AC System Monitoring Device

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Executive Summary

The alternating current (AC) system monitoring device is used to monitor voltages on AC power systems. These devices are also known as programmable logic controllers (PLCs), and are used in industry for power distribution control and system automation. The AC system monitoring device will use digital processing to monitor and control AC systems. Digital processing removes the need for the traditional electro-mechanical controls used throughout industry for the last 60 years, resulting in improved system reliability.

The project will cover the design of a device to monitor an AC power system and provide power factor correction. Specifically this project will have the objective of building a device that will monitor AC voltage, AC current, and power factor. Additional functionality of the device would include power factor correction by adding capacitors in parallel with inductive loads.

The AC system monitoring device will be designed through the process of investigating various methods available to perform the functions for the device. The possible solutions found to implement the device will be used to propose a primary design solution and an alternative design solution for the project. The proposed solution is the implementation of an industrial grade PLC available from Schweitzer Engineering Laboratories with AC monitoring and automation capabilities that can be used to provide the desired system monitoring and power factor control.

The various solutions will be further analyzed based on cost considerations for the project implementation. The cost of the project will be estimated based on the main parts required for the project. To reduce costs, the project will use existing equipment available in the ECE laboratories and equipment provided by Schweitzer Engineering Laboratories Inc. and Caterpillar Inc.

Defining key milestones for the project will help determine a preliminary schedule for the project and define critical elements of the project that need to be assigned high priority. The project schedule will show the feasibility of implementing the project by the end of the 2016 spring semester.

Environmental and societal considerations will show the importance of the project research and development of the AC system monitoring device. The power factor correction functionality of the device would make the power distribution network more efficient, reducing the energy losses from the transmission of power. Programmable logic controllers would also enhance system reliability, eliminating older electro-mechanical controls that require periodic maintenance. Increasing the reliability of the power distribution network promotes economic progress for industry and society.

Abstract

This document will cover the design of a device to monitor an alternating current (AC) system. The device will be able to monitor AC voltage, AC current, and calculate the power factor of the AC system it is monitoring. The design develops subsystems which enable the device to perform the various intended functions. Device design will also develop the preliminary state diagram for the operations of the Programmable Logic Controller (PLC) used to implement the various device functions. Functional and non-functional requirements for the device provide metrics to quantify the design solutions. The selection of different means to perform the functions will determine the solution for the device. Investigation of the methodologies available to perform the functions for the device will also permit proposing an alternative solution for the device design. Finally, discussion of the environmental and societal impact will demonstrate the importance of the project research and the development of the AC system monitoring device.

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I. INTRODUCTION AND OVERVIEW

A. Problem Background

The alternating current (AC) system monitoring device is used to monitor AC voltages on power systems. To permit processing by the AC system monitoring device, AC voltages and currents must be transformed down to lower values with potential and current transformers. The real time monitoring capability of this device would give power distribution companies the ability to perform power factor correction in real time, reducing power loss during transmission of energy on AC power systems.

B. Problem Statement

Professor Gutschlag requested the design of the AC system monitoring device. The AC system monitoring device will allow users to quickly view AC power characteristics. The system will have voltage monitoring, current monitoring, power factor monitoring, and programmable logic output for power factor correction. The AC system monitoring device will use any required voltage or current step-down conversions to provide accurate measurements of the AC voltage and current, and also permit AC power factor calculations. All signal processing of the high voltage inputs has to maintain very high safety standards to ensure the device is safe to operate. The power to operate the AC system monitoring device will be provided from the AC power supply. Voltage, current, and power factor monitoring will provide the device with the ability to control the power factor on the AC power system.

C. Constraints

Based on the client's needs, the list of required constraints for the AC system monitoring device is shown in Table I. The constraints will be defined as pass or fail for the AC system monitoring device. Safe operating standards were obtained from the National Institute of Technology for moderate to high voltages [1].

TABLE I. LIST OF AC SYSTEM MONITORING DEVICE CONSTRAINTS

AC monitoring device **must** be safe to operate
AC monitoring device **must** be secure
AC monitoring device **must** be a digital system
AC monitoring device **must** operate up to 250 Vac
AC monitoring device **must** operate with 60 Hz AC signals

D. Scope

The AC system monitoring device problem statement will determine what is in scope and out of scope for the project. The scope of the project is defined in Table II.

TABLE II. DEFINING THE SCOPE OF AC SYSTEM MONITORING DEVICE

Scope	Out of Scope
Monitor AC Voltage	Monitor DC Voltage
Monitor AC Current	Monitor DC Current
Calculate Power Factor	Calculate Current Differential
Power Factor Correction	Transformer Protection
Single-Phase AC Systems	Three-Phase AC Systems
Display Interface	Network Interface
Digital Processing	Electro-mechanical Controls

II. STATEMENT OF WORK

A. System Description

i. System Block Diagram

The system block diagram for the AC system monitoring device was constructed to provide overall input-output relationships. The system block diagram shown in Figure 1 was derived from the functional requirements for the AC system monitoring device. The device will be powered from the AC power system and accept user input, AC voltage and current, and will perform the operations necessary to provide the user with a display and power factor control. To calculate power factor, the device will need to measure both AC voltage and current. User input would be used for navigating the display menus through the user interface.

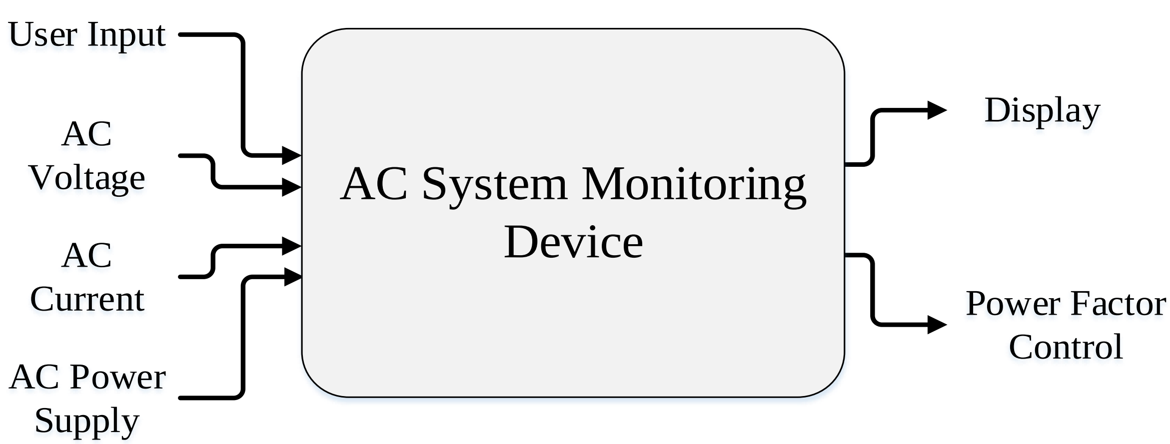


Fig. 1. System block diagram for AC System Monitoring Device

ii. Subsystem Block Diagram

The subsystem block diagram indicates the internal functionality of the AC system monitoring device. The subsystem block diagram is shown in Figure 2. AC power input to the device will require

AC-to-DC voltage conversion to power the microcontroller. Signal conditioning would be used to process the AC voltage and current to permit the microcontroller to perform the required computations. The microcontroller would then simply output the AC voltage, current, and power factor calculation results to the user interface. Controlling the power factor of the AC power system will require signal conditioning to control solid-state relays used to add capacitance in parallel with the load to control the power factor.

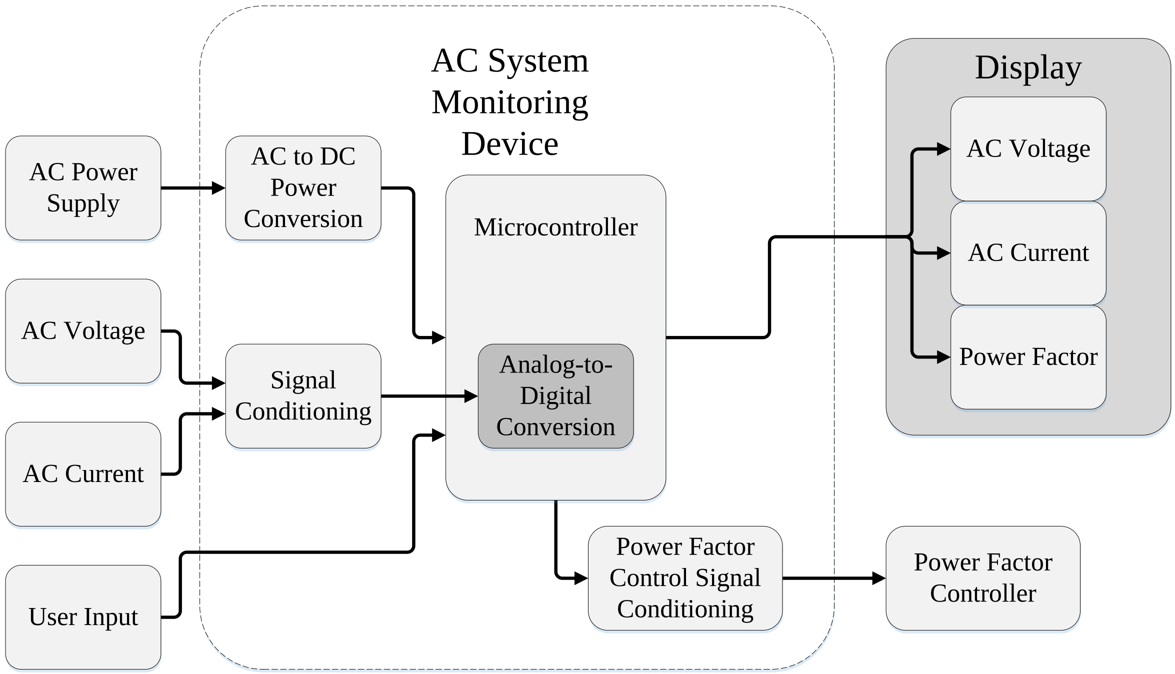


Fig. 2. Subsystem block diagram for AC system monitoring device

iii. State Diagram

The state diagram in Figure 3 shows the logic flow of the embedded microcontroller in the AC system monitoring device. The flowchart's logic flow is derived from the list of functional requirements. The microcontroller program flow will first perform initialization of the ports of the controller and other functionalities of the device. The program will then enter a looping state in which it will read inputs from the user interface. Then the next step specifies that the microcontroller will retrieve data from the various AC voltage and current inputs. The microcontroller then will perform the necessary calculations and implement the necessary controls. Finally, the program sends out AC power system data to the user through the user interface.

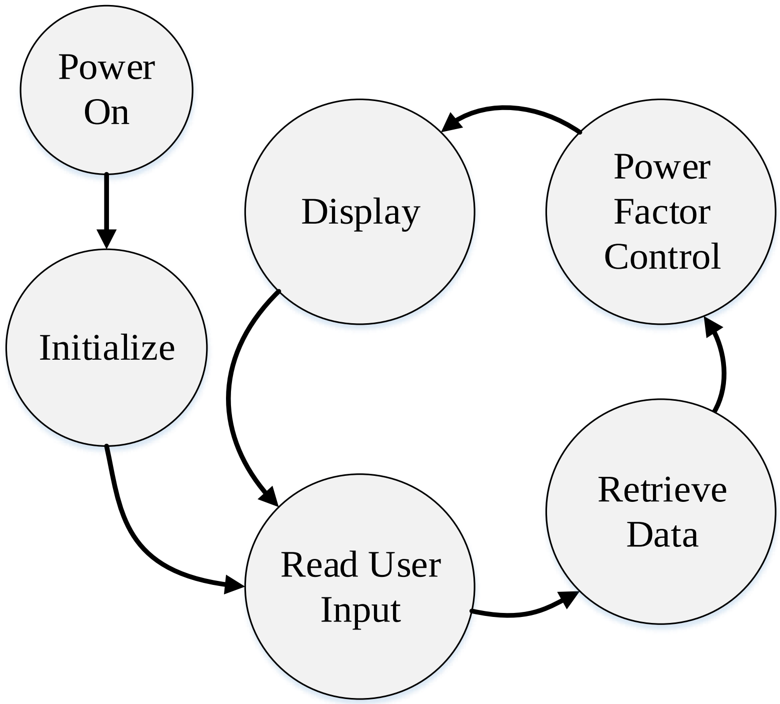


Fig. 3. State diagram for embedded microcontroller for AC system monitoring device

iv. Nonfunctional Requirements

The non-functional requirements describe quality characteristics of the AC system monitoring device. A list of non-functional requirements were identified from the problem statement and identified in Table III. A combined objective tree for the AC system monitoring device is located in Appendix A. The AC system monitoring device will have two non-functional requirements.

Reliability dictates that this device should be able to operate for a length of time without failure of the functions it is required to perform. Reliability is important in the application of the AC system monitoring device because the device is intended to operate over long periods of time, and operational failure can result in the failure of systems the device is expected to control. The metrics of the length of time that will measure reliability are located in Table VIII in Appendix B.

The second non-functional requirement would be the usability of the device as perceived by the user. Usability of the device will determine the ability to use the device without requiring excessive time to understand system operation. This will be based on the user's experience and ease of use of the device, and would be tested by conducting user surveys. The metrics for the usability requirement is located in Table IX in Appendix B.

TABLE III. LIST OF AC SYSTEM MONITORING DEVICE OBJECTIVES

AC monitoring device **should be** reliable
AC monitoring device **should be** usable

Using the objectives identified Table III, a pairwise comparison chart was constructed in Table X in Appendix B. This pairwise comparison chart shows the comparison of the objectives to quantify which are the most critical and should be considered first. Rating assigned in the pairwise comparison chart compare importance of the non-functional requirements for the AC system monitoring device. Rating the importance of both reliability and usability indicates they are equally important.

v. Functional Requirements

A list of functions were identified from the problem statement and identified in Table IV. Each of the functions include secondary functions that are italicized. The functions identify what functions the AC system monitoring device should provide. The device will monitor both AC voltage and current, calculate the power factor, and then activate solid-state relays to correct the power factor if necessary. More detailed specifications of the functional requirements are identified in Table V.

TABLE IV. LIST OF AC SYSTEM MONITORING DEVICE FUNCTIONAL REQUIREMENTS

AC monitoring device **shall** monitor voltage
System will accurately calculate AC voltage within voltage range.
System will display present voltage data within refresh rate specifications.
AC monitoring device **shall** monitor current
System will accurately calculate AC current within current range.
System will display present current data within refresh rate specifications.
AC monitoring device **shall** monitor power factor
System will accurately calculate present AC power factor within power factor calculation specifications.
System will display calculated present power factor data within refresh rate specifications.
AC monitoring device **shall** control power factor
System will control switching of relays to control power factor with at least one switching control.

TABLE V. LIST OF AC SYSTEM MONITORING DEVICE FUNCTION SPECIFICATIONS

Specifications	Max	Min	Tolerance
Voltage Range	250 Vac	100 Vac	±15%
Current Range	5 A	0 A	±15%
Power Factor Calculation	1.0	0.3	±15%
Refresh Rate	1000 ms	1 ms	N/A
Control Power Factor	N/A	1 Switch	N/A

B. Design Approach and Method of Solution

The proposed solution for the AC system monitoring device will use an industrial automation controller. The device will be provided through the courtesy of Schweitzer Engineering Laboratories (SEL) to promote education and provide application experience for future electrical engineers. This device will be used to display AC voltage, AC current, and power factor. The SEL automation controller will also perform power factor correction.

The specific device provided for the project is the SEL-2411 Automation Controller. This device will adequately perform the required functions for AC system monitoring. The device can be connected to an AC power supply to power the device. Input/output cards are added to the automated controller to add the function of AC voltage monitoring, AC current monitoring, and power factor control. Additional features of the SEL controllers is that they are constructed with enclosed circuity, providing safe operation. The SEL controllers also incorporate multi-level security measures for programming to limit unauthorized access associated with modifying device settings. Device specifications are shown in Table VI. The specifications of the SEL-2411 meet or exceed device functionality requirements as defined in Table V.

TABLE VI: SEL-2411AUTOMATION CONTROLER SPECIFICATIONS[2]

Specification	Max	Min	Tolerance
Power Supply	250 Vac	125 Vac	N/A
AC Voltage Input Card (300V Model)	250 Vac	100 Vac	±0.08%
AC Current Input Card (5A Model)	10.0 A	0.05A	±0.5%
Power Factor Calculation	1.0	0	±1%
Analog Output Refresh Rate	100ms	N/A	N/A
Digital Electromechanical Contact Outputs	8	N/A	N/A

The SEL-2411 will be programmed through SEL's ACSELERATOR Quickset® software to acquire the AC voltage and current and send the information to the device display. The device will also be programmed to control the power factor through the switching of capacitors using solid-state relays. Only capacitors will only be used for power factor correction because most loads associated with power transmission are inductive.

The ACSELERATOR Quickset® software used to program the SEL-2411 will utilize graphical logic diagrams to build the control functions for the device. The device will calculate AC voltage and current used in the logic diagrams to control power factor correction. Microcontroller operations will be performed by the SELogic processor in the device which will communicate with the expansion card added to the SEL-2411. The analog input cards used to read the AC voltage and current will refresh the data to the processor every 100 ms (as shown in Table VI) sampling the data at a rate of 4 times per cycle [2].

Controlling the power factor will require the use of capacitors connected in parallel with the inductive loads on power transmission systems. The amount of power factor correction will be limited to the size of the capacitor bank which the device is controlling. To find the amount of capacitance needed for the load on the system, the controller must calculate the impedance of load. Once the impedance of the system is computed, the controller will compute the capacitance needed to correct the system power factor.

Testing the AC system monitoring device proposed solution will be conducted using equipment available in the ECE power lab to measure the AC voltage, current, and active power. AC voltage and current monitoring will be compared to the voltage and current measured with the ECE power lab equipment.

Monitored power factor will be compared to the power factor computed using the voltage, current, and active power readings from the lab equipment. Depending on the results from the solution testing, the effectiveness of alternative solutions may be investigated. (Alternative solutions for the project are provided in Appendix D.) A more detailed solution testing list is provided in Appendix C.

C. Economic Analysis

The SEL-2411 will be provided by Schweitzer Engineering Laboratories to be used for the AC system monitoring. These controllers are at a relatively premium price as they are industrial grade and are designed to work in the harsh environments frequently found in industrial locations. Costs are covered by SEL through their donation for the project as shown in Table VII. Wires, testing equipment, and high-voltage capacitors for the AC monitoring device will be obtained from the supplies currently available in the ECE power lab or Caterpillar Inc.. The cost of SEL will result in no cost to the proposed solution for the main components needed for the project.

TABLE VII: PROPOSED BILL OF MATERIALS FOR AC SYSTEM MONITOR DEVICE

Parts	Quantity	Price
SEL-2411 Automation Controller (Base Price)	1	$ 950
SEL-2411 Expansion I/O Cards	5	$ 500
615V 600uF capacitors	2	$ 100
	Total =	$1550

D. Project Timeline

The AC system monitoring device timeline for the project is presented in the Appendix E with a more detailed timeline in Appendix F. The time estimation has been based on 21 hours a week dedicated to the development of the project. Dates are determined by the order and key deliverables required to finish the project. To determine the critical path for the project, the formulated program evaluation review technique chart was used, (see Appendix G) which concluded that the majority of the project is going to be time critical as each stage of the project requires previous stages to continue to the next development activity. Project activities will need to conform to the scheduled dates if the project is to be completed on time.

E. Societal and Environmental Impacts

The AC monitoring device is to be used in applications to monitor system voltages and currents. Upgrading existing older technologies that are commonly part of the power transmission grid would provide more reliable power delivery and power factor correction to the application of power transmission. Power factor correction is particularly useful in making power delivery more efficient, resulting in lower power losses during transmission. The older electro-mechanical systems for AC monitoring require periodic maintenance to prevent operational failures. Operational failures can even result in equipment catching fire, leaving downed power lines energized, and putting repair crews in harm’s way. The AC system monitoring device would facilitate economic growth through the increase in reliability of power transmission.

III. CONCLUSIONS

The AC system monitoring device will be used in the monitoring of AC power systems. Functional outputs of the device will include displayed voltage, current, and power factor. The device will also provide power factor control functionality. The system must maintain high safety standards to provide safe implementation and operation of this device. The AC system monitoring device will use a SEL-2411 automation controller with the ability to control all functions for the device. This device will use add-on cards to process the AC voltage and current required by the programmable logic functions to calculate and control the power factor of the AC system. The generous donation of the SEL-2411 automation controller from Schweitzer Engineering Laboratories significantly reduced project implementation costs.

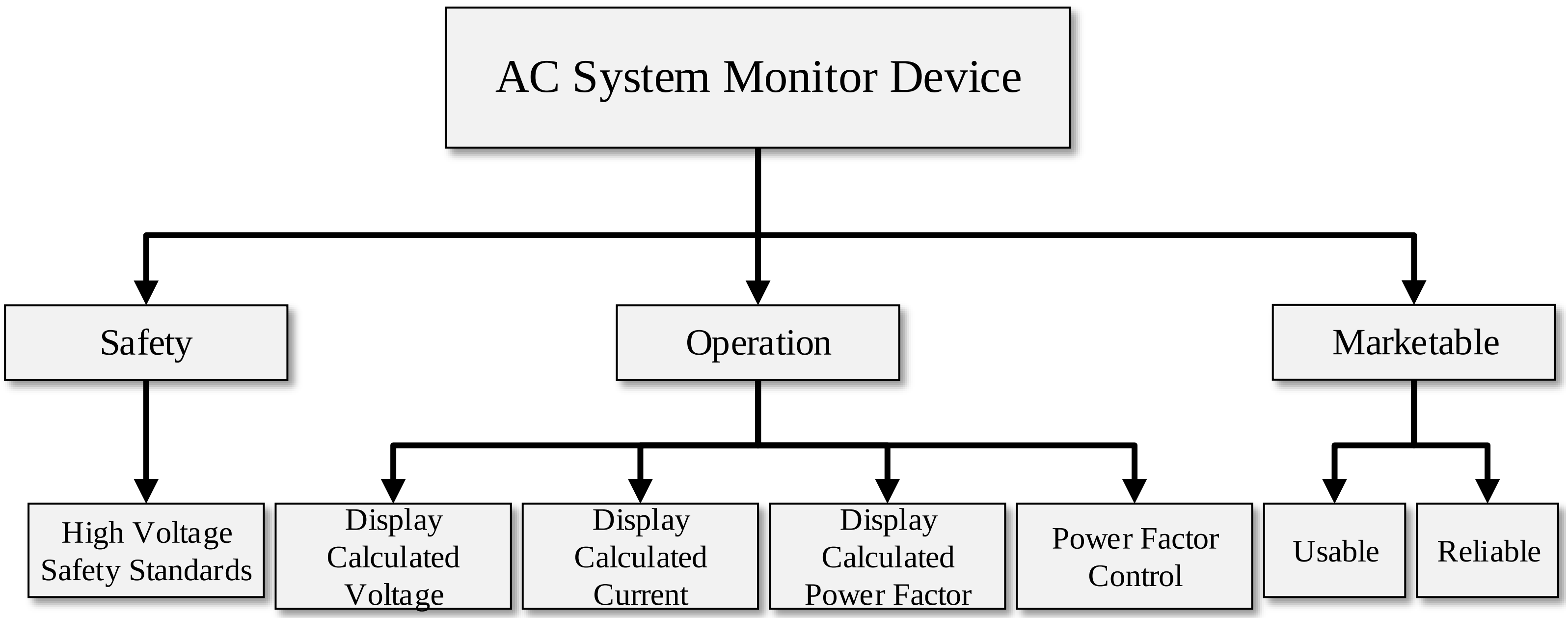
The key milestones for the project determined the proposed preliminary schedule for the AC system monitoring device to ensure it would be completed in the spring semester of 2016. Evaluating the preliminary schedule determined the critical path for the project required that the majority of the project relied on other development activities to be finished before moving forward with the project. The AC system monitoring and power factor correction device will provide a more reliable and more efficient AC power distribution system.

REFERENCES

[1] National Institute of Technology. (2008, Oct. 1). *EEEL Safety Rules for Moderate and High Voltages* [Online]. Available: http://www.nist.gov/el/isd/mmc/upload/high_voltage_rules_revised.pdf

[2] Schweitzer Engineering Laboratories. (2015, Jun. 24). *Product Literature, SEL-2411 Data Sheets* [Online]. Available: https://www.selinc.com/WorkArea/DownloadAsset.aspx?id=1184

APPENDIX A – COMBINED OBJECTIVE TREE



APPENDIX B – NONFUNCTIONAL REQUIREMENT METRICS

TABLE VIII. RELIABLIBILITY PERFORMANCE INDICATOR OF AC SYSTEM MONITORING DEVICE

Performance Index	
MTBF (Hours)	Points
100 >	10
75-99	7.5
50-74	5
25-49	2.5
< 23	0

TABLE IX. USABILITY PERFORMANCE INDICATOR OF AC SYSTEM MONITORING DEVICE

User Satisfaction	Points
User is very satisfied with operating the device	10
User is satisfied with mostly operating the device	7.5
User is neutral with operating the device	5
User is not satisfied with operating the device	2.5
User is very not satisfied with operating the device	0

TABLE X. PAIRWISE COMPARISION CHART FOR THE AC SYSTEM MONITORING DEVICE

Goal	Usability	Reliable	Score
Usability		0.5	0.5
Reliable	0.5		0.5

APPENDIX C – DETAILED TESTING PROCEDURES

1) Testing AC voltage monitoring

Testing the AC system monitoring device will require the use of volt meters from ECE power lab. The volt meter will be connected in parallel with the AC voltage monitoring inputs. The output of the volt meter then will be compare to the outputs of the AC system monitoring device to confirm operation within the functional specifications for AC voltage monitoring listed in Table V.

2) Testing AC current monitoring

Testing the AC system monitoring device will use current meters available in the ECE power lab. The current meters will be connected in series with the AC current monitoring cables from the device. The line would then drive a load to provide a current in the line to monitor. Once a current exists in the line, the AC system monitoring device current value will be compared with the ECE current meter to confirm operation within the functional specifications for AC current monitoring listed in Table V.

3) Testing AC power factor calculation

Testing the AC power factor calculation will only take place when the AC voltage and current monitoring have been successfully tested. This is required because the calculation of the AC power factor requires the values for AC voltage and current. For calculation of the power factor the device must successfully measure the phase angle between the voltage and current. The power factor calculation will be tested by using an oscilloscope to measure the phase shift with current and voltage monitoring probes. The power factor will also be computed using a wattmeter and the values of voltage and current obtained with standard laboratory meters. The power factor result obtained from the monitoring device will then be compared with the power factor calculated with the laboratory oscilloscope and meters to confirm the device operates within the functional specifications for AC power factor calculation listed in Table V.

4) Testing AC power factor correction

Testing the AC power factor correction will only take place when the AC power factor calculation has been successfully tested. The device will be connected to a capacitor bank to control the inductive load power factor. An inductor connected in series with a resistance will be used to provide an inductive load to test the system. The device will correct the power factor of the AC system by controlling solid-state switches to place the proper capacitance in parallel with the inductive load. The corrected power factor calculation will be tested by using an oscilloscope to measure the phase shift with current and voltage monitoring probes. The corrected power factor will also be computed using a wattmeter and the values of voltage and current obtained with standard laboratory meters. The corrected power factor results will then be compared to the functional requirements for the AC power factor correction listed in Table V.

APPENDIX D – ALTERNATIVE SOLUTION

Parts List and Cost

The alternative solution for the AC system monitoring device will use an ATmega128A development board as the controller for the device. Signal conditioning implementeed with a transformer, a full-wave bridge rectifier, and a low pass filter will be used to convert the available AC voltage to a stable DC voltage to provide a power supply for the device. The current monitoring will use a Hall Effect sensor, eliminating any direct connection to the input current. The microcontroller will use a predetermined look-up table to increase the computational processing rate. The device will provide programmed output logic using the same microcontroller to control solid-state power relays for switching capacitors in and out of the circuit to provide power factor correction. Using the same microcontroller for both functions will maintain the reliability objective for the AC system monitoring device. The microcontroller would be the ATmega128A development board available in the ECE laboratories.

TABLE XI: PROPOSED SOLUTION PARTS LIST FOR AC SYSTEM MONITOR

Part	Quantity	Price
Atmel ATmega128A development board	1	$ 58.79
HITACHI HD44780U LCD display	1	$ 14.99
117vac to 24vac Power Transformer	2	$ 47.90
12A 600V full wave bridge rectifier	2	$ 14.80
615V 600uF capacitors	2	$ 100.00
Hall effect sensor (SparkFun ACS712)	1	$ 7.95
120V 120A Power-transistor (IPP041N12N3 G)	5	$ 13.30
	Total =	$ 257.73

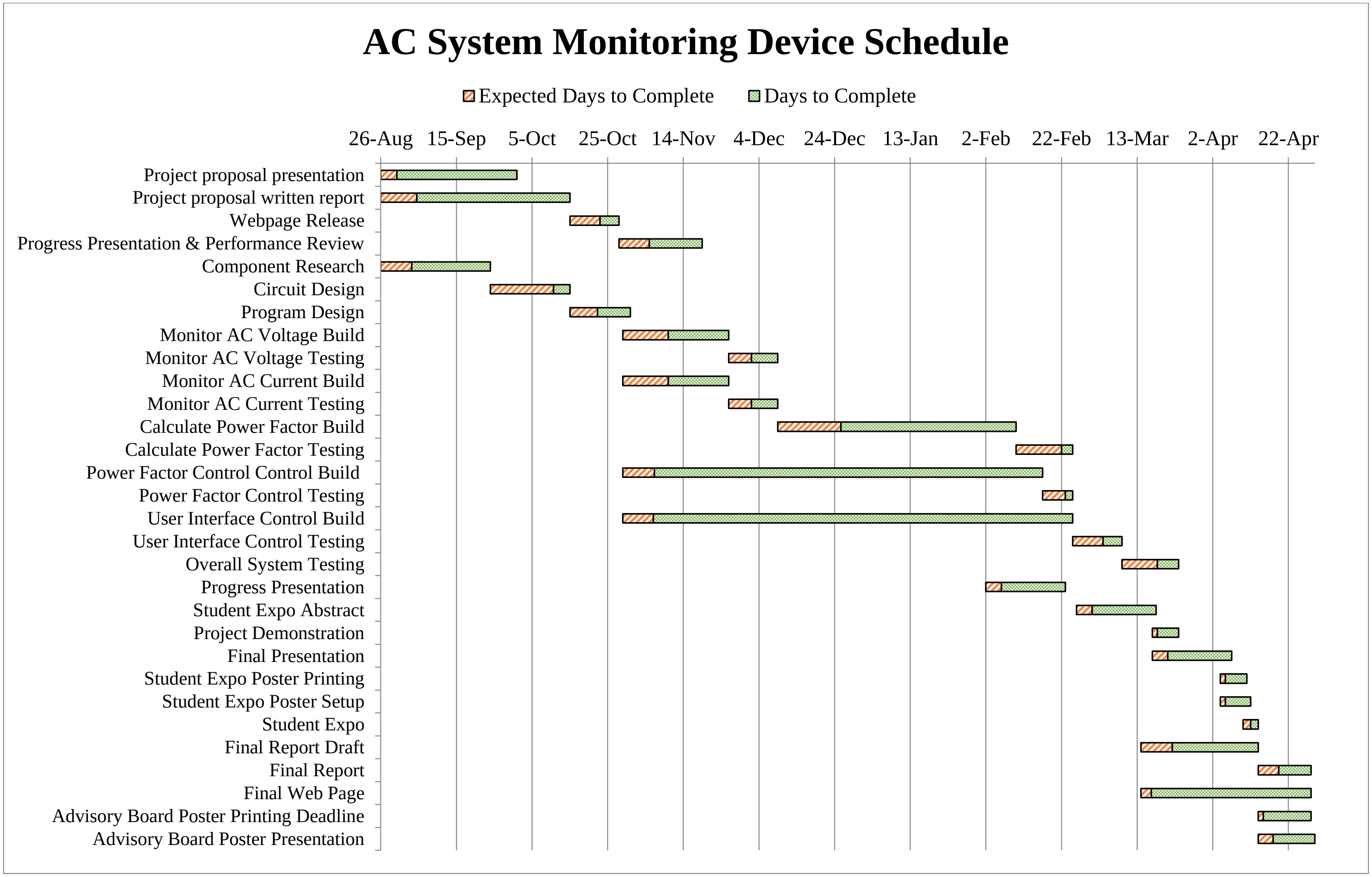
Alternative Solution Testing

Testing the AC system monitoring device proposed solution will be conducted using the equipment from ECE power lab to measure voltage and current. AC voltage monitoring and current monitoring will be compare to the voltage and current measuring equipment. Power factor computations from the AC system monitoring device will be compared with the power factor computed with the voltage, current, and wattmeter readings obtained with the laboratory equipment. The results from the alternative solution testing will be used to evaluate the alternative solution effectiveness.

APPENDIX E – KEY MILESTONES SCHEDULE

Activity	Start	End
Project proposal presentation	08/26/15	10/01/15
Project proposal written report	08/26/15	10/15/15
Webpage Release	10/15/15	10/28/15
Progress Presentation & Performance Review	10/28/15	11/19/15
Component Research	08/26/15	09/24/15
Circuit Design	09/24/15	10/15/15
Program Design	10/15/15	10/31/15
Monitor AC Voltage Build	10/29/15	11/26/15
Monitor AC Voltage Testing	11/26/15	12/09/15
Monitor AC Current Build	10/29/15	11/26/15
Monitor AC Current Testing	11/26/15	12/09/15
Calculate Power Factor Build	12/09/15	02/10/16
Calculate Power Factor Testing	02/10/16	02/25/16
Programmable Logic Control Build	10/29/15	02/17/16
Programmable Logic Control Testing	02/17/16	02/25/16
User Interface Control Build	10/29/15	02/25/16
User Interface Control Testing	02/25/16	03/09/16
Overall System Testing	03/09/16	03/24/16
Progress Presentation	02/02/16	02/23/16
Student Expo Abstract	02/26/16	03/18/16
Project Demonstration	03/17/16	03/24/16
Final Presentation	03/17/16	04/07/16
Student Expo Poster Printing	04/04/16	04/11/16
Student Expo Poster Setup	04/04/16	04/12/16
Student Expo	04/10/16	04/14/16
Final Report Draft	03/14/16	04/14/16
Final Report	04/14/16	04/28/16
Final Web Page	03/14/16	04/28/16
Advisory Board Poster Printing Deadline	04/14/16	04/28/16
Advisory Board Poster Presentation	04/14/16	04/29/16

APPENDIX F – DETAILED SCHEDULE



APPENDIX G – PERT CHART

Program Evaluation Review Technique (PERT) Chart							Legend	
							Critical Path	Non-Critical
Order	Activities	Days to Complete	Forward Pass		Backwards Pass		Free Float (Days)
			Early Start	Early Finish	Late Start	Late Finish	
1	Component Research	8.2	0.0	8.2	4.0	12.2	0.0
2	Circuit Design	16.7	8.2	24.9	12.2	28.9	0.0
3	Program Design	7.3	24.9	32.2	28.9	36.2	0.0
4	Monitor AC Voltage Build	12.0	32.2	44.2	36.2	48.2	0.0
5	Monitor AC Voltage Testing	6.0	44.2	50.2	48.2	54.2	4.0
4	Monitor AC Current Build	16.0	32.2	48.2	32.2	48.2	0.0
5	Monitor AC Current Testing	6.0	48.2	54.2	48.2	54.2	0.0
6	Calculate Power Factor Build	16.7	54.2	70.9	54.2	70.9	0.0
7	Calculate Power Factor Testing	12.0	70.9	82.9	70.9	82.9	0.0
8	Power Factor Control Build	8.3	82.9	91.2	82.9	91.2	0.0
9	Power Factor Control Testing	6.0	91.2	97.2	91.2	97.2	0.0
4	User Interface Control Build	8.1	32.2	40.3	81.1	89.2	0.0
5	User Interface Control Testing	8.0	40.3	48.3	89.2	97.2	48.9
10	Overall System Testing	9.3	97.2	106.6	97.2	106.6	0.0