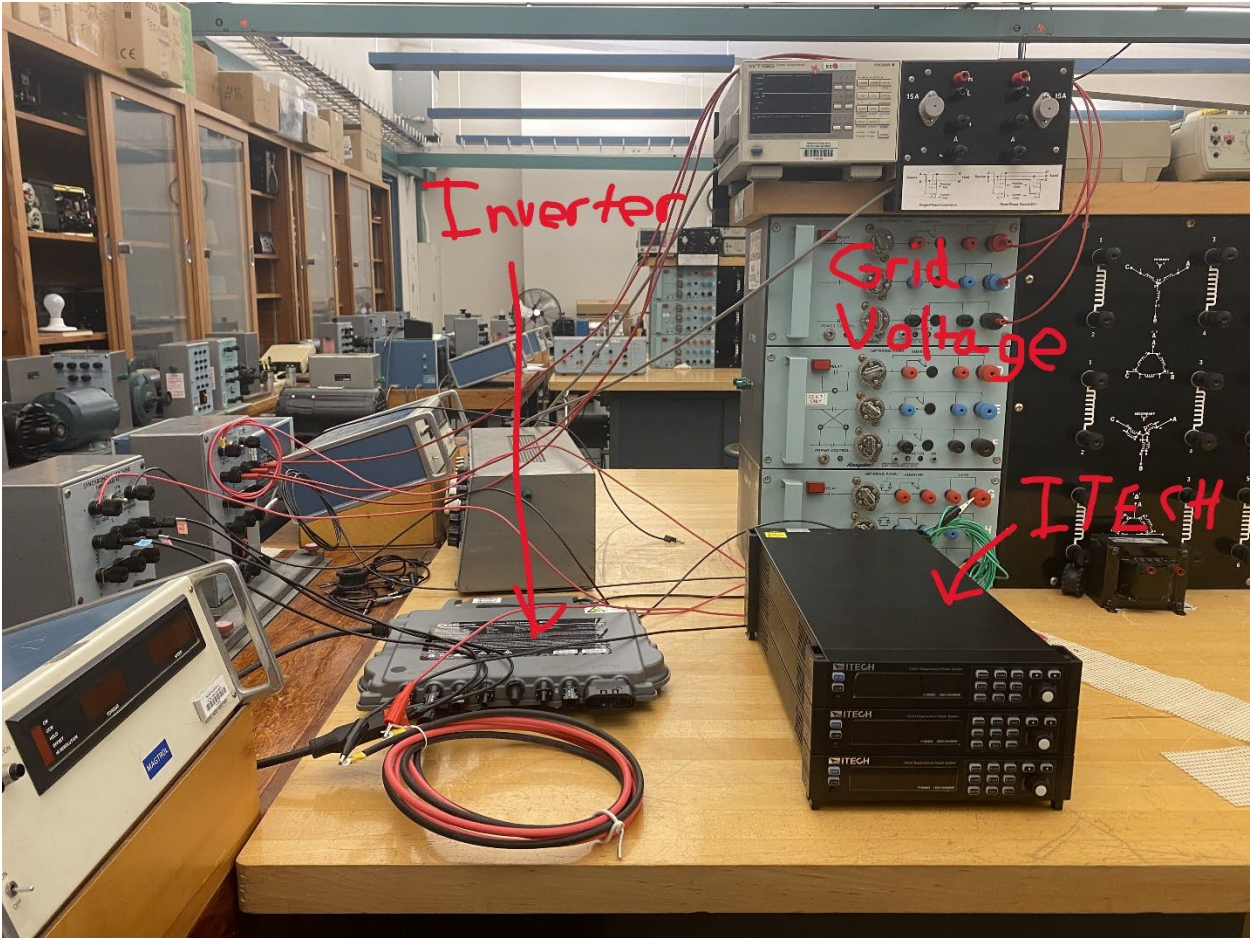


Figure 4-2. Battery Hardware Simulator Lab Setup.

## Chapter 5: Hardware Test and Results

The following describes the procedure that was conducted to setup, test, and gather measurements for the battery hardware simulator:

1. Gather materials: AP Systems QT2 microinverter, ITECH power supply, connectors (see bill of materials), banana to banana (2), SIGLENT oscilloscope, digital multimeter (1)
2. Connect DC output of the ITECH to the AP Systems inverter.
3. Connect the AP systems inverter to the grid voltage using one of the benches in the power electronics lab (room 20-104).
4. For testing the battery discharge profile, measure the ITECH's output voltage using the SIGLENT oscilloscope.
  - a. Collect a DC voltage plot by selecting 'trend plot' mode under the 'multimeter' setting of the scope.
  - b. Start and stop data collection using the 'run' softkey.
5. For testing power transfer through the inverter, measure one of the phase currents using a digital multimeter.

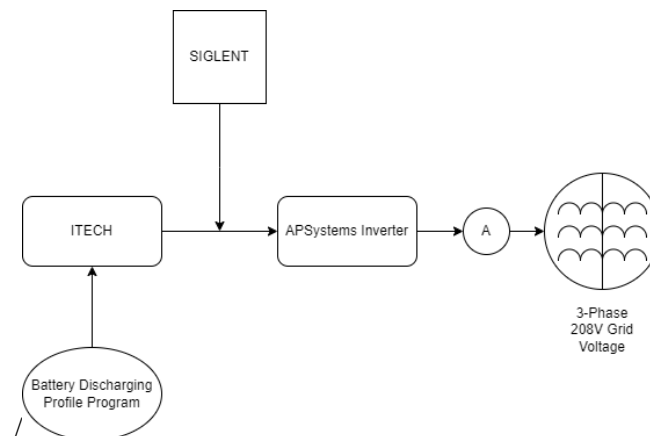


Figure 5-1. Lab Setup Block Diagram.

### Battery Discharge Profile Measurements:

In this project, lithium-ion and lead-acid battery discharge profiles were successfully programmed into the ITECH power supply. These discharge profiles are based on real battery technologies. The data from these profiles were transferred onto an Excel spreadsheet and then programmed into the ITECH. For testing purposes, the discharge time for each profile was condensed down to a practical time to collect measurements. Note that actual discharge times are much longer than what was recorded in lab.

In Figures 5-2 and 5-3, battery discharge profiles for lithium-ion and lead-acid are shown. These data were collected from batteryuniversity.com and electrical2z.com, which dedicate their websites to information on battery technologies.

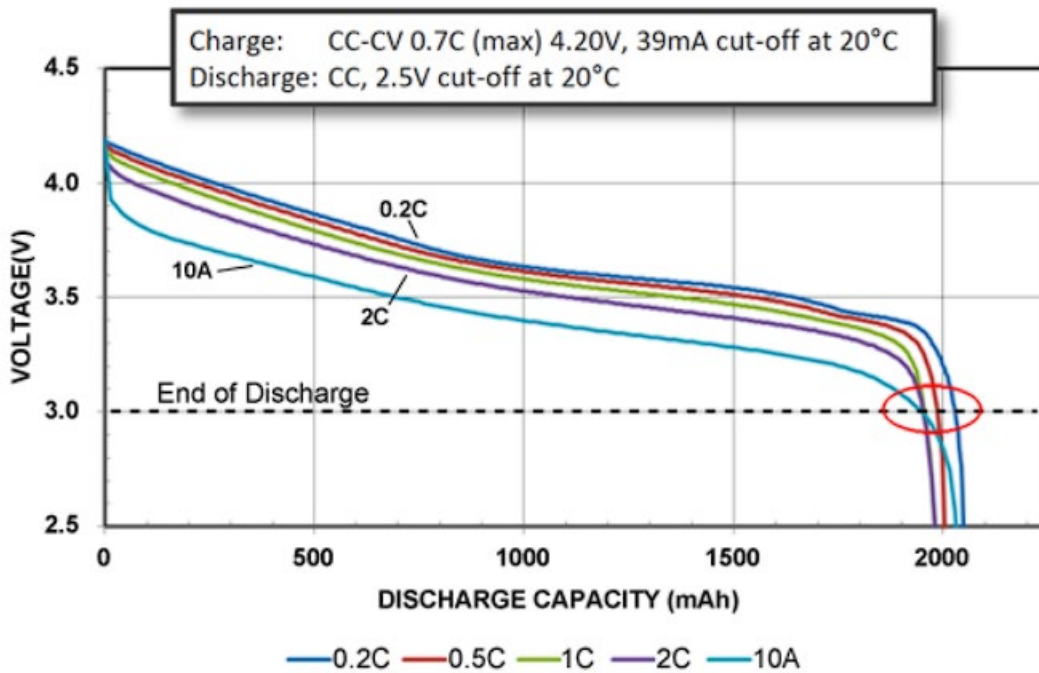


Figure 5-2. Lithium-Ion Battery Discharge Profiles [21].

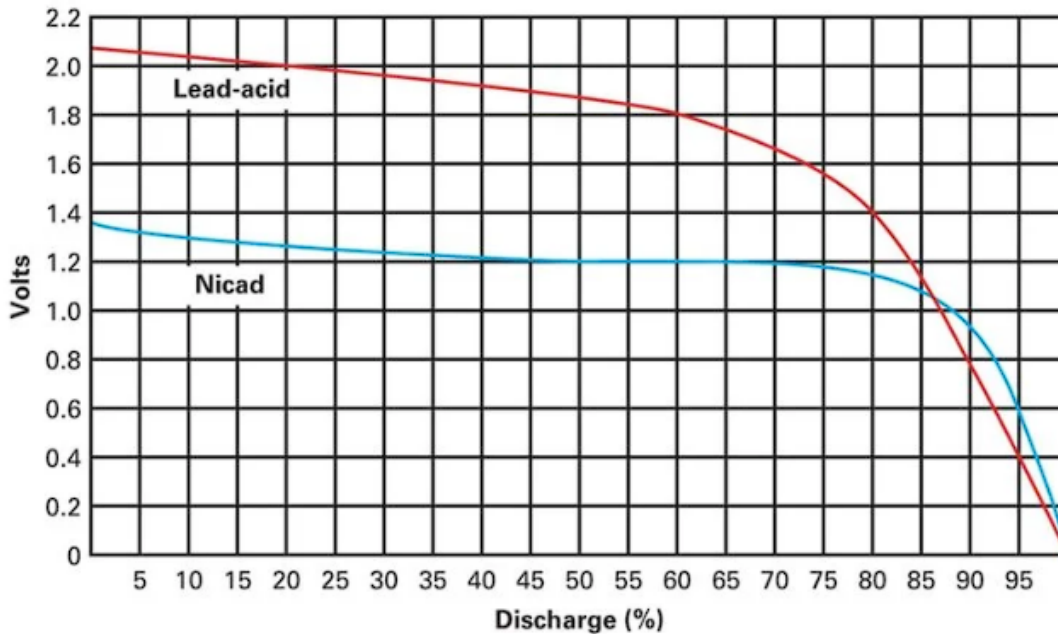


Figure 5-3. Lead-Acid and Nicad Battery Discharge Profiles [22].

Both discharge profiles were programmed into the ITECH using the ‘List’ function (see appendix for detailed procedure on how to use the function). Under ‘List’ mode, the power supply allows the user to enter data points for voltage over time. The user can select up to 100 data points adjusting the voltage and length of time. For example, if for one point the user entered 5V and 5 seconds, the power supply would output 5V for 5 seconds. Stringing together many points like this produces the following measured simulated discharge profiles. All plots are made in Excel for ease of comparison.

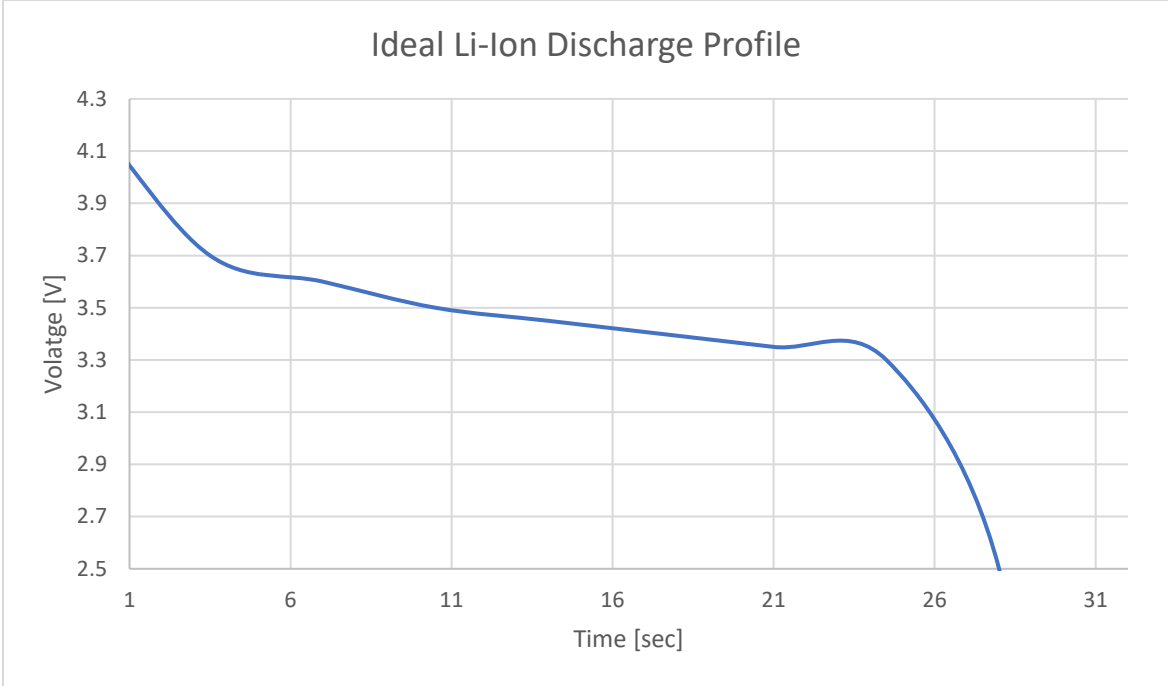


Figure 5-4. Ideal Lithium-Ion Battery Discharge Profile.

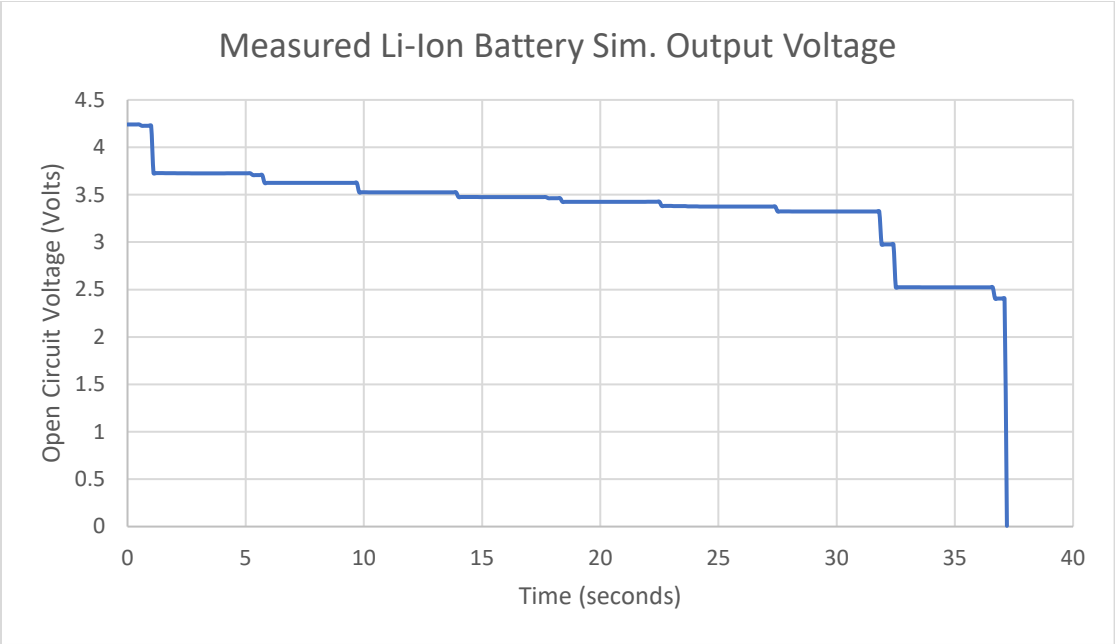


Figure 5-5. Measured Lithium-Ion Battery Discharge Profile.

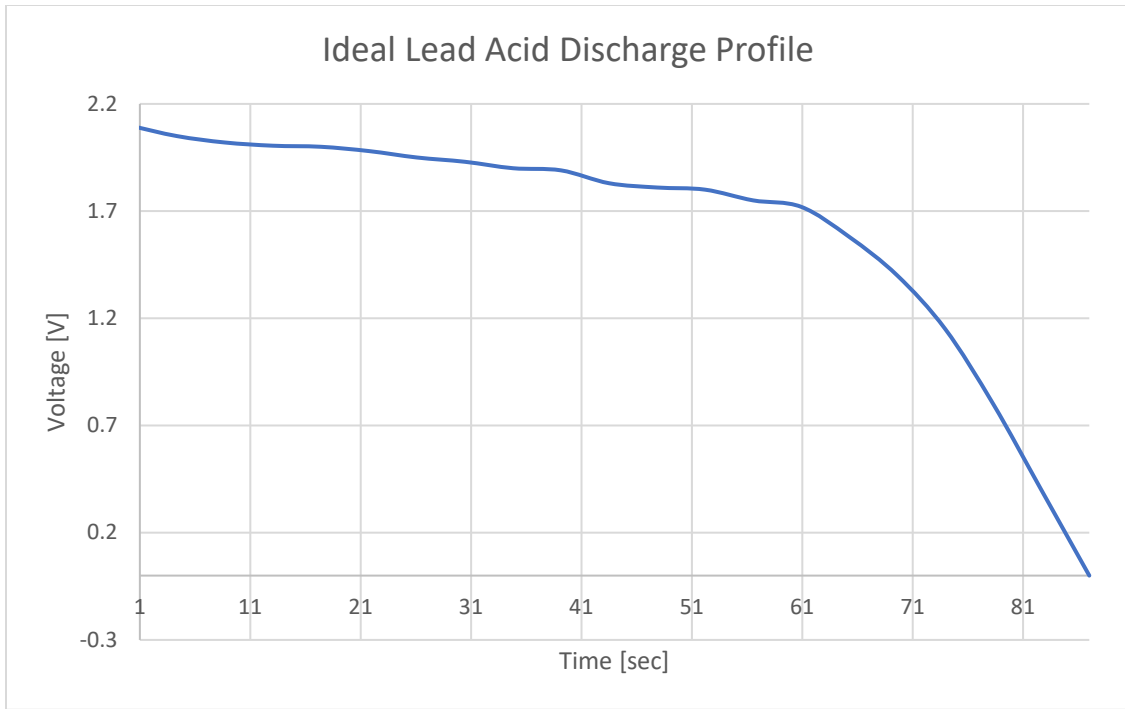


Figure 5-6. Ideal Lead Acid Battery Discharge Profile.

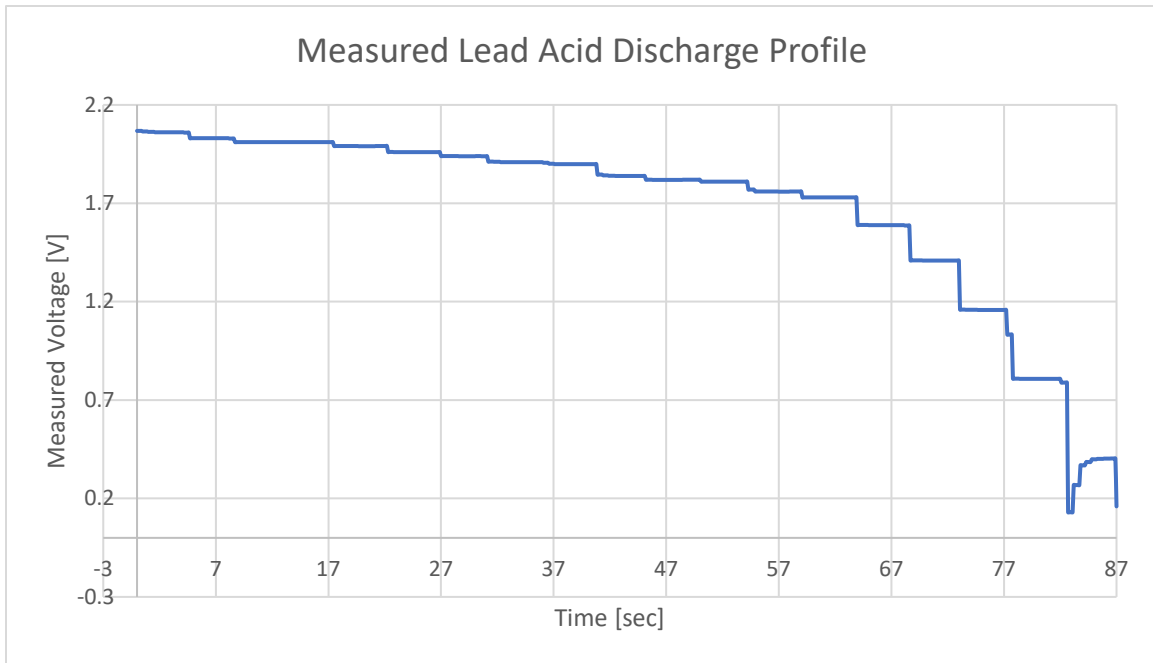


Figure 5-7. Measured Lead Acid Discharge Profile.

Figures 5-4 to 5-7 show plots of battery voltage versus time during the discharge cycle. Depending on the battery technology, the shape of these discharge profiles varies. The lithium-ion profile (Figures 5-4 and 5-5) discharges the fastest at the beginning and end of the cycle while the lead-acid profile (Figures 5-6 and 5-7) shows the more monotonic decay during the beginning and middle of the cycle but rapidly decreases towards the end. Ideal and measured voltages are very close and differ at most by several millivolts. This shows the ITECH's ability to behave like an actual battery.

#### Inverter:

The AP Systems QT2 208V microinverter was not functional throughout the duration of our experiments. The device operates by applying a DC input voltage between 26V-60V and connecting it to a 3-phase grid voltage running at 208V line-to-line at 60Hz. We tried several iterations of the experiment to get the inverter to push power into the grid, but all resulted in little to no current flowing through the device.

The first setup involved connecting the inverter to the grid with a Y-connected resistive load. The reasoning for this setup is that if the inverter was supplying power to the grid, current would flow through the device into the load while also providing power to the grid.

The next experimental setup involved supplying the AC power with a synchronous generator driven by a synchronous machine. The reason behind this is that it would be easier for the inverter to push power into a voltage source that had less power. In a sense, the new 'grid' provided by the synchronous generator would be easier for the inverter to synchronize with. A load was also connected to the synchronous generator and inverter to absorb power.

Since neither setup achieved the desired results, it is likely that the problem has to do with the inverter itself. The AP Systems device is compatible with a web-based application that



can provide real time monitoring for the inverter, including any potential issues with why the inverter may be nonfunctional. Our group was not able to connect the device to the application however since it required a 13-digit code to scan, which our unit did not provide. If a future group were to attempt the same project, it is highly recommended to look into this software for troubleshooting.

## Chapter 6: Conclusion

This project focuses on the development of a battery hardware simulator that serves as a safe and efficient energy storage tool. The main goal is to create a simulation system that can emulate different cell and battery scenarios and allow students studying the microgrid to test battery management systems and battery sensitive electronics without the risks associated with real batteries. The battery simulator is implemented using the ITECH 4-quadrant programmable power supply which has a 'List' function which can accept data points of voltages over time allowing for the emulation of battery discharge and charge cycles. The power supply can also save up to 10 different files for charging/discharging cycles, making it an excellent study tool for students in a microgrid energy branch lab course. Since the battery simulator is primarily intended for the study of microgrids/power systems, a 3-phase grid tied inverter was needed to convert the battery's DC power into AC electricity, allowing it to push power to the grid. This project successfully implemented programming the power supply to output battery discharge cycles, making it an excellent tool for designing a microgrid energy branch.

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## Appendix

### Procedure on emulating discharge profile on the ITECH:

1. Power up device.
2. Press [SHIFT] -> [FUNCTION] to select a function.
3. Select [List] -> [Edit List].
4. Under [Edit List] you can enter a voltage/current and how long that voltage lasts.
5. If you would like to add another point, select [Yes] under [Next].
6. To run, select [Recall] under [List] and select the file you would like to run.
  - a. Select [ESCAPE] then [RUN].
  - b. Select [SHIFT] -> [ON/OFF].
  - c. Select [ON/OFF].
7. To stop running press [SHIFT] -> [FUNCTION] -> [Stop].
8. Remember to press the [ON/OFF] key to turn off the voltage when the device is not in use.
9. For more information, see the itm3600 user manual.