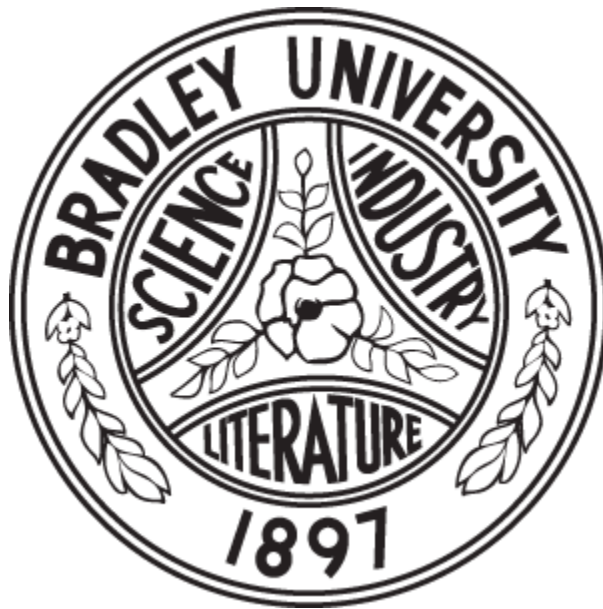


AC System Monitoring Device

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ABSTRACT

This document covers the design of a device to monitor an alternating current (AC) system. The device will monitor AC voltage, AC current, and calculate the power factor of the AC system it is monitoring. The system will use a Programmable Logic Controller (PLC) to perform the various device functions. Details related to the components used in the system design and the software used by the PLC to implement the logic and output functions for the system are addressed. Experimental results used to verify the operation of the final system design are also discussed. Finally, details on the controller programming are presented to provide fundamental operational knowledge and highlight additional features to permit expanding its use in future senior projects.

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I. INTRODUCTION

The alternating current (AC) system monitoring device is used to monitor voltages on AC power systems. The controllers used in the monitoring system are known as programmable logic controllers (PLCs), and are used in industry for power distribution control and system automation. The AC system monitoring device uses 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.

This project report will cover the design of a device to monitor an AC power system and provide power factor correction. Specifically, the objective of this project was to build a system that will monitor AC voltage, AC current, and power factor. The system also includes power factor correction by adding capacitors in parallel with inductive loads as needed.

The AC system monitoring device was designed through the process of investigating various methods available to perform the intended functions for the device. The possible solutions found to implement the device were used to propose a primary design solution and an alternative design solution for the project. The proposed solution was based on 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.

II. SYSTEM DESCRIPTION

A. Project Specifications

A list of functions were identified from the problem statement and identified in Table I. Each of the functions include secondary functions that are italicized. The device will monitor both AC voltage and current, calculate the power factor, and then activate relays to correct the power factor if necessary. More detailed specifications of the functional requirements are identified in Table II.

TABLE I. LIST OF AC SYSTEM MONITORING DEVICE FUNCTIONAL REQUIREMENTS

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

TABLE II. LIST OF AC SYSTEM MONITORING DEVICE FUNCTION
SPECIFICATIONS

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

B. System Circuit Design

i. SEL-2411 programmable automation controller design

The Schweitzer Engineering Laboratories controller was used in the AC system monitor to provide a customizable logic controller with the ability to monitor AC voltage and AC current. The specifications in Table III of the device meet or exceed the specifications that are listed in Table II. Other features of the device making it suitable for the application is a front display with control buttons, and the fact that the controller has been widely tested for reliability.

TABLE III: SEL-2411 AUTOMATION CONTROLLER SPECIFICATIONS ^[1]

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

ii. RL load circuit design

The resistive and inductive (RL) load for the circuit to be used in the testing of the device was selected to provide an inductive load that would require power factor correction. In the initial design the problems associated with rotating motors and prony brake systems available in the ECE laboratories would be avoided. The prony brakes used to load the AC motors in the ECE laboratories are intended to be run only for short periods of time. The limited operating time was considered a serious issue in the original plans due to the necessity of operating the system for extended times during testing. The first design of the RL circuit used a three-phase transformer as the inductor with a 44Ω rheostat in series. Upon closer investigation with an oscilloscope it was discovered that the current through the circuit was a distorted waveform as shown in figure 1. The need for a more linear response required the design to use EXEL loading reactors as the inductance. The RL load consisting of the loading reactors provided a linear response on the current waveform as shown in figure 2. The circuit diagram of the RL circuit is shown in figure 4.

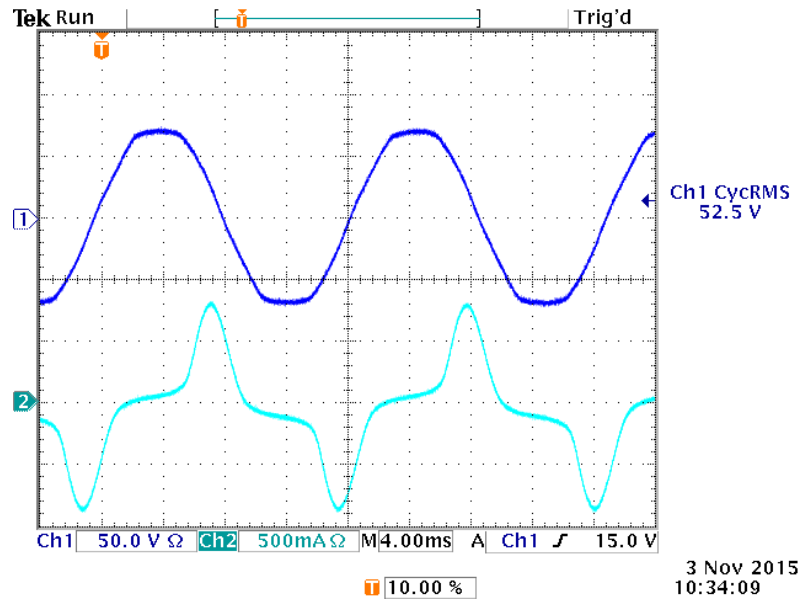


Fig. 1. Nonlinear current waveform introduced by the transformer coil initially used in the RL circuit design

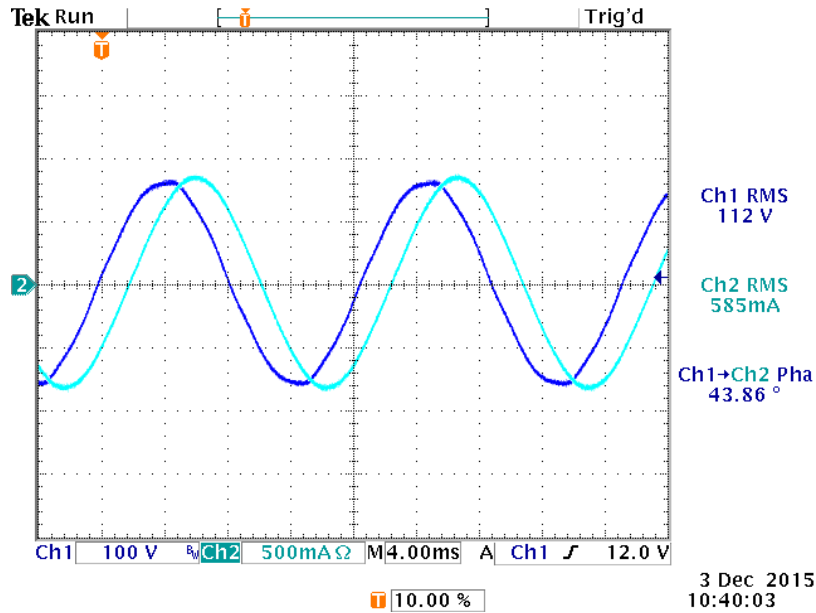


Fig. 2. Linear current waveform of the EXEL loading reactor in the RL circuit design

iii. Power factor correction design

The power factor correction portion of the system utilized capacitor banks connected to relays to switch them off and on in parallel with the RL load. The capacitor switching was controlled by the SEL-2411 programmable automation controller with outputs to the relays. Sizing of the capacitor banks requires calculation of the current power factor and load of the circuit being used. To find the capacitance required, the existing imaginary power is calculated using equation 1 to determine the inductive reactive power to be negated by the power factor correction. The corrective component

reactive power will be equal and opposite to the inductive component reactive power as shown in equation 2. The imaginary component of power will then be used to solve for the needed capacitive impedance using equation 3 (which simplifies to equation 4).

$$Q = V_s I_s \sin \theta \quad (1)$$

$$Q_{cor} = -Q \quad (2)$$

$$C_{cor} = \frac{1}{2\pi f X_{cor}} \quad (3)$$

$$C_{cor} = \frac{Q_{cor}}{2\pi f V_s^2} \quad (4)$$

iv. *Harmonic filter design*

Further investigation of the power factor correction system led to the discovery that current distortion was introduced when the capacitor banks were used for power factor correction. The Fast Fourier Transform (FFT) option available on the laboratory oscilloscopes was used to determine harmonics of the fundamental 60Hz present in the distorted current waveform. The most prominent frequencies were the 7th and the 11th harmonics shown in figure 3. Excessive amounts of current distortion introduced to the AC system would not be ideal as it could result in stability issues related to other equipment used on the line. Solutions used in industry are to use harmonic filters to provide a lower impedance at a tuned frequency so the harmonics can be filtered out of the system. The design selected for the harmonic filter was an RLC harmonic filter tuned to the 7th harmonic. The final design of the RLC harmonic filter is shown in figure 4. The resonate frequency of RLC circuit was tuned to the 7th harmonic of the system using available capacitors of 10.9μF. The required inductance was computed using equations 5 and 6 shown below. After computing the required inductance, eight 1.6mH inductors were connected in series to obtain an equivalent inductance of approximately 13.19mH. The resistor in the harmonic filter controls the bandwidth of the filter. Solving for the quality factor of the RLC circuit permits calculating the pass band for the filter as shown in equation 7.

$$\omega = \sqrt{\frac{1}{LC}} \Rightarrow L = \frac{1}{\omega^2 C} \text{ with } \omega = 2\pi f_0 h = 2\pi(60)(7) = 2639 \frac{rad}{s} \quad (5)$$

$$L = \frac{1}{(2639)^2 10.9 \times 10^{-6}} = 13.19mH \quad (6)$$

$$Q = \frac{\sqrt{\frac{L}{C}}}{R} \rightarrow \delta = \pm \frac{1}{2} Q = \pm \frac{1}{2} \cdot \frac{\sqrt{\frac{0.01319H}{10.9 \times 10^{-6}F}}}{44\Omega} = \pm 39.5\% \rightarrow (252Hz, 588Hz) \quad (7)$$

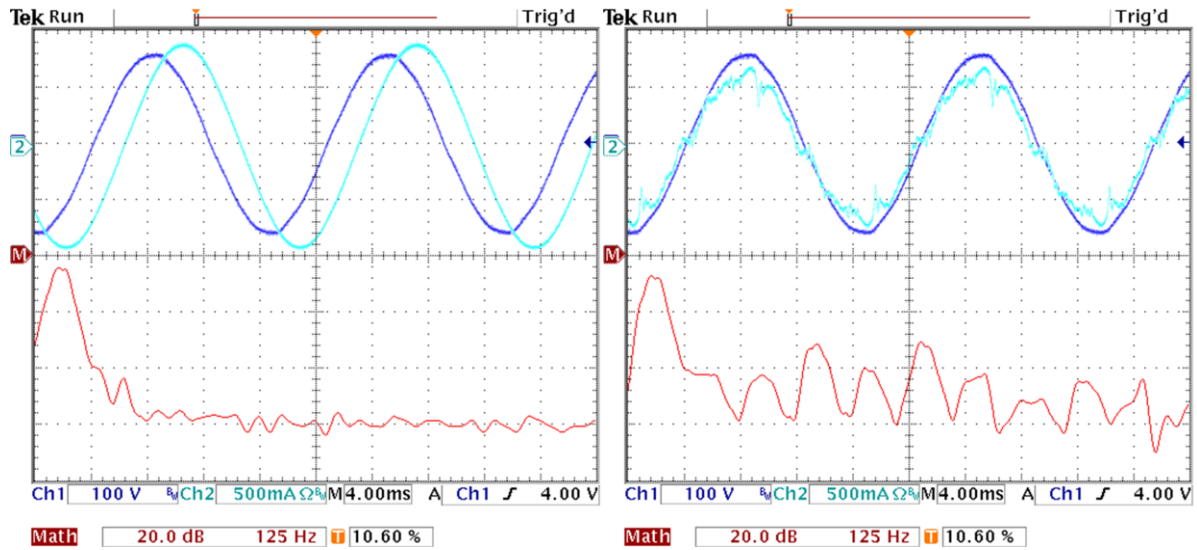


Fig. 3. Left plot is with no power factor correction. Right plot exhibits current distortion introduced by the power factor correction of the capacitor bank

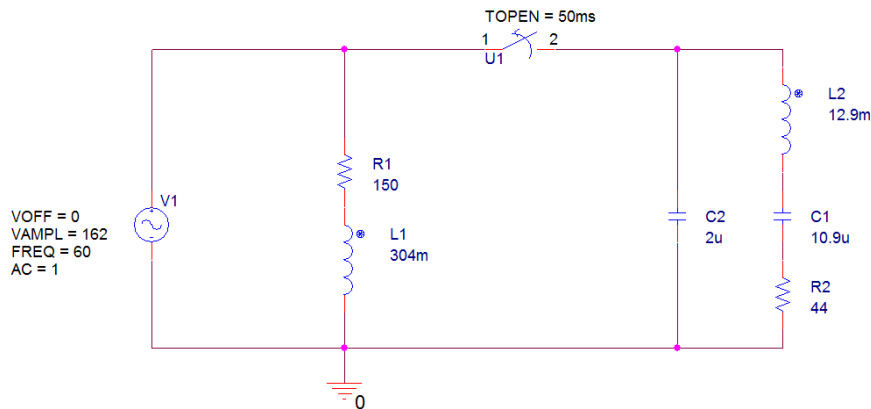


Fig. 4. Harmonic filter design to the right of the switch with the RL load to the left

v. 3-phase motor power factor correction diagram

Ultimately the system was redesigned for 3-phase AC motor power factor correction to investigate larger scale power factor correction with motor applications. The system used a DC motor to control of the load applied to the 3-phase AC motor. The DC motor required rated field coil current available at full DC line voltage of 115VDC. A 44 ohm rheostat with a current rating of 3.1A was used to control the load on the DC generator connected to the 3-phase AC motor. As the DC generator load resistance was reduced, higher torque was applied to the 3-phase AC motor. Conversely, decreasing the resistance would then decrease the torque applied to the 3-phase AC motor. Increasing the torque on the 3-phase AC motor increases the power factor of the motor, and reducing the torque decreases the power factor of the AC motor. Power factor correction was performed by implementing 3-phase capacitor banks to ensure the power factor correction was balanced. The combination of the 3-phase AC motor and the DC generator permitted testing the

power factor correction system at higher current and power levels over extended periods of operation.

III. EQUIPMENT LIST

A. *SEL-2411 Automation Controller*

The SEL-2411 programmable automation controller is also referred to as a programmable logic controller in industry. Programmable logic controllers allow the user to define logic to be easily programmed into the device for use in a particular application. This controller has the ability to customize the inputs and outputs for each specific application. For this application the SEL-2411 used 3-phase power cards that can sample 3-phase AC voltages and AC currents. The system also included electro-mechanical relays used to switch the capacitor banks for power factor correction.



Fig. 5. SEL-2411 programmable automation controller with the first successful program

B. *OMRON MKS2PIN Relays*

The OMRON relays are 2-switch relays with a single coil to control both switches. This relay was used to switch the capacitors to control the power factor. The voltage rating for the relay is 220V AC.



Fig. 6. Two OMRON MKS2PIN relays used to switch the capacitor banks

C. EXEL Loading Reactor

The EXEL loading reactor was used in the RL load circuit design to provide the inductive load used for power factor correction testing. The EXEL loading reactor was measured with a Hewlett/Packard LCR meter and was found to have an inductance of 145mH and an equivalent series resistance of 17Ω at a test frequency of 100Hz.



Fig. 7. EXEL Loading reactor to the right connected to the Hewlett/Packard LCR Meter on the left

D. Capacitor Banks

The capacitor banks are used to correct the power factor of the AC system. Most AC systems in practice will be inductive since most loads are 3-phase AC motors. To correct a lagging current system from the inductive effects of the AC motors, capacitors are added in parallel with the AC motors to add a reactance to the system that provides a current that leads the voltage in each phase. Connecting this to the circuit increases the power factor of the system, thereby reducing the apparent power drawn from the system to making it more efficient. The capacitor banks available in the ECE laboratories have the ability to be varied from $1.6\mu\text{F}$ to $40\mu\text{F}$ by connecting the 5 discrete capacitors in various series and parallel combinations.

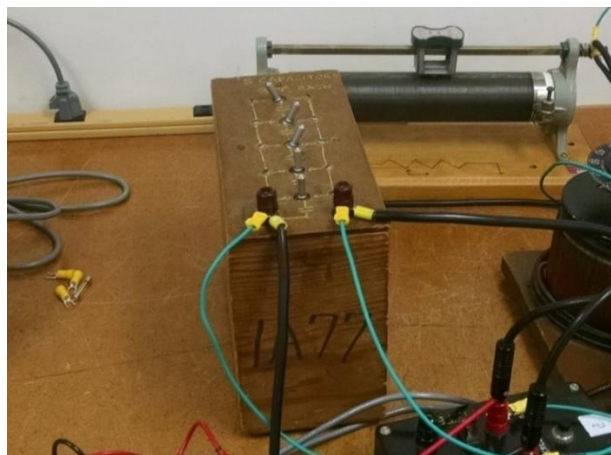


Fig. 8. - Reconfigurable capacitor bank consisting of 5 discrete $8\mu\text{F}$ capacitors

E. Harmonic Filter

The harmonic filter is an RLC circuit tuned to the 7th harmonic of the 60Hz AC system. The harmonic filter was design to remove harmonic distortion due to the application of the power factor correction components. Figure 9 shows the harmonic filter built with eight 1.6mH inductors in series, two 5 μ F capacitor in parallel, and a single 2 μ F capacitor in parallel with the RLC harmonic filter. The circuit diagram for the harmonic filter is shown in figure 4.

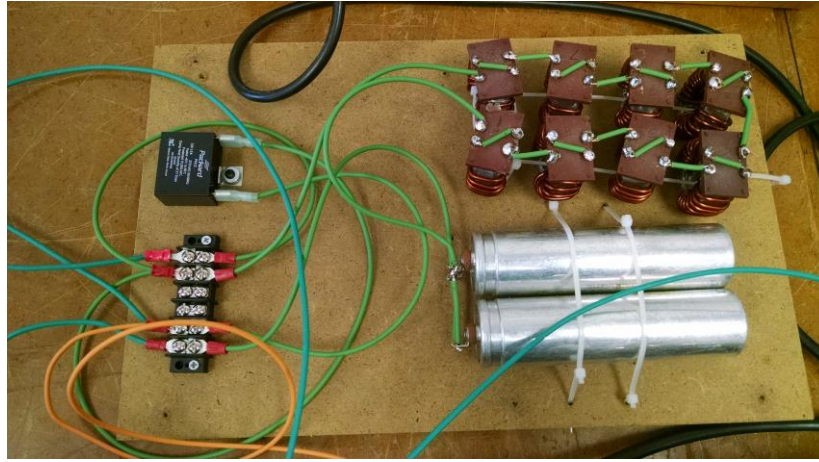


Fig. 9. Band-reject filter tuned to the 7th harmonic

F. Hampden Type WRM-100 Three Phase Motor

The Hampden Type WRM-100 three-phase Motor is rated at 1.4 A, 220 VAC, and 1/3 HP at 1725 RPM. As shown in figure 10, the attached Hampden DC motor was used to provide a stable load to vary the power factor of the ac motor during operation.



Fig. 10. Hampden 3-phase AC motor on the left. Motor platform with a Reliance DC motor on the right.

G. Hampden Type DCM-100 DC Motor

The Hampden DC motor is used to provide a load to the AC motor, as shown in figure 10. The motor is rated at 1/3 HP, 115VDC, 3.0Amps armature current, and 0.4Amps field current. The load is varied by adding resistance across the armature of the DC motor while it is configured as a DC generator. Using a 44 ohm rheostat as the generator load provides a generator torque applied to the 3-phase AC motor. Current levels through the rheostat had to be monitored carefully since exceeding the current ratings of the rheostats can cause overheating and destruction of the resistive element. As the resistance is reduced on the rheostat the power factor of the AC motor increased, and as the resistance increased the power factor decreased. The control of the 3-phase AC motor power factor obtained by simply altering the DC generator load resistance provided a very effective means of testing the controller's ability to correct the power factor of the AC system.

IV. SOFTWARE

A. Logic control

The logic control for the SEL-2411 programmable automation controller utilizes SEL's own proprietary software to program the device. The software to be used in the programming of the device is called ACSELERATOR QuickSet[®], and can be downloaded and installed with no license fee. The software allows users to simply program logic points to produce personal logic schemes. One of the key tools used was the graphical logic designer to convert a visual logic scheme to the logic point registers of the controller.

The logic design implemented incorporated both manual and automated functions. Manual function allows the user to manually control the switching of the relay, while the automated function would automatically turn on the relay for the power factor correction when the power factor was less than 0.8 lagging. The automated function would also turn off the power factor correction if it went past a 0.8 leading power factor. The logic uses the power factor values calculated in the power card of the controller and provides the AC current phase angles which are used in the automation logic. The logic diagram is shown in figure 11.

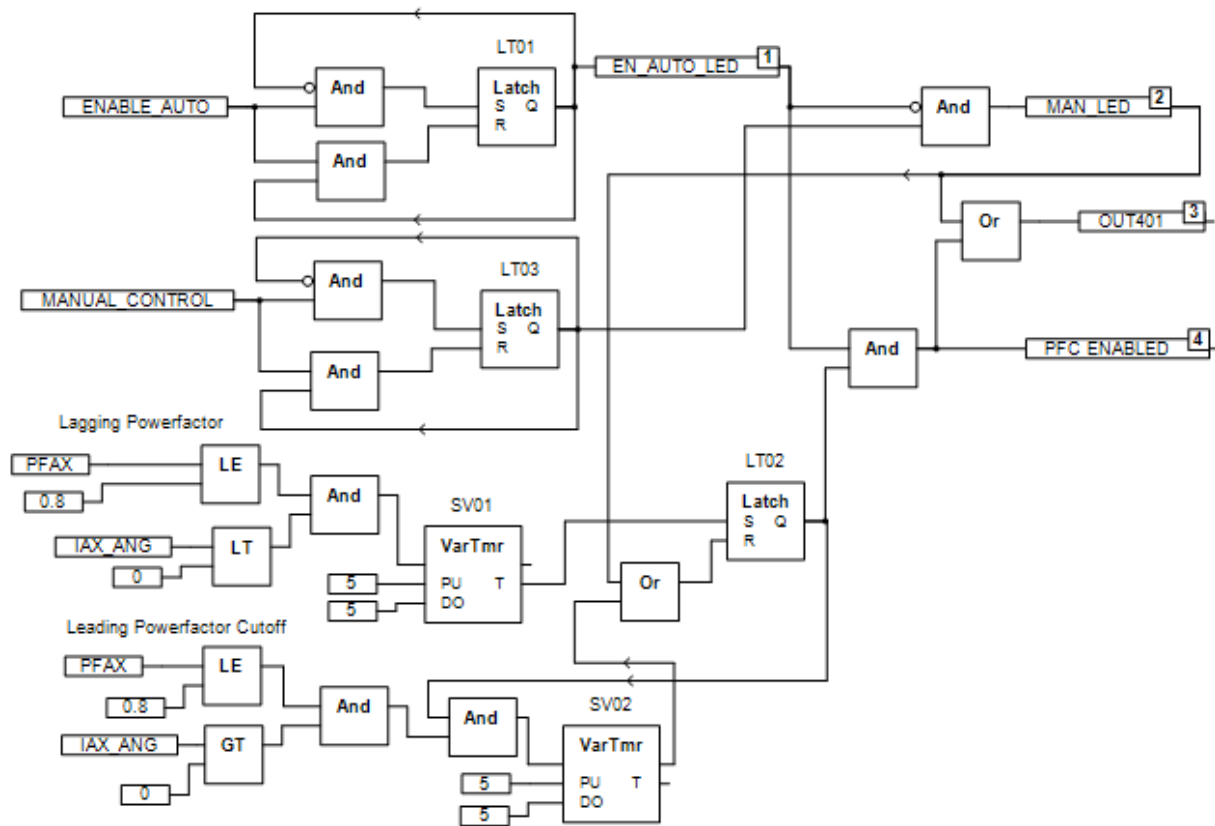


Fig. 11. Logic diagram for the SEL-2411 for control of the capacitor bank for power factor correction

B. Front Display

The front display of the SEL-2411 programmable automation controller can be programmed to display information to the user. The display is a two line display and only allows one data parameter per line. To have more data displayed to the user, the SEL-2411 cycles through display points. The display for this application displayed ac voltage, ac current, current phase angle, and power factor. The display shows the ac voltage and current on the screen first, then switches to the phase angle and power factor. (The timing of the display transitions for the SEL-2411 could not be changed via the software.) The software also can be used to program how many digits before and after the decimal point are displayed. As shown in figure 12, for each data variable to be displayed to the screen, the variable is placed first, then a comma with quotations around the content to be displayed. The decimal padding is then placed within the brackets with the first number representing the number to pad before the decimal and the second number after the decimal. The scale of the units can be changed by adding a comma within the brackets with a scaler to change to the desired units. This can be seen on the display point 2 (DP02) shown in figure 12.

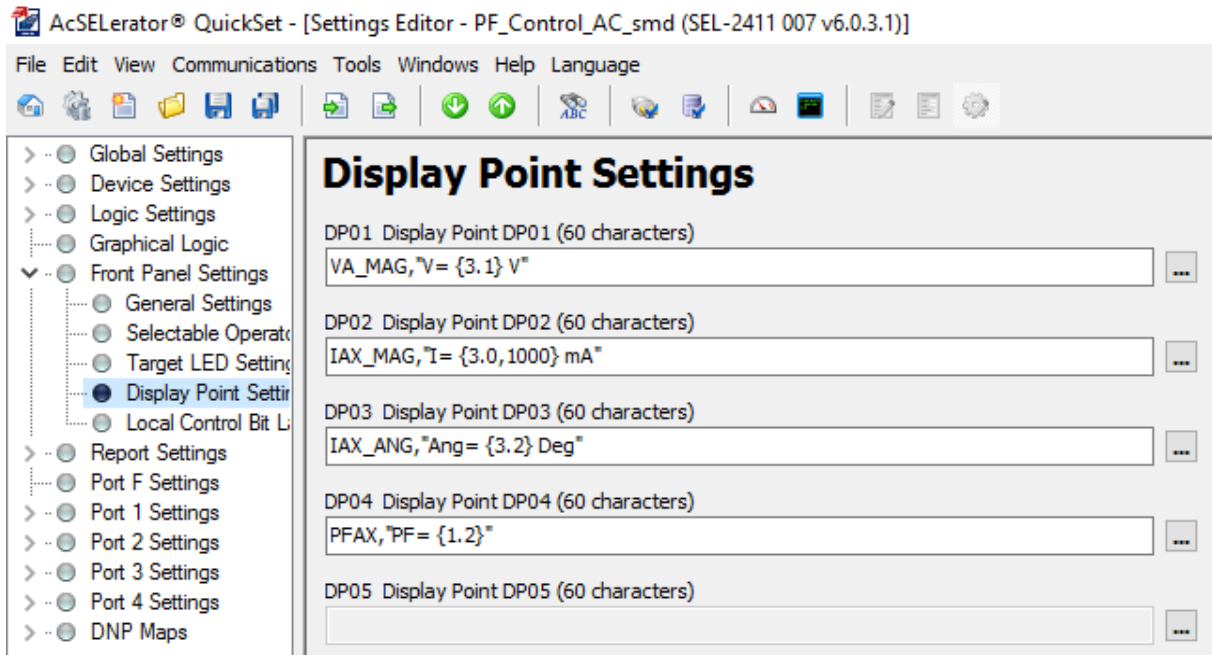


Fig. 12. ACSELERATOR QuickSet® software control of display points settings for the front screen

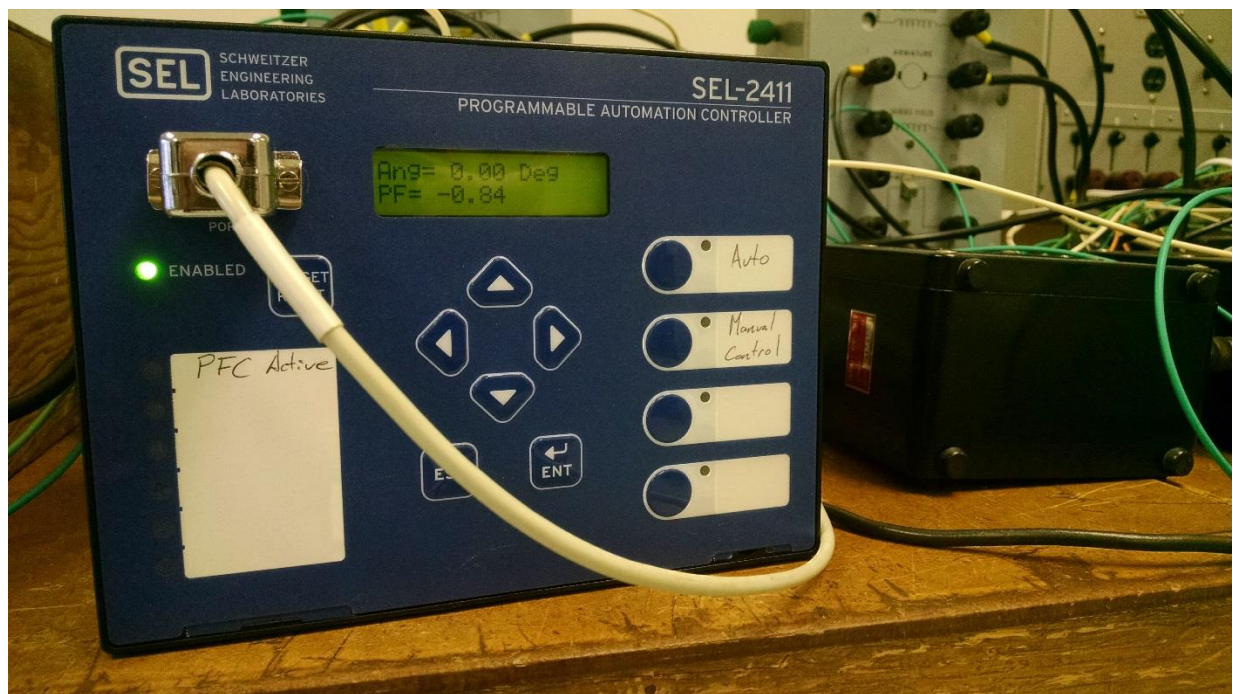


Fig. 13. SEL-2411 Programmable Automation Controller showing phase angle and power factor

V. RESULTS

A. Monitoring AC System

The monitoring of the AC system was performed by the SEL-2411 programmable automation controller. The specifications of the SEL-2411 are listed in table 2. To test the system specifications provided by the manufacturer, tests were conducted to verify the operations of the controller. This test could only be performed using the analog meters available in the ECE power laboratory with meter accuracies of $\pm 0.5\%$. These meters have higher tolerances than the listed voltage accuracy of $\pm 0.08\%$ for the SEL-2411. Therefore, the tests were conducted to confirm the listed SEL-2411 voltage accuracy is within the worst case scenarios measurable in the ECE laboratories. The specification sheet for the SEL-2411 controller indicates it is specified for the range of 100Vac to 250Vac. The test was performed with a line to line setup from 100Vac to 210Vac, and the average voltage error was -0.15% . The worst case for the voltage to be in specification with the available equipment would be $\pm 0.58\%$. Because -0.15% is less extreme than the $\pm 0.58\%$ the data suggests the SEL-2411 is operating within the specifications the manufacture stated. The data tables of the voltage monitoring test results are available in appendix B.

Testing of the current utilized the RL load to change the load current of the circuit. This test was performed while using a $\pm 0.5\%$ AC ammeter using the lower voltages from 20Vac to 110Vac. The current range tested was from 160mA to 833mA, and the final result of the average current reading error was 0.39% . This is reasonable number as the worst case for testing would be $\pm 1\%$ as the specified current reading error for the SEL-2411 is $\pm 0.5\%$. The data tables of the current monitoring test results are available in appendix B.

The testing of the power factor was performed using a power meter and current meter to calculate the power factor to be compared to the SEL-2411 power factor calculation. Equation 7 was used to calculate the power factor of the load to be compared to the controller. The load was controlled by the changing the resistance of the rheostat for the RL load. Changing the resistance in the RL load would change the power factor of the system. The final result of the testing shows that there is correction to 0.9994 for the power factor on the SEL-2411. The stated error for the power factor calculation is $\pm 1\%$, and the tests show the reading of the power factor to be -0.0982% which is within the specification for the SEL-2411. The data tables of the power factor test results are available in appendix B.

$$\text{Power Factor} = \frac{P}{V \times I} \quad (7)$$

B. Power Factor Correction

The power factor correction utilizes the SEL-2411 programmable automation controller to control relays to switch the capacitors to perform power factor correction for the load. The first inductive load used an RL circuit to provide the inductive load to be power factor corrected as shown in figure 2. Using the calculated capacitance, the system would switch the capacitor bank to the load. The resulting waveform with the power factor correction is shown in figure 14. With the power factor correction the current phase angle is adjusted to be nearly identical to the voltage phase angle. The shifting of the current waveform reduces the apparent power of the system by also reducing the required current. The apparent power for

the non-power factor corrected load was 68.9 Watts, and for the power factor corrected load the apparent power was 46.8 Watts, or a 22.1 Watt reduction in the power usage.

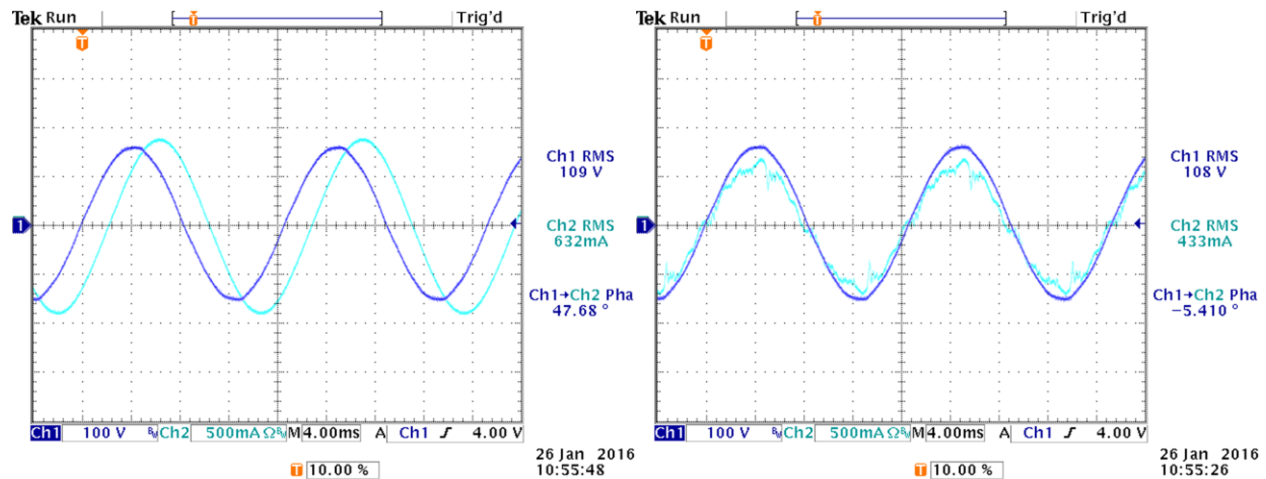


Fig. 14. Power factor correction on the RL load with capacitor bank

The testing of the power factor correction did reveal an issue with the power factor correction. When the capacitance is increase in the system the distortion of the current waveform was present when using the power factor correction. This led to the additional investigations associated with the current harmonic distortion mitigation.

Testing of the power factor correction then was expanded to a three phase motor system. This system was selected to see effects of power factor correction harmonics introduced into a three-phase system. As shown in figure 15 the harmonics still exist with the power factor correction. The power usage of the non-power factor corrected motor load was calculated to be 124 watts. When the capacitor bank was used for power factor correction, the power consumption was reduced to 85 watts, or a 39 watt reduction in the power consumption of the circuit.

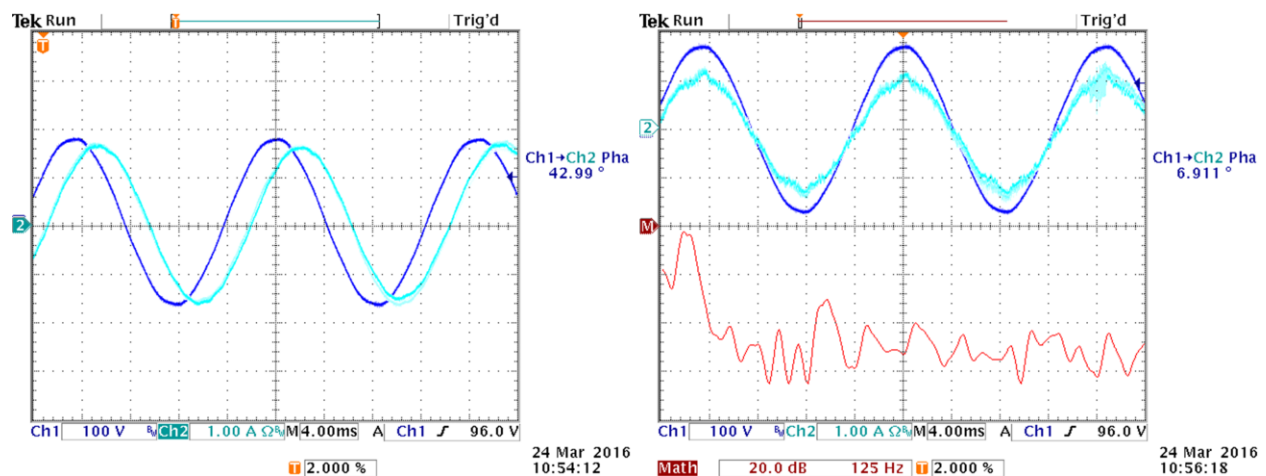


Fig. 15. Left plot: uncorrected 3-phase load waveform. Right plot: the 3-phase power factor correction waveform

C. Harmonic Current Distortion

Investigation of current harmonic distortion was not intended to be a part of this senior project. Analysis of the harmonics discovered that it was based on the fundamental frequency of 60Hz. A harmonic filter was designed to be tuned to the 7th harmonic of the system. As shown in figure 16, the harmonic filter reduced current distortion, but at the cost of slightly increasing the current compared to the power factor correction system without the harmonic filter shown in figure 14. Unfortunately, this design removes the harmonic distortion, but does not increase the efficiency of the system with the power factor correction. An additional 22 watts of power is consumed when applying the harmonic filtering. The testing of the harmonic filter verifies the conceptual design to remove 7th harmonic, but it is not practical for this size of equipment unless stability is an important issue with the power factor correction system.

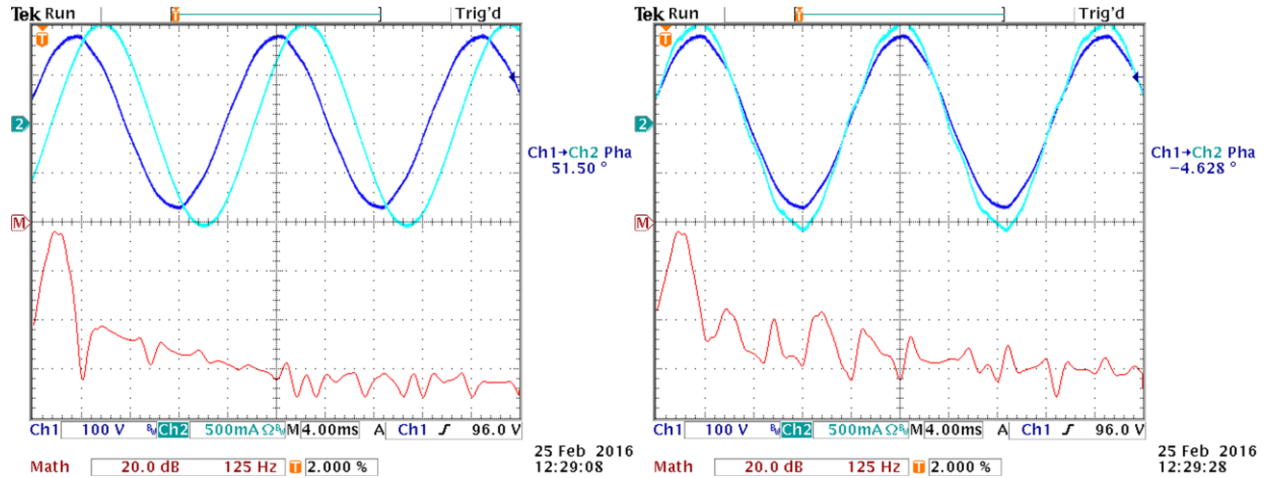


Fig. 16. Left plot: uncorrected load waveform. Right plot: power factor correction with harmonic filtering using the RLC harmonic filter

VI. SEL CONTROLLER PROGRAMMING TUTORIAL

A. ACSELERATOR QuickSet[®] Software

The SEL-5030 ACSELERATOR QuickSet[®] software is the proprietary software used to program SEL controllers. This software can be obtained by registering to create an account on selinc.com, and the free version of the software can then be downloaded. From the program one can create settings for the controllers easily and efficiently. No programming knowledge is needed to program the device since the logic programming for the controllers are based on logic points (or registers).

To make a *new setting project file* the part number of the SEL controller is needed since this tells the QuickSet[®] program what modules are installed in the SEL controller. After the *new setting project file* is created, a *settings menu* tree will appear to indicate where the logic point settings are located. Referring to the manual for the SEL controller will be of particular interest at this point since the manual will cover the descriptions for each of the settings definitions.

B. Communication to the device

Although communication with the SEL controller can be implemented in multiple ways, the method used for this project was serial communication with the front RS-232 serial port. The serial communication connection to the front port must use a null modem type connector. Drivers for the USB to serial conversion must be installed to establish communication since many modern computers do not have an RS-232 connection available. After completing the physical connection configuration in the QuickSet[®] software, click on the communication tab on the top bar, then click on parameters to bring up the different communication settings. The serial connection should have the active connection type set as serial, 9600 baud data speed, 8 data bits, 1 stop bit, no parity, RTS/CTS off, DTR off, and XON/XOFF on. Default level-one password is OTTER, and the second-level password is TAIL. After completing the settings for communication, the host computer should then be able to establish connection with the SEL controller. (The SEL controller must be powered on when starting communication with the device.) To send program settings to the SEL controller click the icon labeled as *send active settings* on the main toolbar. After clicking the *send active settings* icon, the user is given a selection of settings that can be sent to the device.

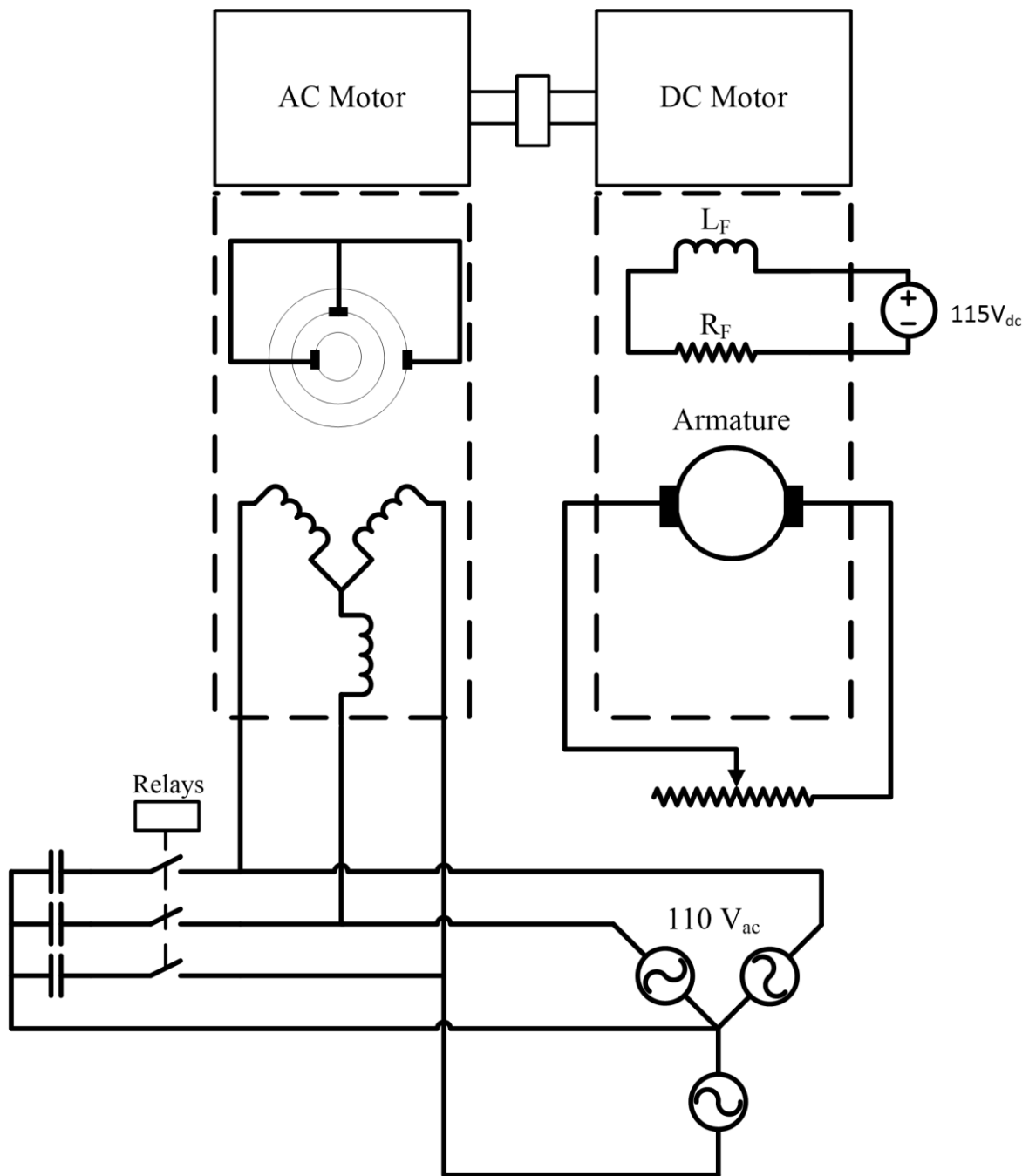
C. Graphical Logic Programming

The graphical logic tool available with the ACSELERATOR QuickSet[®] software is useful for building logic for the SEL controllers. In this application one can use Boolean logic, counters, edge triggers, latches, math functions, timers, and inputs/outputs to configure the control system. Details of these functions will be described in the on-line manuals available for each SEL controller. When using the graphical logic application, functions like the latches, timers, and counters must be enabled to be used in the application. The graphical logic application can be changed under the logic settings with the *SELogic Enables* tab. The input/output section can be used to select the logic variables for the logic design to define input voltages, relay values, button inputs, led outputs, or general constant values. Blocks will remain orange until all the inputs of the block are connected properly, and will then turn white. After finishing the logic to be implemented in the controller, clicking the compile button will convert the graphic logic into logic settings in the controller.

REFERENCES

- [1] 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 – 3-PHASE MOTOR POWER FACTOR CORRECTION SETUP



APPENDIX B – MONITORING AC SYSTEM TEST RESULTS

TABLE IV. TESTING SEL-2411 PROGRAMMABLE AUTOMATION CONTROLLER AC
VOLTAGE MONITORING

Actual Voltage (V_{rms})	Read Voltage (V_{rms})	Voltage Reading Error
101.5	101.3	0.20%
110.0	111.5	-1.36%
121.0	121.7	-0.58%
132.0	132.5	-0.38%
142.5	142.9	-0.28%
152.0	152.1	-0.07%
163.0	163.0	0.00%
169.8	169.8	0.00%
175.0	174.8	0.11%
182.2	182.4	-0.11%
189.8	189.2	0.32%
296.4	296.6	-0.07%
204.0	203.6	0.20%
210.5	210.8	-0.14%
Average Reading Error		-0.15%

TABLE V. TESTING SEL-2411 PROGRAMMABLE AUTOMATION CONTROLLER AC CURRENT
MONITORING

Actual Current (mA_{rms})	Read Current (mA_{rms})	Current Reading Error
160	162	-1.25%
230	230	0.00%
310	302	2.58%
385	378	1.82%
455	447	1.76%
518	514	0.77%
600	601	-0.17%
675	678	-0.44%
710	710	0.00%
748	746	0.27%
792	796	-0.51%
832	833	-0.12%
Average Reading Error		0.39%

TABLE VI. TESTING SEL-2411 PROGRAMMABLE AUTOMATION CONTROLLER AC POWER FACTOR MONITORING

V_s (Volts)	I_s (A)	P (Watts)	PF	PF on SEL-2411	Error
122	0.63	76	0.9888	0.99	-0.1189%
122	0.62	73	0.9651	0.97	-0.4902%
122	0.65	74	0.9332	0.92	1.3165%
122	0.51	50	0.8036	0.82	-1.6400%
122	0.6	55	0.7514	0.75	0.1366%
122	0.71	57	0.6580	0.66	-0.1953%
122	0.85	52	0.5014	0.50	0.1446%
122	0.95	36	0.3106	0.31	0.0613%
Average Reading Error					-0.0982%