Electrical Engineering Department

California Polytechnic State University:

San Luis Obispo

Micro-Inverter Improvement

For The

Energy Harvesting From Exercise Machines Project

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Abstract

The Energy Harvesting from Exercise Machines (EHFEM) project at California Polytechnic State University consists of several different projects coming together to add human generated power to the grid. This project focuses on implementing a more efficient micro-inverter. The micro-inverter used to convert DC to AC voltage requires up to 5 minutes before the conversion process begins. This time lag significantly diminishes the power produced from an exercising individual. Research of micro-inverters approved by the CEC introduces desirable micro-inverters, available for use in California, to the EHFEM project. Testing the two most desirable micro-inverters found from research allows for quantifying of the most suitable micro-inverter. A new CEC improved micro-inverter aims to improve synchronization time as well as improved efficiency. This project finds improvement options in start up time and integrates the micro-inverter with the existing energy harvesting system to provide the grid with human generated energy.

Chapter 1: Introduction

California Polytechnic State University's Energy Harvesting From Exercise Machines (EHFEM) project, led by Dr. Braun, seeks to convert human power into electrical power. The EHFEM project started in 2007 by a team of electrical and mechanical engineers seeking to design a system that creates DC and AC power from a stationary bicycle. [1] The project now focuses on harvesting energy from elliptical trainers and supplying the grid with this energy. Harvesting energy from exercise machines provides the grid with sustainable energy, reducing the dependence on natural resources. The energy-harvesting project reduces energy loss within the exercise machines that dissipate excess electricity as heat. By utilizing this normally wasted power, less heat enters the gym environment. Less heat allows for reduced use of air conditioning units to cool the gym, ultimately saving energy.

The EHFEM project contains several subprojects. One subproject consists of outputting $36V_{DC}$ from a $5V_{DC}$ to $65V_{DC}$ input from the exercise machine. Several past projects design DC-DC converters to function specifically to the EHFEM project parameters. In his thesis report, Martin Kou develops a PWM-switching SPEPIC topology DC-DC converter. The design failed however [2]. Byung-Jae Yoo and Sheldon Chu develop a Buck-Boost DC-DC converter for their senior project, costing less and requiring fewer parts. This design failed, possibly from malfunctioning MOSFETS or mishandling the DC-DC converter [1]. A current project seeks to design a working 4-switch Buck-Boost DC-DC converter.

Another subproject consists of voltage and current limiting to protect components. The current limiting system ensures the micro-inverter does not attempt to draw too much current from the DC-DC converter, ensuring the micro-inverter stays within power limitations. Zack Weiler and Ryan Turner developed a system to limit the input voltage, utilizing capacitor banks. They also worked on limiting the output current from the DC-DC converter [3]. Eric Funsten and Cameron Kiddoo improved the protection circuitry from Weiler's and Turner's project. Funsten and Kiddoo create an efficient and modifiable protection system to protect the DC-DC converter regardless of maximum input voltage [4]. Feedback and feed forward systems provide the means for current and voltage protection [4].

This project consists of implementing a new micro-inverter. The micro-inverter converts DC voltage into AC voltage and synchronizes this with the grid. Micro-inverters differ from inverters mainly because of the difference in power conversion. Micro-inverters typically convert up to 300-watt range, while inverters convert up to 300-kilowatt range. Micro-inverts became popular in 2010 when solar companies began to install micro-inverters on each solar panel instead of connecting multiple solar panels to one central inverter. [5]

Two approved micro-inverters existed in California when the EHFEM project started. One of the original micro-inverters, the Enphase M175, became the micro-inverter for the EHFEM project. Since the selection of the Enphase M175, many more micro-inverters gained approval from the California Energy Commission to operate in California [6].

The original micro-inverter (Enphase M175) has significant start up time that causes unwanted power conversion delays. Efficiency for the Enphase M175 micro-inverter maximizes at 94.5% according to the California Energy Commission [7]. This project seeks to find and implement a micro-inverter that has a shorter start up time and an efficiency of 95% or better.

This report examines the following: micro-inverters available for use in California, micro-inverters that qualify for the EHFEM project, micro-inverters selected to work best for the EHFEM project, the best micro-inverter for the project, and connecting the micro-inverter to the elliptical trainer.

The next chapter examines the first steps of an engineering project; Customer needs, requirements, and specifications for the micro-inverter needed for the EHFEM project.

Chapter 2: Customer Needs, Requirements, and Specifications

This chapter examines the customer needs, requirements, and specifications associated with the micro-inverters involved in the Energy Harvesting From Exercise Machines project at California Polytechnic State University.

2.1 Customer Needs Assessment

Customer needs derived from the Recreation Center at California Polytechnic State University.

Customers need safe and reliable exercise equipment. The project must not decrease user safety in any way. Customers need economically reasonable equipment; power delivered to the grid offsets the energy harvesting exercise machine cost. User experience on the energy-harvesting machine cannot change when compared with the same machine that does not contain energy-harvesting capabilities. The system must fit within the enclosure of the Precor EFX 561i elliptical machine. The system must tolerate changing humidity levels and withstand eighteen hours of use a day for ten years. Efficiency must exceed 95%.

2.2 Requirements and Specifications

The customer needs assessment determine the marketing requirements. The system must avoid altering the users exercising experience. The system must maintain a low initial cost as well as low maintenance costs. The system must function in a gym environment while fitting into the compartment allotted by the elliptical trainer. The energy harvesting system and wiring must mount securely to sturdy frame elements inside the elliptical trainer. The mechanical components of the elliptical create risk for the micro-inverter and wiring harness. If any wires or the inverter enter the path of the moving components of the elliptical, the project immediately becomes unsafe to operate.

The DC-DC converter provides voltage and current the inverter must operate with. The system must tolerate 32 V_{DC} to 40 V_{DC} input from the DC-DC converter. The system must tolerate an input current up to 7amps.

Supplying power to the grid in California requires a micro-inverter approved by the California Energy Commission [6]. The micro-inverter must output 240 V_{AC} synchronized to the phase of the grid.

The 240 V_{AC} output requires special consideration due to safety concerns. All parts of the system containing 240 volts must conform to NEC and UL requirements.

The efficiency of the micro-inverter, measured by a ratio of output AC power to input DC power, must exceed 95%.

Use of banana plugs for input and output connections allows for easy integration with other EHFEM projects. The EHFEM project must use different connectors for completion of the project. Use of banana plugs for this stage in the EHFEM project allows for easy testing and integration with other projects within the EHFEM project.

Table 2-1: Micro-inverter improvement Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
2	240 V_{AC} output	Must output 240 V_{AC} to operate
5	Efficiency of input power to output power must exceed 95%	Achievable efficiency of micro-inverter [6]
8	Can operate with input current between 1 uA and 7 A_{DC} and input voltage between 32 V_{DC} and 40 V_{DC}	Inputs the micro-inverter must handle from DC-DC converter. [1]
1	System must fulfill NEC, IEEE1547, and NEMA electrical safety standards	Must fulfill National Electric Code standards, IEEE1547, and NEMA electrical safety standards to ensure safe operation. [8] [9] [10]
4	Micro-inverter and wiring harness must not exceed 6"x6"x3" space	Available space in Precor EFX 561i elliptical machine
3	Micro-inverter and interfacing components must cost less than $200	Available budget for project
7	Micro-inverter must begin converting power in less than 4 minutes after no power input for 8 hours and less than 2 minutes for no power input for 15 minutes	Minimize power loss during startup
6	Must operate up to 90°C and 25g/cubic meter humidity levels	Environmental conditions that insure proper operation in a gym environment
9	CEC approved micro-inverter	Allows for connection with grid in California [6]
10	Banana plugs for input and output connectors	Allows for integration with other EHFEM projects

Marketing Requirements

1. Conforms to safety standards
2. Outputs useful grid voltage
3. Inexpensive
4. Fits in Precor EFX 561i elliptical
5. Efficient
6. Can operate in gym environment
7. Begins operating quicker than current micro-inverter
8. Integrates with DC-DC converter
9. CEC approved
10. Easy to connect to other components

Table 2-2: Micro-Inverter Improvement Deliverables

Delivery Date	Deliverable Description
Jan 19th 2016	Design Review
Feb 23rd 2016	Design Review
March 11th 2016	EE 461 report
May 12th 2016	EE 462 demo
May 27th 2016	ABET Sr. Project Analysis
May 27th 2016	Sr. Project Expo Poster
June 6th 2016	EE 462 Report

The next chapter provides a high level look into the project. Block diagrams and tables explain the inputs and outputs of the system.

Chapter 3: Functional Decomposition

This chapter examines the inputs and outputs associated with a micro-inverter and important systems within a micro-inverter.

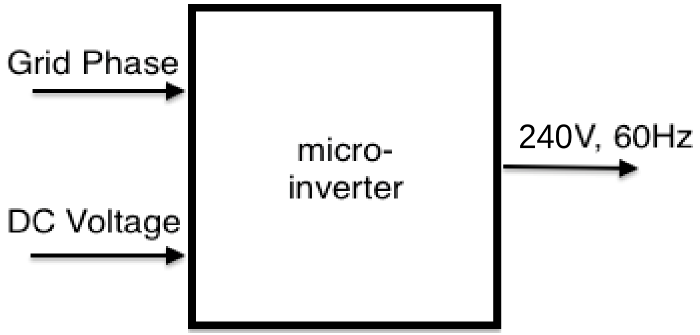


Figure 3-1: Level Zero Block Diagram

The level zero block diagram, seen in Figure 3-1, shows a two input, one output system. The system takes in information regarding phase from the grid and DC power from a DC-DC converter.

Table 3-1: Level Zero Functional Analysis

Module	Alternative Control System
Inputs	- 240 $V_{AC\ from}$ power grid - DC Voltage to convert (5 V_{DC} – 40V_{DC})
Outputs	- Power to grid: 240 V_{AC} 60 Hz
Functionality	Convert $V_{DC\ to}$ V_{AC} and synchronize AC phase with grid

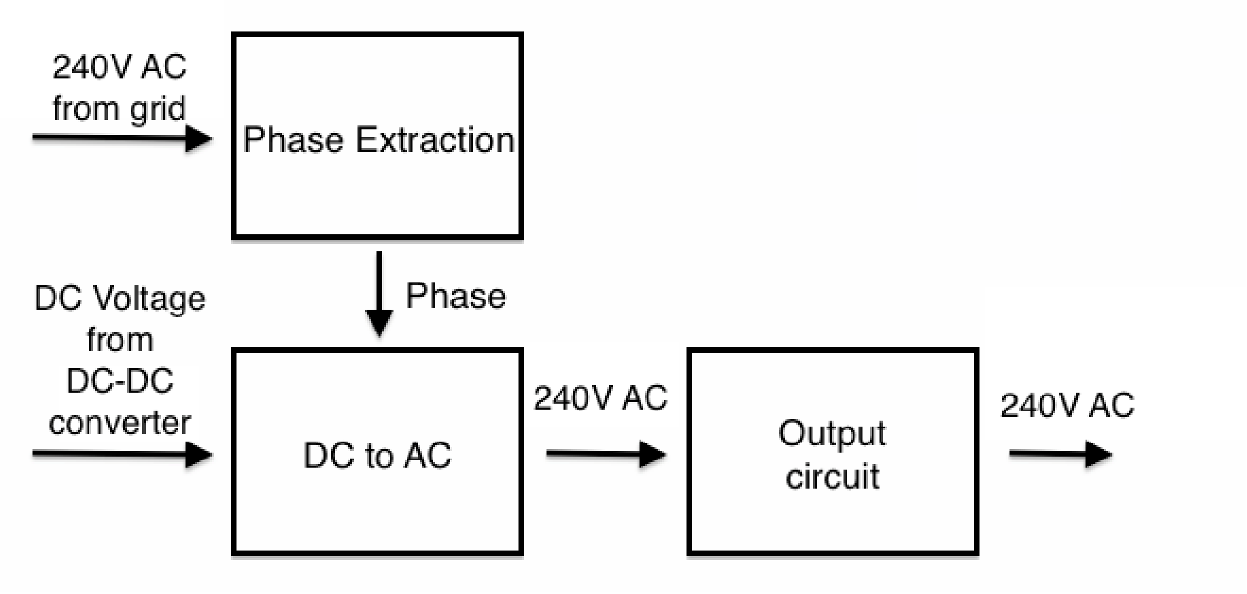


Figure 3-2: Level One Block Diagram

Table 3-2: Level One Functional Analysis

Module	Phase Extraction
Inputs	- 240 $V_{AC\ from}$ power grid
Outputs	- Phase of grid
Functionality	Determine phase of 240 V_{AC} voltage on grid

Module	DC to AC
Inputs	- DC voltage from DC-DC converter (Between 5 V and 40 V) - Phase of grid voltage
Outputs	- 240 V_{AC} 60 Hz, synchronized with grid
Functionality	Converts DC voltage to AC voltage

Module	Output Circuit
Inputs	- 240 V_{AC} 60 Hz, synchronized with grid
Outputs	- 240 V_{AC} 60 Hz, synchronized with grid
Functionality	Buffers output, shuts off inverter when not enough power input

Level one functional analysis shows the three main components of the micro-inverter: phase extraction, DC to AC conversion, and output driver. Figure 3-2 shows how these sub-systems of the micro-inverter interact. These components allow for voltage conversion from DC to AC, phase synchronization, and outputting to the grid.

The next chapter examines the project plan throughout the senior project courses: EE460, EE461, and EE462. Objectives for each week appear in Gantt charts.

Chapter 4: Project Planning

This chapter outlines the scheduling process of the project and estimates the costs associated with the project.

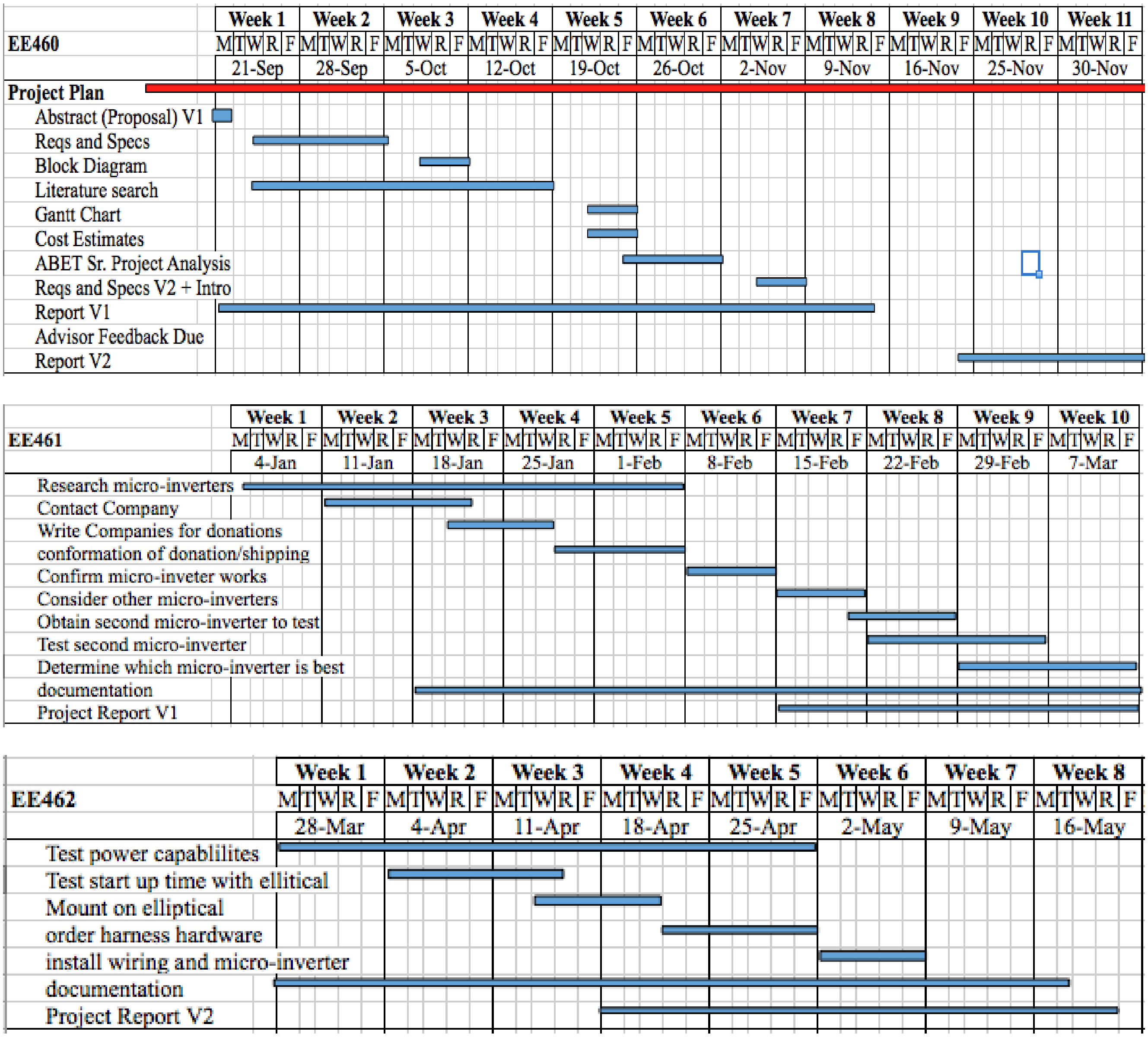


Figure 4-1: Project Gantt Chart

Figure 4-1 shows this project’s anticipated schedule. EE460 covers the project-planning phase during fall of 2015. EE461 contains research and the communication process with companies that produce micro-inverters. EE462 contains testing and integration of the micro-inverter during the spring of 2016. Project completion must occur by May 27th.

Table 4-1: Initial Cost Breakdown

Costs:	Pirce	quantity	Price ($)
wire harness	10	1	$ 10.00
mounting hardware	$5.00	1	$ 5.00
microinverter	$150	1	$ 150.00
			$ -
Design Labor	34/hour	20 hours	$ 680.00
Technician labor	25/hour	10 hours	$ 250.00
		total =	$ 1,095.00

Figure 4-2 shows the estimated cost breakdown for micro-inverter improvement. The wire harness consists of banana-to-banana connectors, with 14-gauge wire connecting banana terminals. This cost also consists of stress relief and hardware for securing wires. Mounting hardware consists of components needed to secure the inverter to the elliptical as well as creating a water resistant area. Design labor consists of research and verification of applicable micro-inverters. Technician labor includes testing and mounting of the micro-inverter.

The next chapter explains the research phase of the project. Micro-inverters approved for use in the state of California receive consideration for the EHFEM project. Comparison of the characteristics of the micro-inverters allows for desirable micro-inverters for the EHFEM project to stand out.

Chapter 5: Micro-Inverter Research

This chapter examines the micro-inverters available for use in California and hypothesizes the best micro-inverter for the EHFEM project.

The California Energy Commission regulates inverters used in California. Inverter approval by the California Energy Commission requires safety certification (UL 1741) from a Nationally Recognized Testing Laboratory as well as submission of conversion efficiency data obtained by a Nationally Recognized Testing Laboratory. The California Energy Commission confirms all data received for inverters.

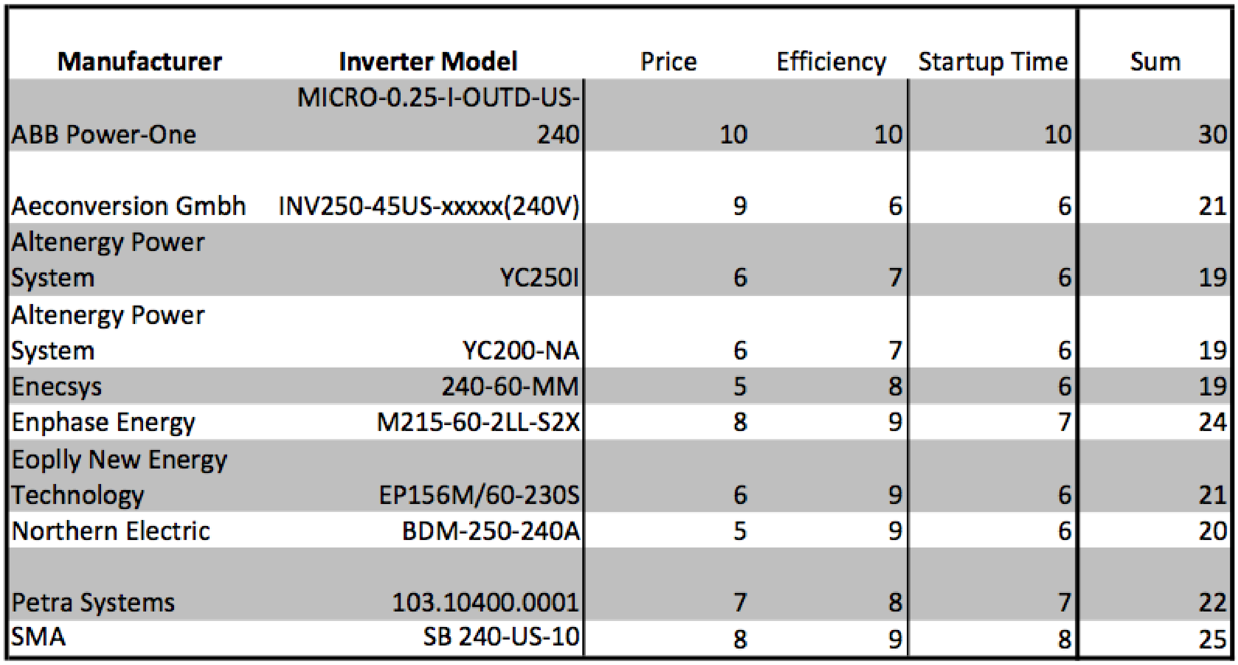
A summarized list of Micro-inverters suitable for the EHFEM project, and approved by the California Energy Commission, exists in Table 5-1. Table updated on February 1, 2016. [6]

Manufacturer	Inverter Model	Power Rating (Watts)	Weighted Efficiency
ABB	MICRO-0.25-I-OUTD-US-240	250	96%
ABB	MICRO-0.3-I-OUTD-US-240	300	96%
Aeconversion Gmbh	INV250-45US-xxxxx(240V)	240	92%
Aeconversion Gmbh	INV350-45US-xxxxx(240V)	300	92.5%
Altenergy Power System	YC250I	225	94%
Altenergy Power System	YC200-NA	220	94%
Andalay Solar	LW-230-1-AC0-D-B	215	96%
Andalay Solar	LW-230-AC1-A-B	190	95%
AU Optronics	PM060MA0_245	225	94.5%
AU Optronics	PM060MA1_245	240	95%
Darfon Electronics	MIG300UL00	220	95%
Enecsys	240-60-MM	240	96%
Enphase Energy	M215-60-2LL-S2X	215	96.5%
Eoplly New Energy Technology	EP156M/60-230S	230	96%
ET Solar Industry	ET-P660245BBZAC	240	95%
Hoymiles Converter Technology	MI-250	250	96.5%
LG Electronics	LM305UE-G1	305	96%
Northern Electric	BDM-250-240A	225	95.5%
Petra Systems	103.10400.0001	240	96%
Samil Power	SolarPond240HF-US	235	95.5%
Siemens Industry	SMIINT250R60	215	96%
SMA	SB 240-US-10	240	96%
SolarBridge Technologies	SBT250LV-240	240	95%
Sparq Systems	S215NA2240	207	93%

Table 5-1: Eligible Micro-Inverters [6]

Of the micro-inverters available for use in California, many don't qualify for the EHFEM project. Several micro-inverters available for use in California go through manufacturing techniques that physically connect the inverter to a solar panel, making it difficult to incorporate the inverter into the EHFEM project. Several other micro-inverters are simply duplicates with different names. For example, Andalay Solar uses an Enphase micro-inverter and attaches the inverter to a solar panel, selling the unit as an Andalay Solar product.

Table 5-2 contains a list of micro-inverters that qualify for the EHFEM project.



Manufacturer	**Inverter Model**	Price	Efficiency	Startup Time	Sum
ABB Power-One	MICRO-0.25-I-OUTD-US-240	10	10	10	30
Aeconversion Gmbh	INV250-45US-xxxxx(240V)	9	6	6	21
Altenergy Power System	YC250I	6	7	6	19
Altenergy Power System	YC200-NA	6	7	6	19
Enecsys	240-60-MM	5	8	6	19
Enphase Energy	M215-60-2LL-S2X	8	9	7	24
Eoplly New Energy Technology	EP156M/60-230S	6	9	6	21
Northern Electric	BDM-250-240A	5	9	6	20
Petra Systems	103.10400.0001	7	8	7	22
SMA	SB 240-US-10	8	9	8	25

Table 5-2: Micro-Inverter Decision Matrix

The most suitable inverter for the EHFEM project needs a low price, high efficiency, and low startup time. A list of qualifying inverters and rankings for price, high efficiency, and low startup time exists in table 5-2. Each category receives a score between zero and ten; zero the worst and ten the best. Research of inverters allowed for compilation of a list containing each associated characteristic for each inverter. The best inverter in each category received the highest mark, a ten. The remaining inverters receive ranks based on where they rank next to the other inverters. Inverters with the same characteristic receive the same score.

The ABB Power-One inverters receive the highest rankings. Enphase Energy and SMA also receive high rankings.

Chapter 6 contains test setup for the ABB Power-One Aurora micro-inverter and Enphase Energy M215 micro-inverter. Chapter 7 contains the test results for the Ephase Energy M215 micro-inverter and Chapter 8 contains the test results for the Aurora micro-inverter.

Chapter 6: Micro-Inverter Test Setup and Procedure

This chapter outlines how to properly test the micro-inverters. Micro-inverter testing allows for verification of start up time and verification of efficiency.

1. Connect the micro-inverter to the electrical grid using a lab bench. Figure 6-1 shows the wiring diagrams for connecting the Enphase M215 micro-inverter. **The test setup involves working with 240V_{AC}, which poses a hazard. Any measurements around energized equipment require at least two people present.**

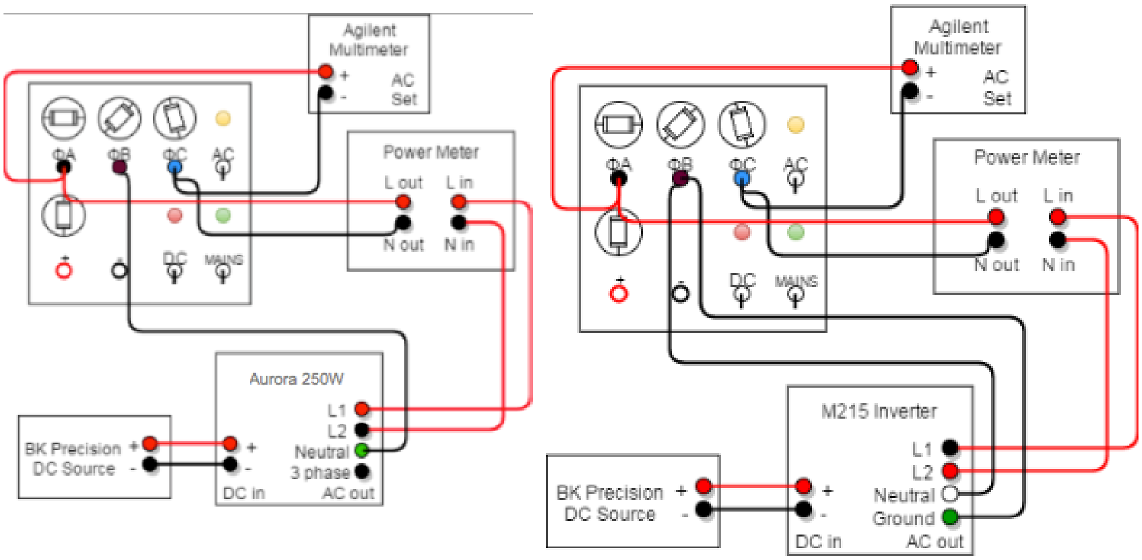


Figure 6-1: ABB Power-One 250W and M215 Inverter bench connection wiring diagram [11]

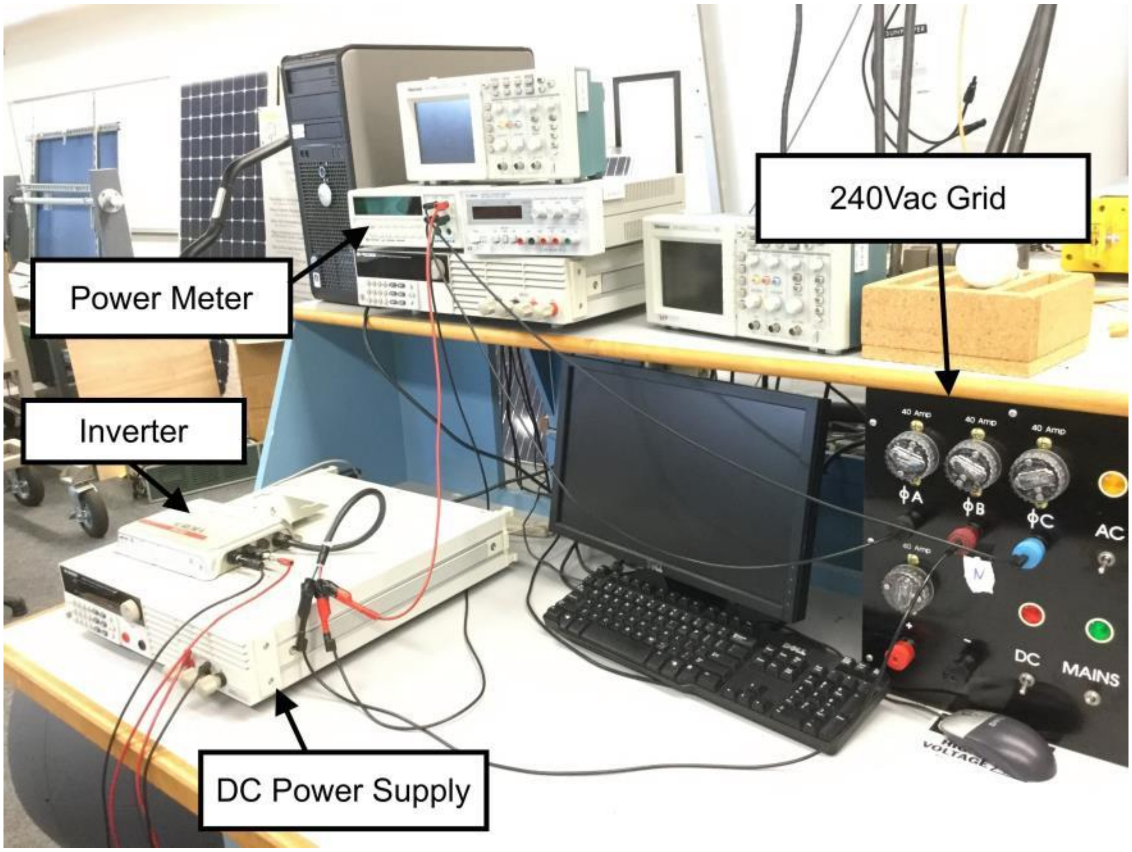


Figure 6-2: Bench connection in Building 20 room 150 at Cal Poly

2. Test the micro-inverters using a high-power lab bench, a DC source capable of supplying up to 36 V and 6.4 A, a power meter, and a multimeter.
3. Connect the DC Source to the input of the micro-inverter via banana-to-banana cable. The banana ends of the cables connect directly to the DC input of the micro-inverter.
4. **For the Enphase M215 micro-inverter:** Connect the output of the micro-inverter to the electrical grid in the lab. L1 and L2 of the micro-inverter must feed the input and output of the power meter.
    - 4.1. Connect the black output port of M215 micro-inverter, L1, to the red input port of the power meter, L in. Use a banana-to-banana cable.
    - 4.2. Connect L out of the power meter to the ϕA terminal of the power bench. Use a banana-to-banana cable.
    - 4.3. Connect the red output port of the M215 micro-inverter, L2, to the black input port of the power meter, N in. Use a banana-to-banana cable.
    - 4.4. Connect N out of the power meter to the ϕC terminal of the power bench. Use a banana-to-banana cable.
    - 4.5. Connect the white output port of the M215 micro-inverter, neutral, to the ϕB terminal of the power bench. Use a banana-to-banana cable.

   4.6. Connect the green output port of the M215 micro-inverter, ground, to the ϕB terminal of the power bench. Use a banana-to-banana cable.

5. **For the ABB Power-One 250W micro-inverter:** Connect the output of the micro-inverter to the electrical grid in the lab. L1 and L2 of the micro-inverter must feed the input and output of the power meter.
   5.1. Connect the red output port of 250W micro-inverter, L1, to the red input port of the power meter, L in. Use a banana-to-banana cable.
   5.2. Connect L out of the power meter to the ϕA terminal of the power bench. Use a banana-to-banana cable.
   5.3. Connect the black output port of the 250W micro-inverter, L2, to the black input port of the power meter, N in. Use a banana-to-banana cable.
   5.4. Connect N out of the power meter to the ϕC terminal of the power bench. Use a banana-to-banana cable.
   5.5. Connect the white output port of the 250W micro-inverter, neutral, to the ϕB terminal of the power bench. Use a banana-to-banana cable.
   5.6. Connect the green output port of the 250W micro-inverter, ground, to the ϕB terminal of the power bench. Use a banana-to-banana cable.
6. Verify micro-inverter functions before collecting data.
7. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing or swapping the micro-inverters.
8. Set the DC source to 35 V, the current limit to 3.5 A, and supply a DC input to the micro-inverter.
   8.1. **The M215** has a minimum startup voltage of 22 V and a turn off voltage of 16 V.
      8.1.1. Once the system has powered up, a green LED blinks six times. This occurs after about 80 seconds after DC input. The inverter continues to flash green when connected to the Enphase Envoy remote monitoring system. The LED flashes orange when not connected to the Envoy but operating normally. If the LED flashes red, then the micro-inverter does not operating normally.
   8.2. **The ABB Power-One 250W** has a minimum startup voltage of 25 V and a turn off voltage of 12 V.
      8.2.1. Once the system has powered up, about 4 minutes, the power meter shows power transferred to the grid.
      8.2.2. No status LED exists on the ABB Power-One 250W. A remote monitoring device, the Aurora CDD, shows the status of the inverter. Without the CDD, the inverter operates normally.
9. Record Data. Use digital camera to photograph supplied voltage and current from DC power supply as well as the output power readings from the power meter. Because the supplied voltage and/or current constantly vary, taking a photograph allows for easy capturing of input and output power readings simultaneously. Note: For the
   9.1. Capture data for the current limit starting at 1A and increment by 0.5A up to 7A. For each current limit, vary the voltage. Note: Set Voltage and Current rarely output due to the inverter attempting to draw more power from the DC power supply. For each increment, record actual output from the power supply, not set output.

9.1.1. **For the M215**, set voltage to 16V and increment by 1V up to 48 volts. NOTE: Minimum turn on voltage - 22V   Maximum turn on voltage - 48 volts.

9.1.2. **For the ABB Power-One 250W**, set the voltage to 12V and increment by 1V up to 60 volts. NOTE: Minimum turn on voltage - 25 volts.

Chapter 7 contains the test results of the M215 and Chapter 8 contains the results for the ABB Power-One Aurora 250W.

Chapter 7: Enphase M215 Micro-Inverter Testing Results

This chapter examines the results of the Enphase M215 testing.

7.1 Startup Time for M215

Testing the Enphase M215 Micro-inverter began with determining the time required by the inverter to start transferring input power to the grid. See Chapter 6.1 for information regarding the test setup and procedure.

The M215 Enphase micro-inverter requires 85 seconds to output power with an acceptable DC input introduced. The inverter requires 85 seconds to start regardless of the period of no DC input. NOTE: Inverter must remain connected to $240V_{AC}$.

7.2 M215 Efficiency Testing

Dividing measured output power by calculated input power provides the efficiency of the inverter. A few calculated efficiencies exceeded 100 percent as well as a few below 80%. These values derived from input values that surpassed the rated input powers; these values do not exist in the efficiency data.

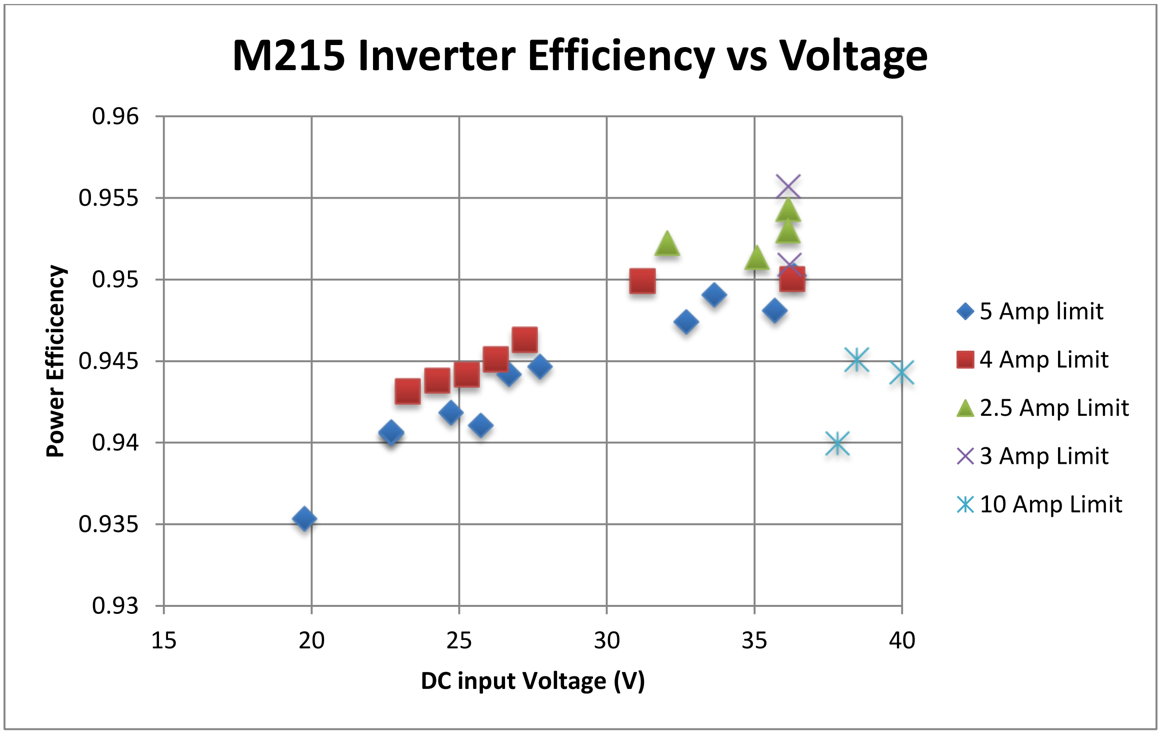


Figure 7-1: M215 Inverter Efficiency vs. Voltage

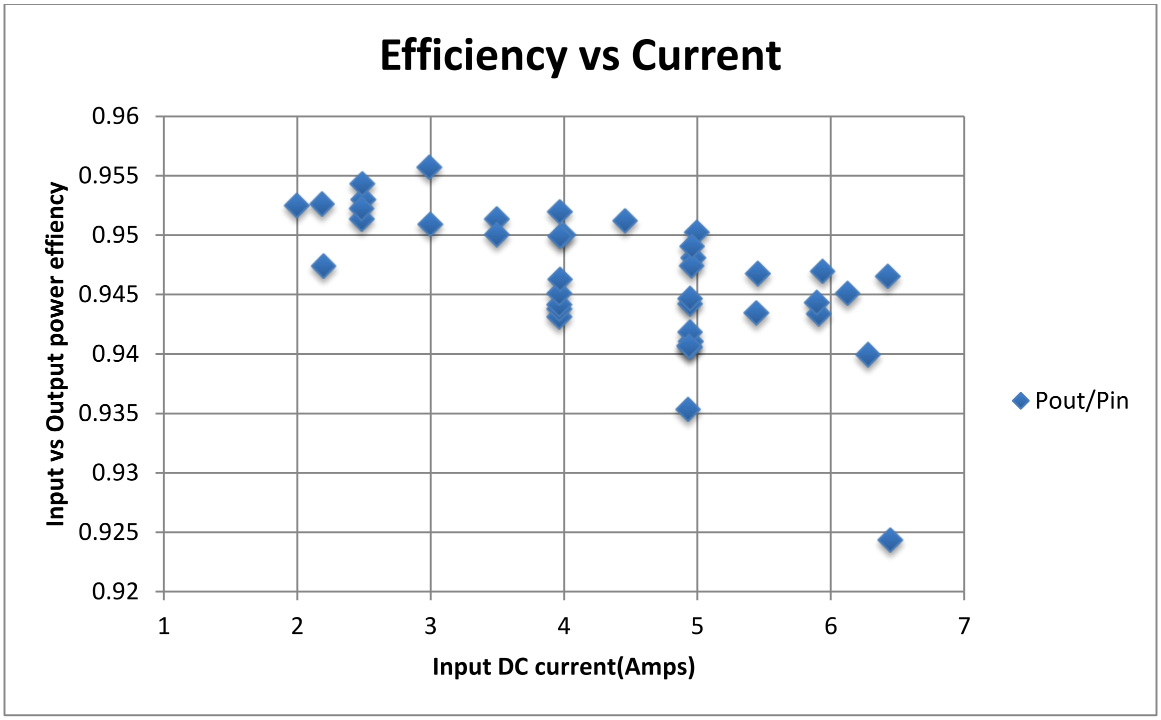


Figure 7-2: M215 Inverter Efficiency vs. Current

Figure 7-1 and 7-2 show trends in efficiency due to input voltage and input current. Figure 7-1 shows a trend of increased efficiency as the input voltage approaches 36 volts. The data sheet claims peak power tracking voltage lies between 27V and 39V, consistent with testing [12]. The inverter fought to keep the input voltage at 36V when the input voltage exceeded 36 volts. This observation coupled with the maximum efficiency of the inverter occurring at a 36V input confirms that the ideal input voltage for this inverter equals 36 volts.

Figure 7-2 shows a trend of decreasing efficiencies with increasing current. The maximum efficiency recorded, 95.5%, occurs with a 3A input current at 36V. Figure 7-2 shows a trend in the current limit constantly influencing the DC input. The M215 micro-inverter attempts to draw the most current available by reducing the internal load of the inverter to draw more current. This occurs until the input voltage drops enough to stop the inverter from reducing the load.

The next chapter looks into the testing results of the ABB Power-one Aurora 250W inverter.

Chapter 8: ABB Power-one Aurora 250W Micro-Inverter Testing Results

This chapter examines the results of the ABB Power-one Aurora 250W testing.

8.1 Startup Time for ABB Power – One 250W Micro-inverter

The ABB Power-one Aurora obtained top scoring for start-up time. According to James Gonzales, a Technical Sales Engineer from ABB, the inverter may produce power after about 30 seconds, given connection to utility gird without interruption. Upon first connecting to the grid, the inverter requires a minimum of 5 minutes to output power.

First startup of the ABB Power-one Aurora micro-inverter required over six minutes before the inverter output power. Next, The connection to the grid remained connected while the DC input toggled off and on. The inverter required more than 5 minutes to output power, significantly less than the anticipated 30 seconds. Testing to verify the 30-second start-up time occurred several times with no success in confirming a start up time less than 5 minutes. James Gonzales, a Technical Sales Engineer from ABB, responded to the difficulty of achieving the claimed start-up time by stating that the United States version of the micro-inverter operation causes the start up time to take 5 minutes, not 30 seconds. To make the inverter capable of starting up in less than 5 minutes, the country code within the CDD must change from United States to a custom setup. The custom setup required to reduce the start up time of the inverter fails to meet requirements for grid-tie inverters in the United States, disqualifying possible use for this project.

8.2 ABB 250W Micro-inverter Efficiency Testing

Dividing measured output power by calculated input power provides the efficiency of the inverter. Initial inverter testing produced unsatisfying results. Many recorded efficiencies exceeded 100%, suggesting the inverter output more power than it input. Modification of the procedure resolved this error. Modification included video recording of the input and output power. This technique of acquiring data allowed for averaging the power input and outputs over a period of 5 seconds. Error bars account for additional error not captured by averaging. The additional error in the error bars accounted for the difference between the highest recorded average efficiency, and the maximum reported efficiency of the ABB Power-One 250W inverter. The CEC reported a maximum efficiency for the ABB Power-One 250W inverter of 96 percent. Testing with the averaging method provided a maximum efficiency of 99.4 percent. Addition of error bars settled the high efficiency. The error bars consist of plus and minus the error difference of the maximum efficiency measurements, or 3.4 percent. The error bars exist in figure 8-1 and figure 8-2.

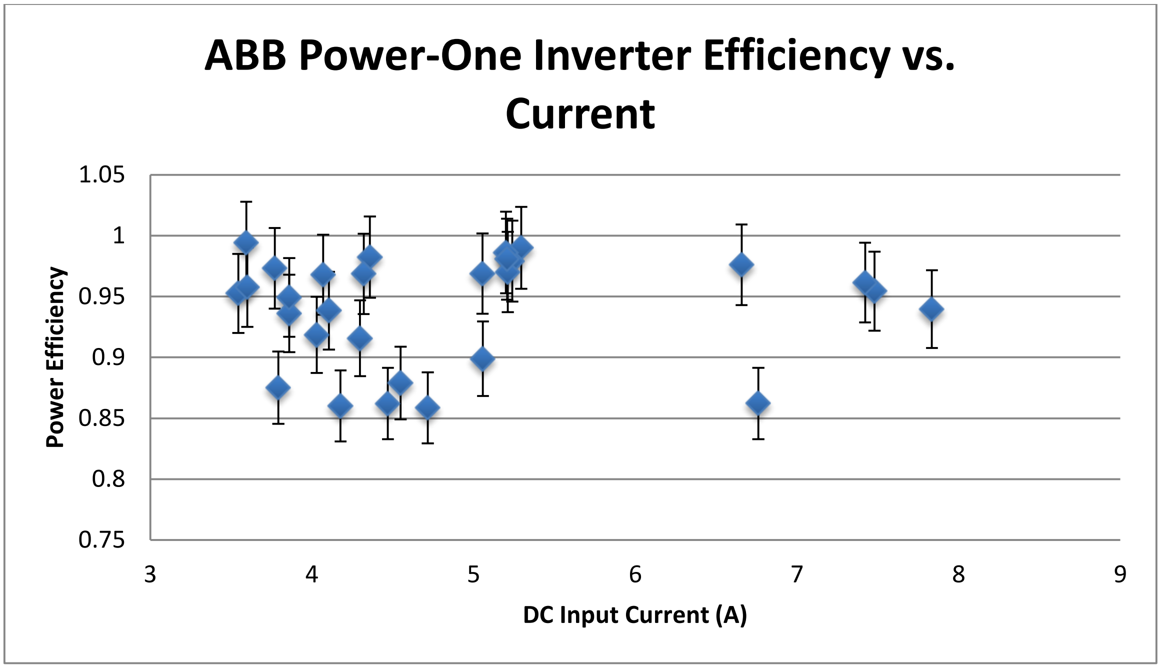


Figure 8-1: ABB Power-One 250W micro-inverter Efficiency vs. Input Current

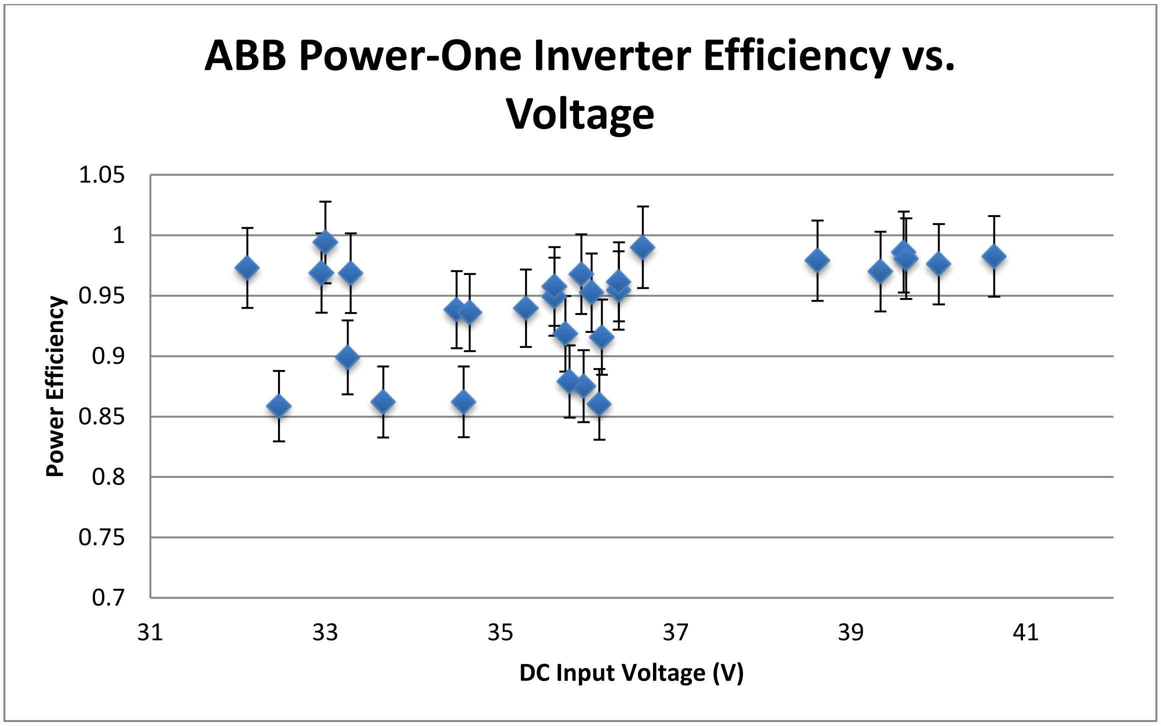


Figure 8-2: ABB Power-One 250W micro-inverter Efficiency vs. Input Voltage

Testing for the ABB Power-One 250W micro-inverter did not provide insight into the best operating voltage.

The next chapter examines the ABB Power-One 250W micro-inverter and the Enphase M215, determining the best-suited micro-inverter for the EHFEM project.

Chapter 9: ABB Power-One 250W vs. Enphase M215

Testing shows that the Enphase M215 micro-inverter provides more optimal characteristics than the ABB Power-One 250W micro-inverter for use with the EHFEM project.

The maximum efficiency of the ABB Power-One 250W micro-inverter appears to exceed the Enphase M215. The maximum efficiency for the ABB Power-One 250W contains too much error, however, for determination. The Enphase M215 exhibited a maximum efficiency of 95.5%.

The rate at which the maximum power point tracking influenced input power for the ABB Power-One 250W micro-inverter far exceeded the rate of the Enphase M215. The ABB Power-One 250W micro-inverter changed load value at an average of 1.875 times per second, regardless of input. The Enphase M215 changed input load value at a rate of 1.62 times per second but reached a steady state (no changing of loads) within 5 seconds of a new input. The inability for the ABB Power-One 250W micro-inverter to reach steady state quickly makes it an undesirable for this project.

Start up time remains the largest parameter to determine the best micro-inverter for this project. The Enphase M215 constantly started outputting power in 85 seconds. The ABB Power-One 250W micro-inverter required up to 5 minutes to output power. Research of the ABB Power-One micro-inverter found it capable of outputting power within 30 seconds of receiving DC input power. Further research found that the firmware on the ABB Power-One micro-inverter causes the 5-minute delay. Programming of the micro-inverter with the monitoring device allows for change in the firmware on the micro-inverter; however, it would no longer comply with regulations for connecting to a public grid in the United States.

Chapter 10: Aurora CDD setup (Used with Aurora Micro-inverter)

This chapter outlines setup of the Aurora CDD (concentrator data device) for use with the Aurora 250W micro-inverter.

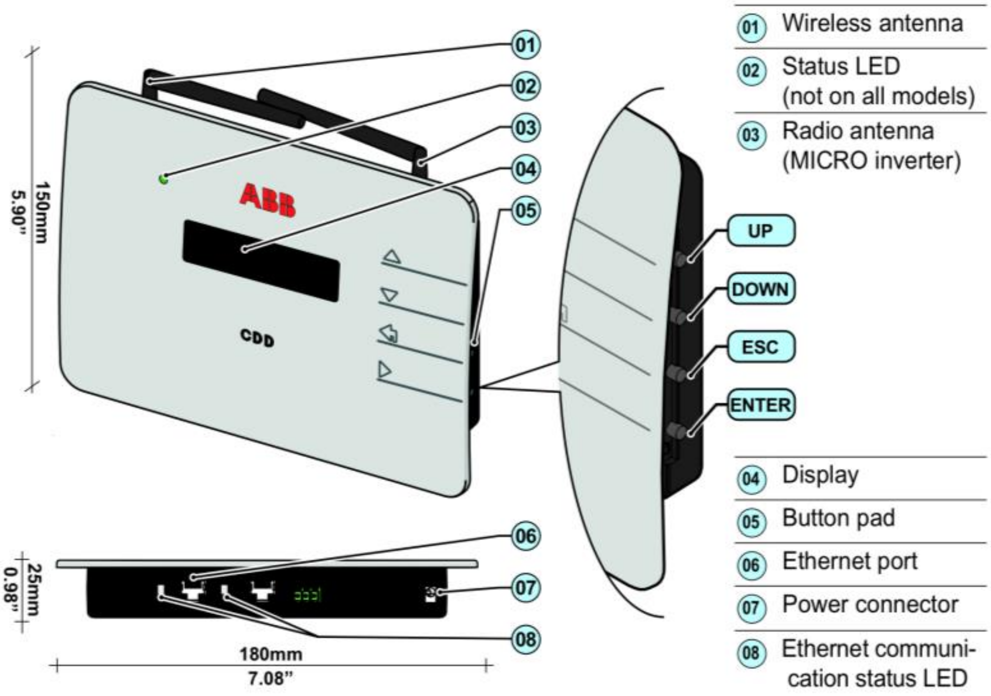


Figure 10-1: Aurora CDD Part Description [13]

The Aurora 250W micro-inverter requires connection to a remote monitoring device. The Aurora 250W micro-inverter only transfers power to the grid when connected with the monitoring device. Otherwise the micro-inverter shuts off.

10.1 Position of CDD

For proper and uninterrupted operation of the system, the CDD must remain within 100 feet of the micro-inverter and maintain a clear line-of-sight. The micro-inverter and CDD RF communication must remain secure during micro-inverter operation.

10.2 Connecting CDD to network

A wired or wireless connection between the CDD and the Internet makes it possible for the CDD to transfer data to the web portal.

Wireless Internet connection to the CDD requires a router with IEEE 802.11b communication protocol. The CDD provides Wireless connection as the default setting on the CDD. Ensure wireless connection enabled by pressing the down key to scroll to “Wless enabled”. If “Wless enabled” doesn’t appear, access the advanced menus by pressing and holding the up and down buttons together for 5 seconds. Enter password “0010” when prompted. Select “CHANGE SETTINGS” > “NETWORK” > “SELECT NEWORK” > “WLESS” and then press enter. The CDD automatically restarts. Use the down button to scroll to “Wless enabled” after restart. Verify that underneath “Wless enabled” reads “yes”. If “Wless enabled” reads “no”, press enter, press down key, and press enter again to enable wireless.

The CDD automatically looks for wireless networks to join. To join the network, scroll to the network name and press enter. After a few seconds the result of the connection attempt appears and then “Wless Enabled” appears.

To Connect via Ethernet cable, connect an Ethernet cable between the router and CDD. Ensure to put the Ethernet Cable in the proper port (see figure 10-1). To ensure possibility of wired connection, press and hold the up and down buttons together for 5 seconds. Enter password “0010” when prompted. Select “CHANGE SETTINGS” > “NETWORK” > “SELECT NEWORK” > “Ethernet” and then press enter. The IP address of the web server appears on the “General Information” menu.

Connecting the CDD with the network at California Polytechnic State University caused challenges. Wireless connection, the default setting of the CDD, failed due to the security associated with the wireless network at California Polytechnic State University. Ethernet connection allowed for connection to the network in room 150 of building 20. Connecting to the Ethernet port required the network administrators to establish a temporary campus IP address.

10.3 Connecting CDD to the micro-inverter

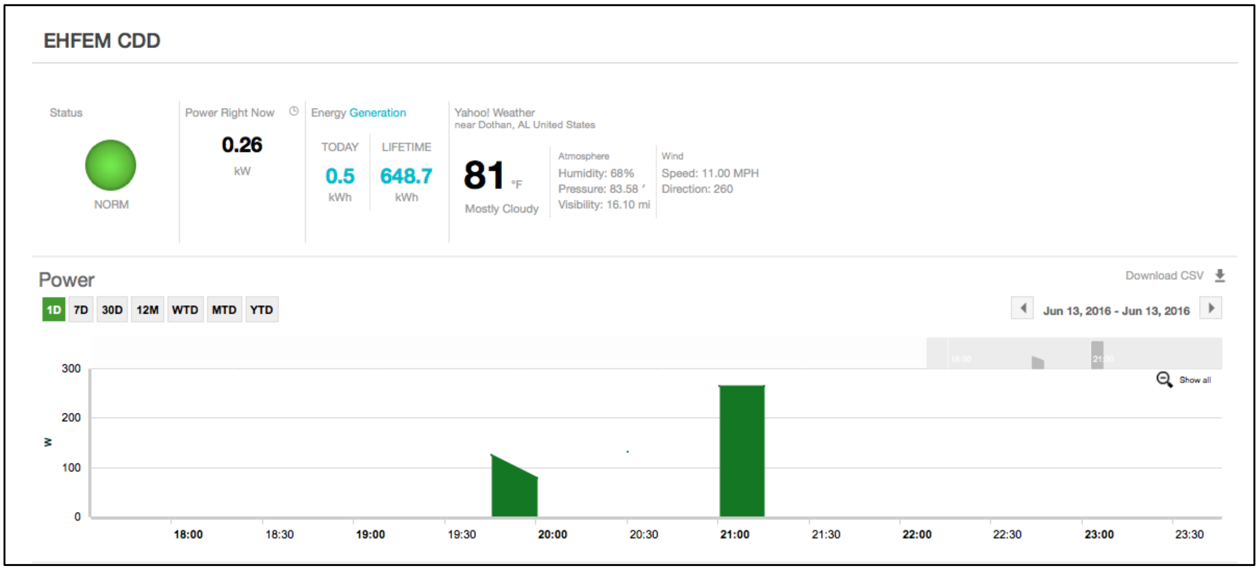
The following steps outline the process of adding a new micro-inverter for the CDD to monitor. The CDD allows for monitoring of up to 30 micro-inverters.

To add a new micro-inverter, press and hold the up and down buttons together for 5 seconds. Enter password “0010” when prompted. Select “CHANGE SETTINGS” > “Micro Manager” >

“[Add] Inverters” and then press enter. The CDD starts acquisition of micro-inverters within range. Grid connection of the micro-inverter(s) must occur for RF communication between the micro-inverter(s) and CDD. The display on the CDD shows the amount of micro-inverters acquired. After acquisition of micro-inverters by the CDD, press enter to stop the acquisition process. Press the down key to add each micro-inverter shown on the display. Press enter to delete a micro-inverter on the display. Once acquisition of micro-inverters has concluded, entering of country standard occur. From the “CHANGE SETTINGS” menu, select “COUNTRY STD” and press enter. Use the up and down keys to select the Country Standard and press enter to confirm.

10.4 Aurora Vision Plant Viewer

The Aurora Vision Plant Viewer software allows for remote monitoring of each micro-inverter connected to the CDD. The home page displays all the micro-inverters with their serial numbers, instant energy output, and radio signal level. A table on the left of the screen shows data for the whole system, including, energy output, total energy, CO_2 savings, and system status. Figure 10-2 shows the Aurora Vision Plant Viewer software.



EHFEM CDD

Status: NORM

Power Right Now: 0.26 kW

Energy Generation: TODAY 0.5 kWh, LIFETIME 648.7 kWh

Yahoo! Weather near Dothan, AL United States: 81 °F Mostly Cloudy

Atmosphere: Humidity: 68%, Pressure: 83.58 ′, Visibility: 16.10 mi

Wind: Speed: 11.00 MPH, Direction: 260

Power: 1D

Jun 13, 2016 - Jun 13, 2016

Figure 10-2: Aurora Vision Plant Viewer Screenshot

Figure 10-2 shows the capabilities of the Aurora Vision plant viewer software when used with the Aurora CDD to monitor ABB Power-One micro-inverters. The CDD monitors up to 30 micro-inverters, allowing for monitoring of up to thirty exercise machines. Monitoring with the software allows for gym managers to access data including total power generated, system status, and total CO_2 savings.

The next chapter examines the placement of components within the elliptical trainer and routing of wires. Careful consideration of placement of components reduces the chance of equipment damage from moving parts and reduces the chance of harm to users.

Chapter 11: Mounting and Wiring of components with elliptical trainer.

This chapter examines where to place the micro-inverter and DC-DC converter systems within the elliptical trainer.

The EHFEM project seeks to equip the Precor EFX-546i elliptical trainer with components that produce AC voltage. The Recreation Center at California Polytechnic State University requires no additional space consumption. All components must reside within elliptical housing.

The back end of the Precor elliptical provides most of the available confined space. Figure 11-1 shows space available within the back end of the elliptical.

Figure 11-1: Precor EFX-546i elliptical

Figure 11-1 shows the back end of the elliptical for component housing. This area of the elliptical houses the circuitry that converts the user's mechanical energy into electrical energy. The next section shows proposed locations for EHFEM components.

11.1 Precor EFX-546i component housing compartment

Consideration of component placement and safety appears in this section

Instructions for accessing the rear compartment of the elliptical appear in Appendix B.

Figure 11-2 below shows the available space within the rear component housing. Custom brackets secure the EHFEM elements in place, similar to the ones seen in figure 11-2 holding the resistors. These brackets must fit within the allocated space and provide enough strength to hold the elements securely during operation of the elliptical trainer.

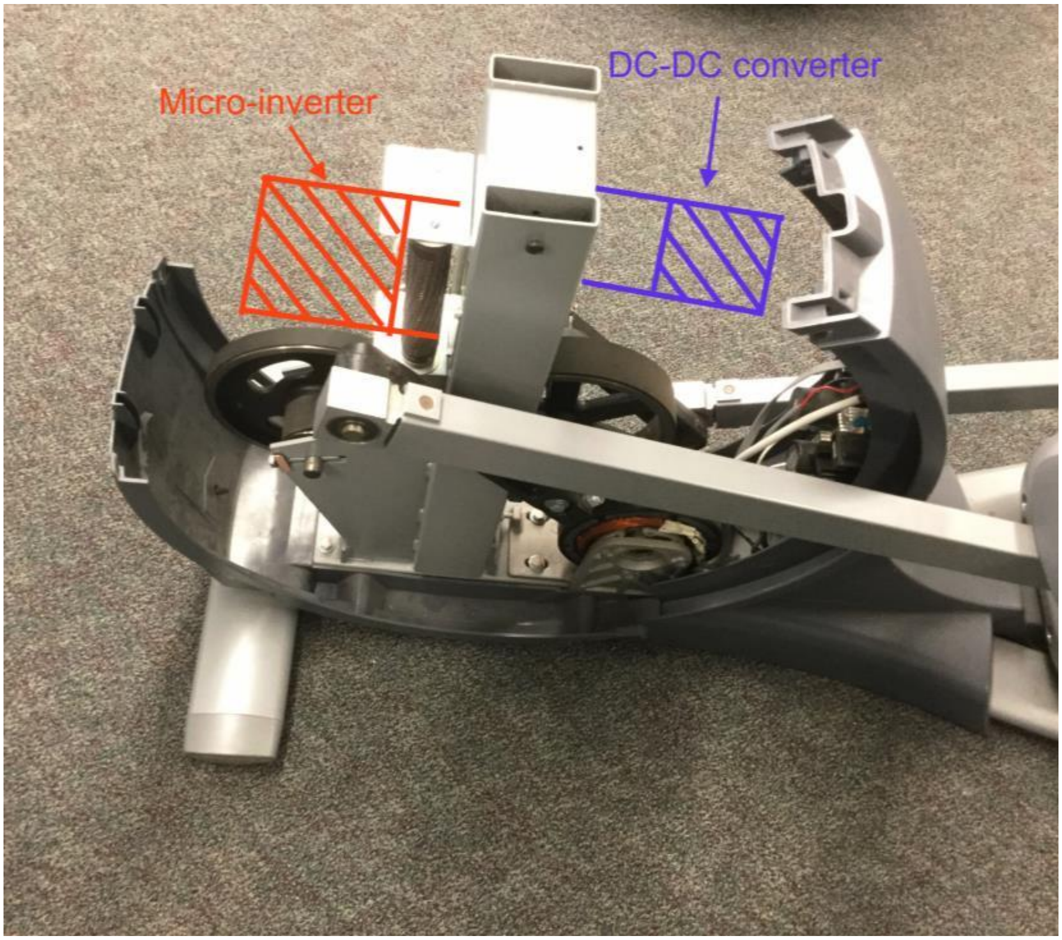


Figure 11-2: Precor EFX-546i elliptical component housing side view

The two sections shown in figure 11-2 provide space for the DC-DC converter as well a micro-inverter. Moving mechanical arms occupy space immediately outside of the allocated area. To ensure safety of the user and to avoid damage to equipment, properly secure components in the highlighted areas of figure 11-2. Figure 11-3 shows top view of components and clearance convers with mechanical arms of elliptical.

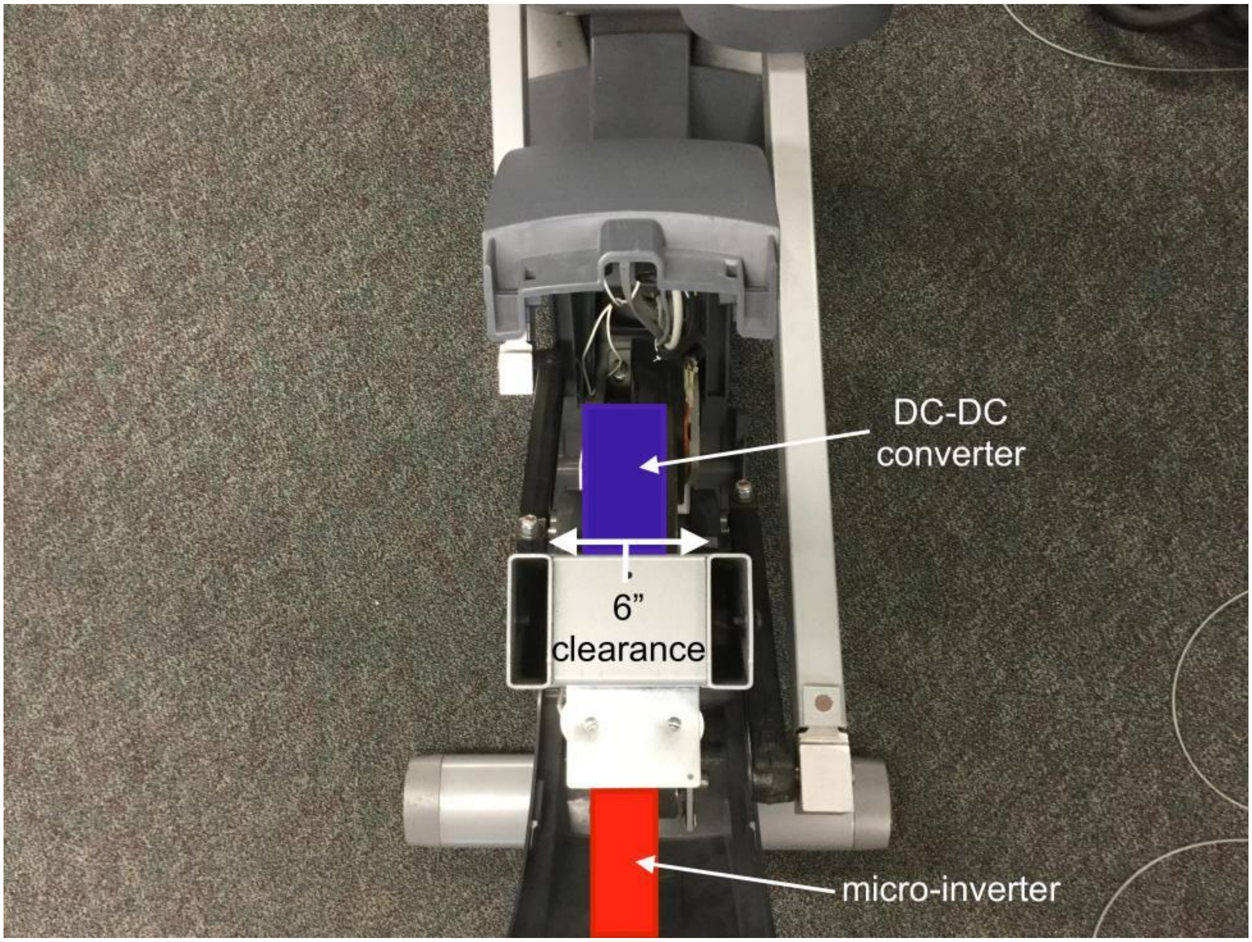


Figure 11-3: Precor EFX-546i elliptical component housing top view

11.2 Precor EFX-546i wire routing

Electrical connections between components require wiring within the elliptical. The DC-DC converter must connect to the on board DC generator. The micro-inverter must connect to the output of the DC-DC converter. The output of the micro-inverter must connect with a $240V_{AC}$ grid, requiring additional wiring to extend outside of the elliptical.

The next chapter contains the conclusion for this project.

Chapter 12: Conclusion and Future Projects

Research and testing of desirable micro-inverters for the Energy Harvesting From Exercise Machine project found that the Enphase M215 provides the EHFEM project with the best characteristics for capturing energy created on exercise equipment. The Enphase M215 micro-inverter requires 85 seconds to start up while the ABB Power-One 250W micro-inverter requires over 4 minutes to begin transferring power. The Enphase M215 starts transferring power 155 seconds quicker than the ABB Power-One micro-inverter. This significant time difference makes the Enphase M215 much more desirable.

A future project should address the problem of start up time associated with the micro-inverter, as well as methods for addressing the power point tracking feature of the micro-inverters. The power point tracking of the solar inverters used for the EHFEM project causes excess current draw from the inverter. Possible methods to overcome this issue include adding a battery between the micro-inverter and DC-DC converter or adding a capacitor bank between micro-inverter and DC-DC converter.

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Appendix A –Senior Project Analysis

Project Title: Micro-Inverter Improvement For The Energy Harvesting From Exercise Machines Project

Student: James Ralston

Advisor: Dr. Braun

1. Summary of Functional Requirements:

The micro-inverter currently used to convert DC to AC voltage requires up to 5 minutes before the conversion process begins. This time lag significantly diminishes power produced while exercising. An improved CEC micro-inverter must demonstrate improved synchronization time as well as improved efficiency. This project consists of obtaining a CEC improved micro-inverter, testing to ensure improvement in efficiency, and integration with the existing energy harvesting system.

2. Primary Constraints

Primary constraints develop from the customer needs seen in chapter 2. The primary issue consists of obtaining a CEC approved micro-inverter. The desired type of micro-inverter costs more than the allocated budget. An additional constraint consists of incorporating the micro-inverter into the allocated space in the elliptical. Integration with the DC-DC converter requires careful consideration regarding power, current, and voltage requirements. Safety issues arise from the 240 V_{AC} output of the micro-inverter. Careful consideration must occur with location and exposure of the 240 V_{AC} wiring.

3. Economic

Cost breakdown resides in figure 4-2. Vast economic impacts develop from this project. The individual completing the project obtains an increase in human capital; increased knowledge creates an increased ability to produce economic value. The micro-inverter and test equipment comprise of the majority of the financial capital associated with this project. Small amounts of financial capital also exist with computing and sharing data regarding findings from the project. The electricity, produced by the EHFEM project and sold to PG&E, creates the majority of manufactured capital relevant to this project. Natural Capital exists in the raw materials and fuel used in creation of the micro-inverter and equipment used to test the inverter [7,24].

Labor and parts costs for the project begin accumulating in September of 2015. Costs continue to increase until May of 2016. Maintenance costs continue for the duration of the Energy Harvesting From Exercise Machines Project. Human capital began accumulating in September and continues through May 2016.

Estimated costs for the project total to $1,095. This consists of design and technician labor, the inverter, components for integrating the inverter with the energy harvesting equipment, and mounting the micro-inverter to the Precor EFX 561i. Donation of a micro-inverter from a desired company needs to occur. James Ralston purchases components needed for integration with the EHFEM system.

Technician labor consists of the majority of the cost associated for the project if manufactured on a commercial basis, aside from the micro-inverter. To minimize this cost, design of a micro-inverter built specifically for the Precor EFX 561i elliptical needs to occur. This allows for quicker installation time.

Predictions and estimates show no revenue prior to completion. Human capital consists of the primary benefit, gained by those involved with the EHFEM project.

Emergence of the product occurs in February of 2016 and exists for several years with the Energy Harvesting from Exercise Machine project led by Dr. Braun. Estimated maintenance costs for the project total to $100/year for testing the inverter and ensuring proper operation.

4. If Manufactured on a Commercial Basis:

If the energy-harvesting project moves towards a commercial basis, sales estimates reach 5,000 units per year. Estimation shows micro-inverter production totals $195, including installation and wiring. Selling each devise for $220 generates a profit of $125,000 per year. Estimated maintenance costs total to $25 per year for testing and calibrating.

For the energy-harvesting project to take place on a commercial basis, design of a micro-inverter built specifically for the Precor EFX 561i elliptical needs to occur. A micro-inverter packaged specifically for the exercise equipment allows from secure connections, fast installation, and a safer, more reliable, product.

5. Environmental

Production of micro-inverters, as well as shipping, cause considerable emissions leading to negative environmental impact. Micro-inverters require resources such as silicon, metals, plastic, and considerable amounts of energy for production. The use of the micro-inverter causes small amounts of heat production, ultimately released into the environment. Petroleum based fuel used to transport the device contributes to the reduction of non-renewable resources [14].

The device helps reduce use of fossil fuels by assisting in the production of electricity via renewable resources. By delivering excess electricity produced by the machine's generator to the grid instead of a load, the environment receives less heat from exercise equipment. This allows facilities with energy harvesting equipment to operate air conditioning units less, ultimately saving power.

6. Manufacturability

Production of micro-inverters continues with the original company that created the micro-inverter. Slight modifications must occur for easy integration with the rest of the energy harvesting system. Sending of specifications for the inverter size, types of harnesses, and mounting points to micro-inverter producer allows for obtaining a micro-inverter that fits securely and safely into the allocated space.

Production of a self-designed micro-inverter requires an efficient assembly floor and testing department. The assembly floor must contain skilled workers to solder and assemble components. Automated systems place and solder surface mount components. Automated machines to package micro-inverters must also exist. The testing department must thoroughly test each micro-inverter to confirm each requirement and specification for the micro-inverter. Testing must include extreme temperature and humidity levels, long-term use, and confirmation of output specifications provided by the California Energy Commission.

7. Sustainability

Sustainability on a commercial level requires a constant supply of micro-inverters from the company that produces them. With so many micro-inverters on the market, concerns arise from companies no longer able to compete with the numerous other manufactures of micro-inverters, ultimately going out of business. To ensure long-term sustainability, development of a micro-inverter within the EHFEM team must occur.

Calibration and testing of the micro-inverter must occur once a year to ensure proper synchronization with the grid. Many micro-inverters on the market have systems available that track and log output voltages and power. This type of system allows for frequent monitoring and testing of the micro-inverter.

The product promotes sustainability by synchronizing a renewable power source with the grid. An improved product can occur if the micro-inverter becomes more efficient. A more efficient system would raise the cost of the project.

8. Ethical

Environmental impacts and legal issues from energy harvesting machines cause ethical concerns. Production of the micro-inverter and the rest of the energy-harvesting project require many materials and processes that do not benefit the environment. The EHFEM project does however seek to improve environmental conditions by adding sustainable energy to the grid.

The IEEE Code of ethics states, “disclose promptly factors that might endanger the public or the environment”. The EHFEM project conforms to this aspect of the IEEE code of ethics by properly analyzing environmental impacts. The IEEE code of ethics also states its members must, “improve the understanding of technology; its appropriate application, and potential consequences.” The EHFEM project fulfills this aspect of the IEEE code of ethics by improving the already existing exercise technology [15].

Ethical Principlism states that autonomy, non-maleficence, beneficence, and justice need to all exist for an ethical decision. The EHFEM project achieves autonomy through freedom to choose different designs. Non-maleficence exists in the careful search and testing for hazardous components of the project. Beneficence exists primarily in the scope of the project, creation of a sustainable power source. Justice exists throughout the design process. Conforming to the National Electric Code, IEEE 1547, and NEMA all contribute to the achievement of justice within the project. Through and complete patent searches also contribute to justice within the project.

9. Health and Safety

Numerous safety risks exist within the EHFEM project. One significant health and safety concern resides in the 240 V_{AC} components of the project. In a study of 39 recorded electric shock events with 240 V_{AC}, over a three-year period, zero fatalities occurred [16]. All components at a potential of 240 V_{AC} require insulation that complies with NEC and NEMA.

Component overheating and excess current draw propose health and safety risks. Protection circuitry must prevent too much current from entering components. If a component breaks from excess current, over heating occurs, allowing for burning to develop. If the micro-inverter does not accept power from the exercise machine, circuitry must exist that safely diverts the unneeded current.

Safety risks exist with proper mounting and securing of equipment to the elliptical. Fast moving mechanical components of the elliptical cause shaking and vibration. If not secured properly, electrical components, such and the micro-inverter and DC-DC converter, cause danger to the user and the machine.

This project benefits health of individuals by encouraging users to exercise. The ability to create sustainable energy inspires users and possible users to exercise more. More exercise leads to a healthier life.

10. Social and Political

Social and Political issues associated with the EHFEM project derive from adding renewable energy to the grid.

The direct stakeholders of this project consist of California Polytechnic State University San Luis Obispo, Dr. David Braun, and the students working on the project. Pacific Gas and Electric buys electricity produced by the energy harvesting equipment.

Indirect stakeholders consist of those effected by improvements in renewable and sustainable energy. The EHFEM project harms producers of non-renewable energy. The EHFEM project benefits stakeholders concerned with the environment. This project benefits the company producing micro-inverters for the project by increasing micro-inverter sales. The project benefits those who purchase the machine by allowing for potential to earn income from selling produced electricity.

All stakeholders benefit equally in regards to the benefit of creating a more sustainable world. Stakeholders producing non-renewable energy receive unequal financial benefits.

11. Development

Research of micro-inverters has provided me with insight into the possibilities of renewable energy. The vast expansion of micro-inverters in the last few years clearly shows the movement toward a sustainable world.

Monte Carlo analysis allows for thorough simulation of circuitry. I learned this technique during the course of EE460, allowing for careful consideration of variation within components and environments.

Difficulties associated with projects similar to the EHFEM project arose from readings published through the IEEE.

I further developed my understanding of micro-inverters and the characteristics different characteristics associated with them.

Literature search

The literature search introduced me to many of the codes and requirements for electrical systems. The NEC, UL and IEEE codes contain very thorough requirements that mandate safety. The literature search also allowed for examination of new and developing ideas, published through the IEEE.

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Appendix B –Accessing Rear Compartment in Elliptical

First, remove circular housing sides. Use a 4mm Allen Key to remove two screws shown in figure B-1.

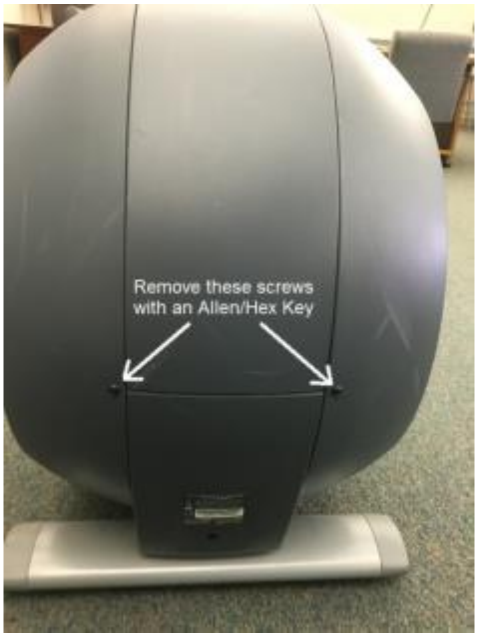


Figure B-1: Screw Location on rear elliptical housing cover [11]

With the screws removed, individually rotate each housing cover, clockwise if facing the “PRECOR” text. Place the removed housing covers in a safe location, away from moving parts and test equipment.

Next, remove two screws that secure the top panel. Screw location shown in figure B-2.

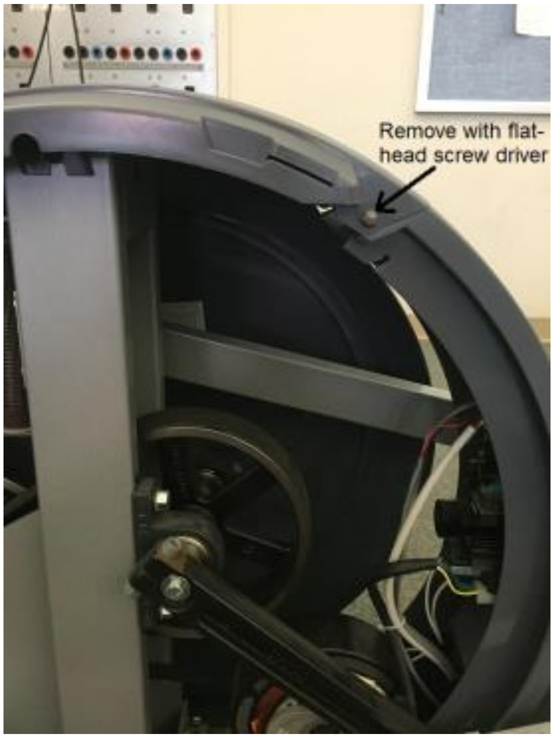


Figure B-2: Screw Location for rear elliptical housing top panel. Second screw not shown in figure. The second screw mirrors the screw shown in figure [11]

Lift up on top panel to remove. Place panel in safe location away from moving parts and test equipment. Figure B-3 shows top removed.

Figure B-3: Rear elliptical housing top panel removed

Appendix C – Pictures of Equipment

C-1 Micro-inverters and monitoring devices for EHFEM project

Figure C-1: Enphase M215 micro-inverter

Figure C-2: Enphase Envoy – monitoring device

Figure C-3: ABB Power-One 250W micro-inverter

Figure C-4: ABB Power-One Aurora CDD – monitoring device

C-2 Micro-inverter test equipment

Figure C-5: BK Precision Model 9153 High Power DC source

Figure C-6: GW Instek GPM-8212 Power Meter

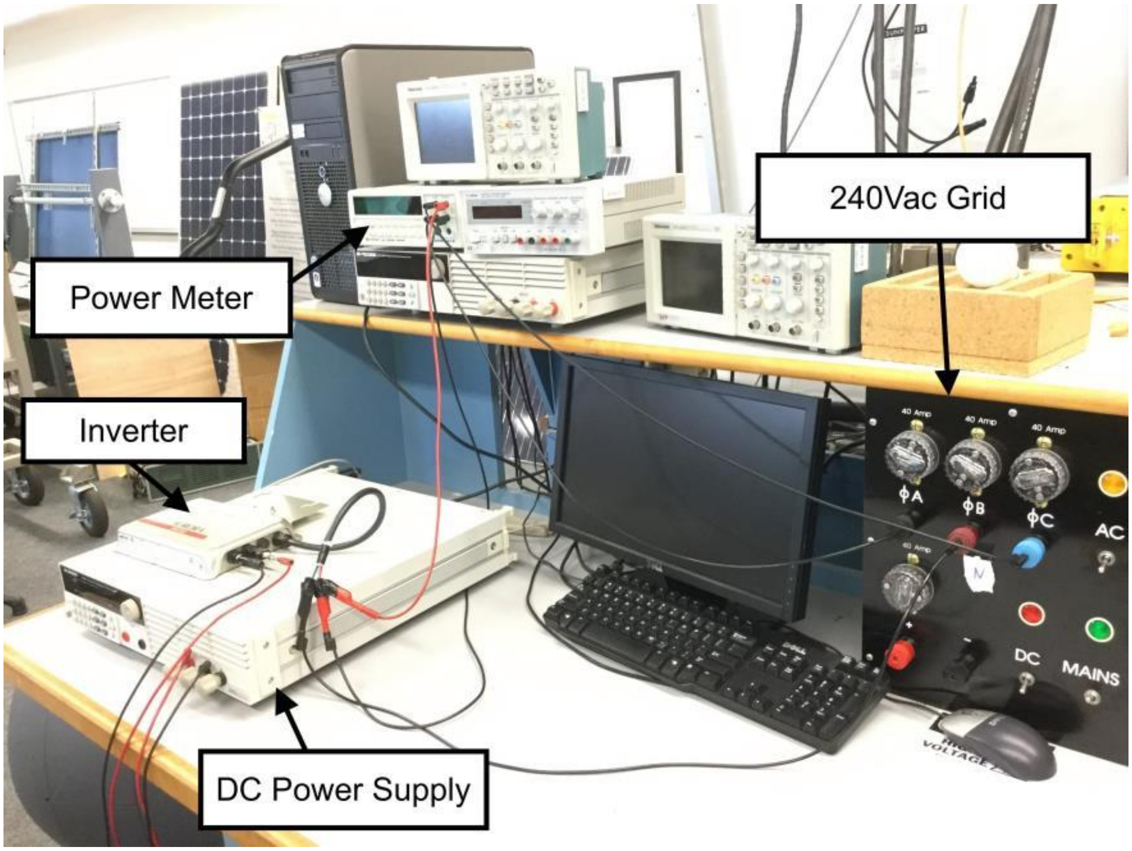


Figure C-7: Test setup in building 20 room 150

Appendix D – Useful Data Obtained from inverters

D-1 ABB Power-One 250W input and output power

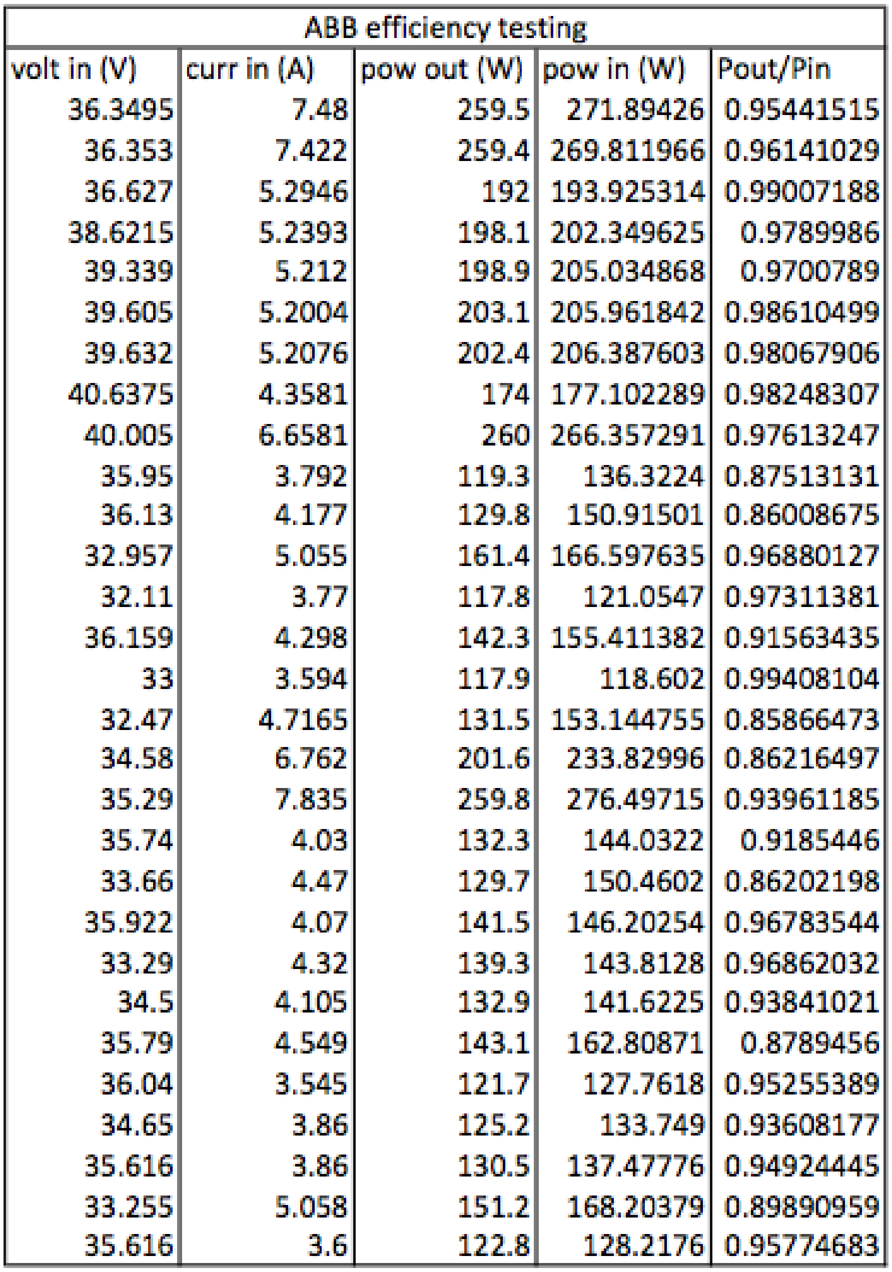
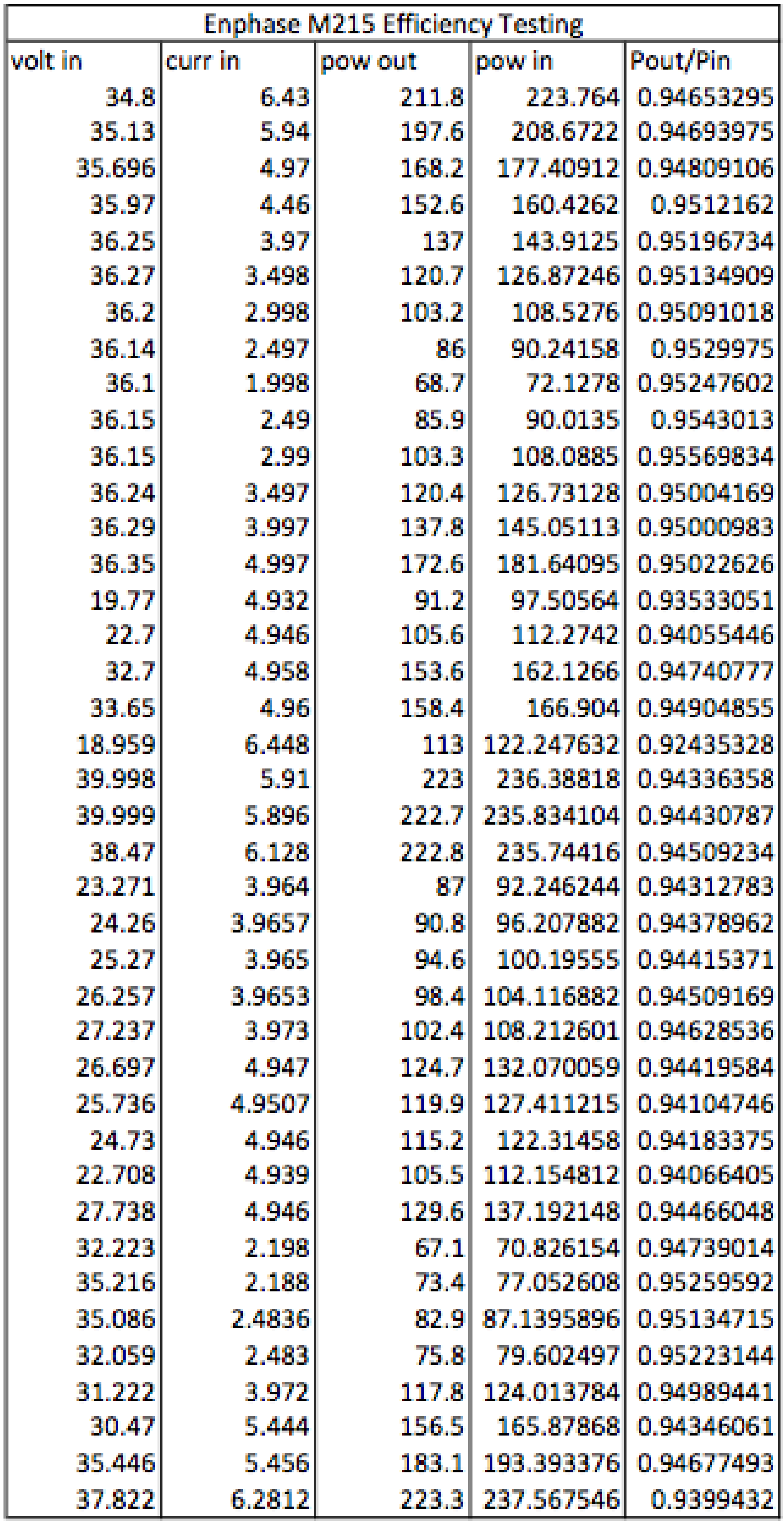


ABB efficiency testing				
volt in (V)	curr in (A)	pow out (W)	pow in (W)	Pout/Pin
36.3495	7.48	259.5	271.89426	0.95441515
36.353	7.422	259.4	269.811966	0.96141029
36.627	5.2946	192	193.925314	0.99007188
38.6215	5.2393	198.1	202.349625	0.9789986
39.339	5.212	198.9	205.034868	0.9700789
39.605	5.2004	203.1	205.961842	0.98610499
39.632	5.2076	202.4	206.387603	0.98067906
40.6375	4.3581	174	177.102289	0.98248307
40.005	6.6581	260	266.357291	0.97613247
35.95	3.792	119.3	136.3224	0.87513131
36.13	4.177	129.8	150.91501	0.86008675
32.957	5.055	161.4	166.597635	0.96880127
32.11	3.77	117.8	121.0547	0.97311381
36.159	4.298	142.3	155.411382	0.91563435
33	3.594	117.9	118.602	0.99408104
32.47	4.7165	131.5	153.144755	0.85866473
34.58	6.762	201.6	233.82996	0.86216497
35.29	7.835	259.8	276.49715	0.93961185
35.74	4.03	132.3	144.0322	0.9185446
33.66	4.47	129.7	150.4602	0.86202198
35.922	4.07	141.5	146.20254	0.96783544
33.29	4.32	139.3	143.8128	0.96862032
34.5	4.105	132.9	141.6225	0.93841021
35.79	4.549	143.1	162.80871	0.8789456
36.04	3.545	121.7	127.7618	0.95255389
34.65	3.86	125.2	133.749	0.93608177
35.616	3.86	130.5	137.47776	0.94924445
33.255	5.058	151.2	168.20379	0.89890959
35.616	3.6	122.8	128.2176	0.95774683

Table D-1: ABB Power-One Micro-Inverter Testing

D-2 Enphase M215 input and output power



Enphase M215 Efficiency Testing				
volt in	curr in	pow out	pow in	Pout/Pin
34.8	6.43	211.8	223.764	0.94653295
35.13	5.94	197.6	208.6722	0.94693975
35.696	4.97	168.2	177.40912	0.94809106
35.97	4.46	152.6	160.4262	0.9512162
36.25	3.97	137	143.9125	0.95196734
36.27	3.498	120.7	126.87246	0.95134909
36.2	2.998	103.2	108.5276	0.95091018
36.14	2.497	86	90.24158	0.9529975
36.1	1.998	68.7	72.1278	0.95247602
36.15	2.49	85.9	90.0135	0.9543013
36.15	2.99	103.3	108.0885	0.95569834
36.24	3.497	120.4	126.73128	0.95004169
36.29	3.997	137.8	145.05113	0.95000983
36.35	4.997	172.6	181.64095	0.95022626
19.77	4.932	91.2	97.50564	0.93533051
22.7	4.946	105.6	112.2742	0.94055446
32.7	4.958	153.6	162.1266	0.94740777
33.65	4.96	158.4	166.904	0.94904855
18.959	6.448	113	122.247632	0.92435328
39.998	5.91	223	236.38818	0.94336358
39.999	5.896	222.7	235.834104	0.94430787
38.47	6.128	222.8	235.74416	0.94509234
23.271	3.964	87	92.246244	0.94312783
24.26	3.9657	90.8	96.207882	0.94378962
25.27	3.965	94.6	100.19555	0.94415371
26.257	3.9653	98.4	104.116882	0.94509169
27.237	3.973	102.4	108.212601	0.94628536
26.697	4.947	124.7	132.070059	0.94419584
25.736	4.9507	119.9	127.411215	0.94104746
24.73	4.946	115.2	122.31458	0.94183375
22.708	4.939	105.5	112.154812	0.94066405
27.738	4.946	129.6	137.192148	0.94466048
32.223	2.198	67.1	70.826154	0.94739014
35.216	2.188	73.4	77.052608	0.95259592
35.086	2.4836	82.9	87.1395896	0.95134715
32.059	2.483	75.8	79.602497	0.95223144
31.222	3.972	117.8	124.013784	0.94989441
30.47	5.444	156.5	165.87868	0.94346061
35.446	5.456	183.1	193.393376	0.94677493
37.822	6.2812	223.3	237.567546	0.9399432

Table D-2: Enphase M215 Micro-Inverter Testing