AC System Monitoring Device

Final Presentation

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Outline

I. Project Overview
   A. Project Description
   B. Project Objectives
   C. Project Specifications
   D. Proposed Solution
II. Work Accomplished
   A. Achievements
   B. Problems Encountered
III. Results
   A. Monitoring AC system
   B. AC Power Factor Correction
IV. Conclusion
V. Q&A

Project Overview

- Project Description
  - Monitor single phase alternating current (AC) system
  - Ability to measure the efficiency of the AC system
  - Optimize the efficiency through power factor correction
  - Implemented with a digital system
  - Displays AC system information on an LCD panel

Project Overview

- Project Objectives
  - Monitor AC Voltage
  - Monitor AC Current
  - Monitor AC Power Factor
  - Power Factor Correction

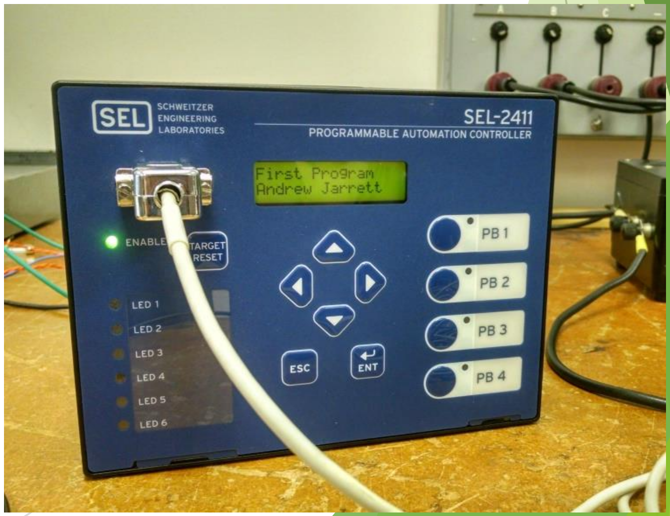
Project Overview

- Project Specifications

Specifications	Min	Max	Tolerance
Voltage Range	100 V_{ac}	250 V_{ac}	±15%
Current Range	0 A	5 A	±15%
Power Factor Calculation	0.3	1.0	±15%
Sampling Period	1 ms	1000 ms	N/A
Digital Electricomechanical Contact Outputs	1	N/A	N/A

Project Overview

- Proposed Solution
  - Schweitzer Engineering Laboratories (SEL)
  - SEL-2411 Programmable Automation Controller
    - AC power expansion card
    - Customizable logic programming
    - Safe Enclosure to 600V_{ac}



Project Overview

- Proposed SEL-2411 Manufacture Specifications

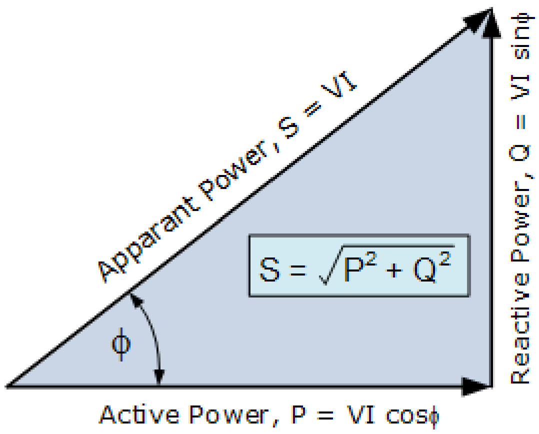
Specification	Min	Max	Tolerance
AC Voltage Input Card (300V Model)	100 V_{ac}	250 V_{ac}	±0.08%
AC Current Input Card (5A Model)	0.05A	10.0 A	±0.5%
Power Factor Calculation	0	1.0	±1%
Sampling Period	N/A	100ms	N/A
Digital Electromechanical Contact Outputs	N/A	8	N/A

Work Accomplished

- Achievements
  - Design Monitoring AC System
    - SEL-2411 Programmable Automation Controller
      - Ordered and researched add-on components to the device
    - Resistive-Inductive (RL) Load
      - Provide a load to measure AC voltage and AC current
      - Variable resistor in series with inductor
      - Provide lagging current load with a power factor of about 0.7
      - Repeatable and controllable load

Work Accomplished

- Achievements
  - Design AC Power Factor Correction
    - Performed by switching of capacitors in parallel with load
      - Performed by relays controlled by the SEL-2411
    - Sizing of the capacitance through equations 1 - 4



$$\bar{Q} = \bar{V}_s \bar{I}_s \sin\theta \qquad (1)$$

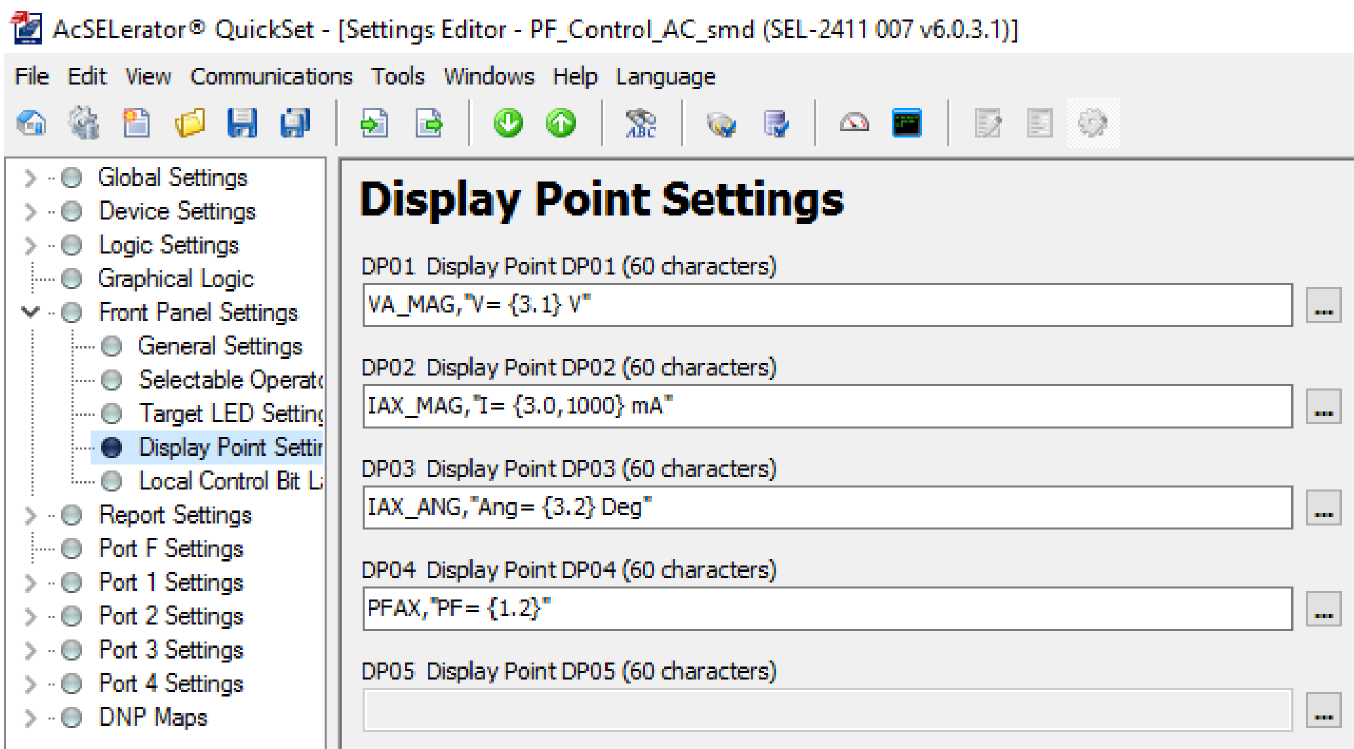
$$\bar{Q}_{cor} = -\bar{Q} \qquad (2)$$

$$C_{cor} = \frac{1}{2\pi f \bar{X}_{cor}} \qquad (3)$$

$$C_{cor} = \frac{\bar{Q}_{cor}}{2\pi f \bar{V}_s{}^2} \qquad (4)$$

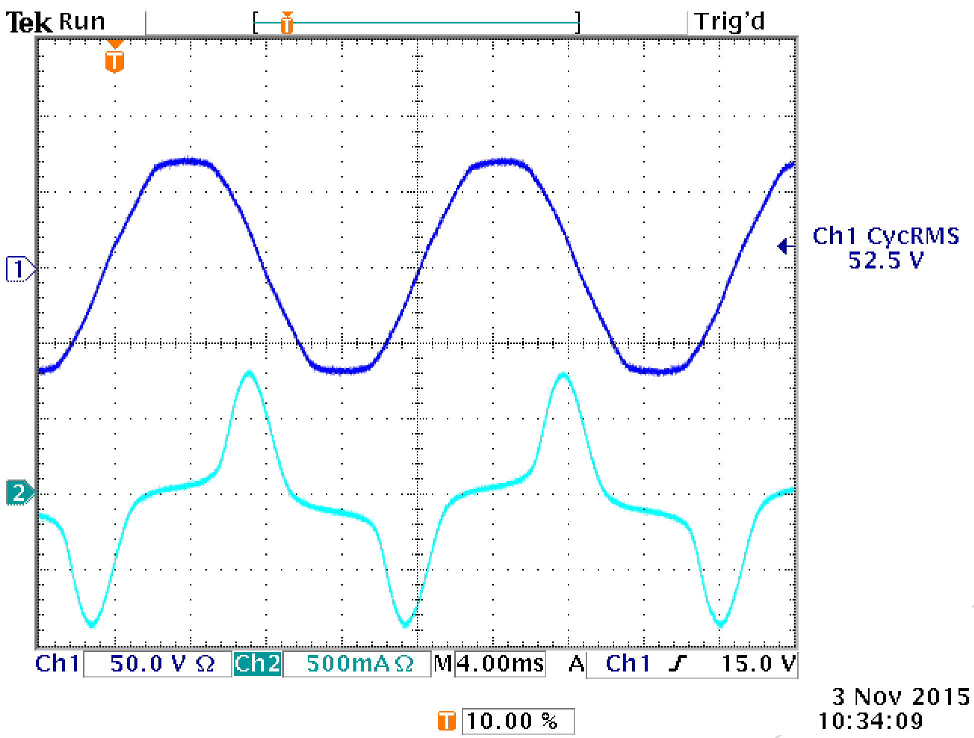
Work Accomplished

- Achievements
  - Programming the SEL-2411 Programmable Automation Controller
    - ACSELERATOR QuickSet® Software
    - Graphical Logic Programming



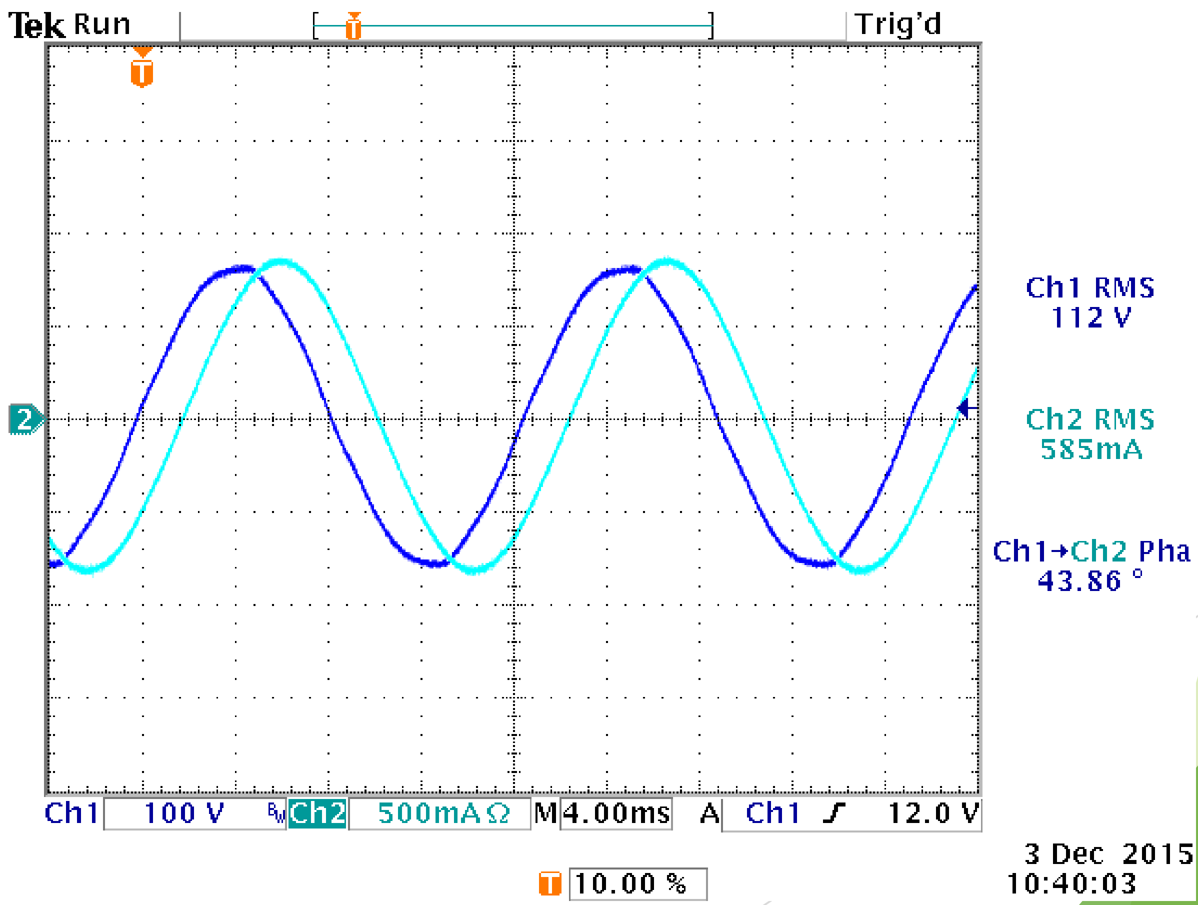
Work Accomplished

- Problems Encountered
  - Resistive Inductive (RL) Load
    - Used transformer winding for inductive load
    - Non-linear waveform



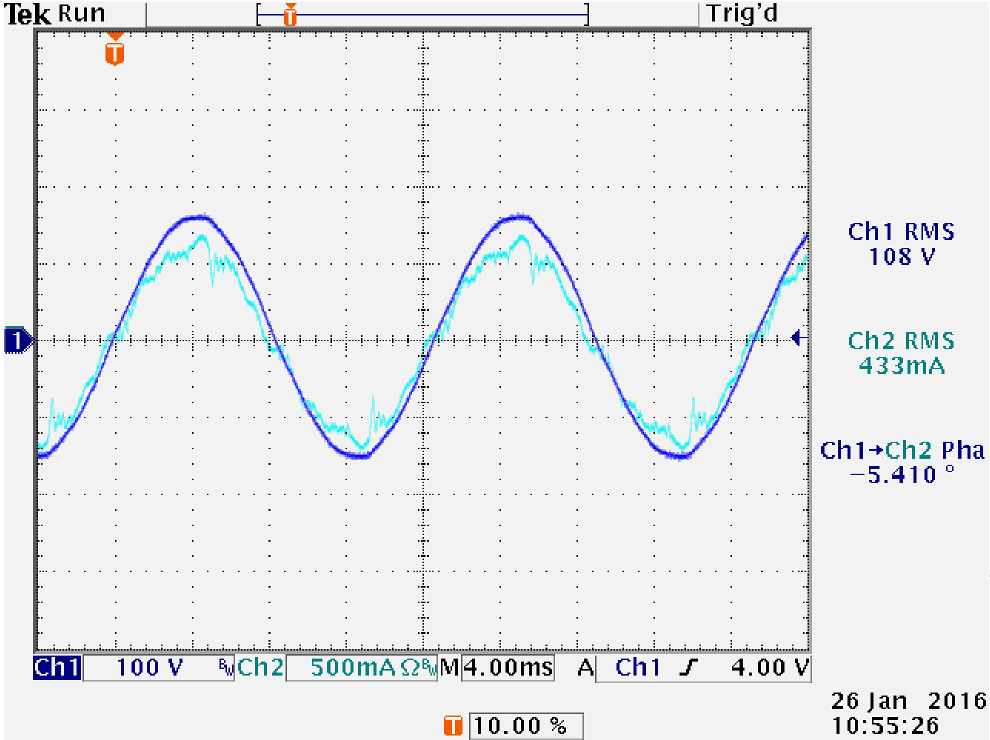
Work Accomplished

- Problems Encountered
  - Resistive Inductive (RL) Load
    - Replaced transformer with Loading Reactor



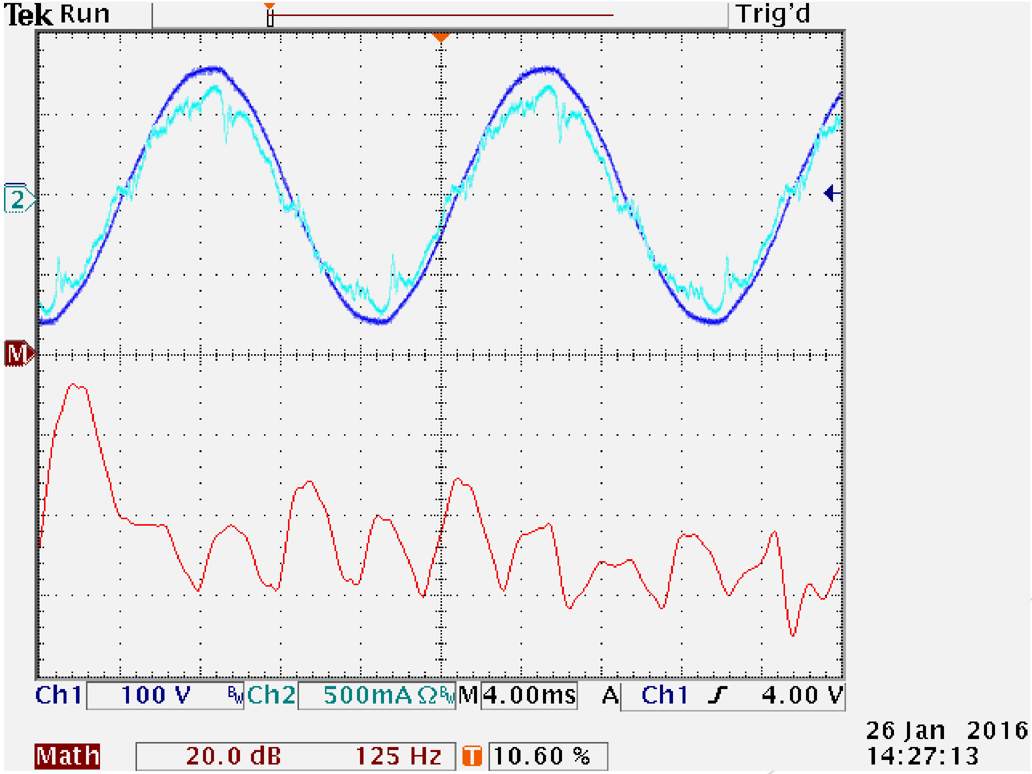
Work Accomplished

- Problems Encountered
  - Power Factor Correction
    - Does perform the power factor correction
    - Introducing the capacitors causes current distortion



Work Accomplished

- Problems Encountered
  - Analysis on the current distortion with FFT determined harmonics are being introduced by the power factor correction
    - Most prominent harmonics are the 7th and 11th



Work Accomplished

- Problems Encountered
  - Design to fix current harmonic distortion
    - Tuned RLC circuit to the 7th Harmonic using equation 5
    - Calculated inductance needed with 10.9μF capacitance, shown in equation 7
    - Resistor controls the bandwidth of the tuned filter

$$\omega = \sqrt{\frac{1}{LC}} \Rightarrow L = \frac{1}{\omega^2 C} \quad (5)$$

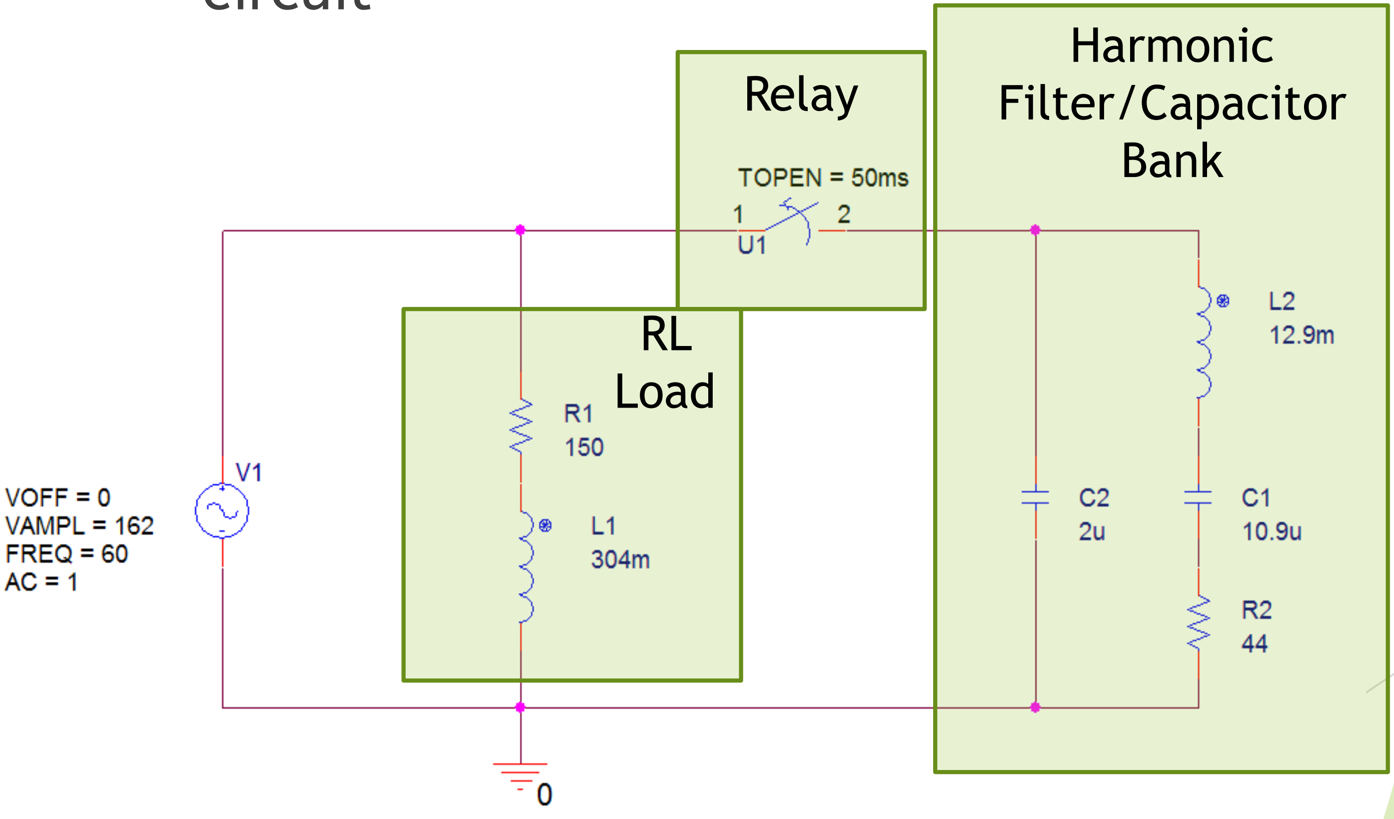
$$\omega = 2\pi f_0 h = 2\pi(420Hz) = 2639\frac{rad}{s} \quad (6)$$

$$L = \frac{1}{\left(2639\frac{rad}{s}\right)^2 10.9\times10^{-6}F} = 13.19mH \quad (7)$$

$$Q = \frac{\sqrt{\frac{L}{C}}}{R} \rightarrow \delta = \pm\frac{1}{2}Q = \pm\frac{1}{2}\cdot\frac{\sqrt{\frac{0.01319H}{10.9\times10^{-6}F}}}{44\Omega} = \pm39.5\% \rightarrow (252Hz, 588Hz) \quad (8)$$

Work Accomplished

- Problems Encountered
  - Tuned 7^{th} harmonic filter using a RLC circuit



Results

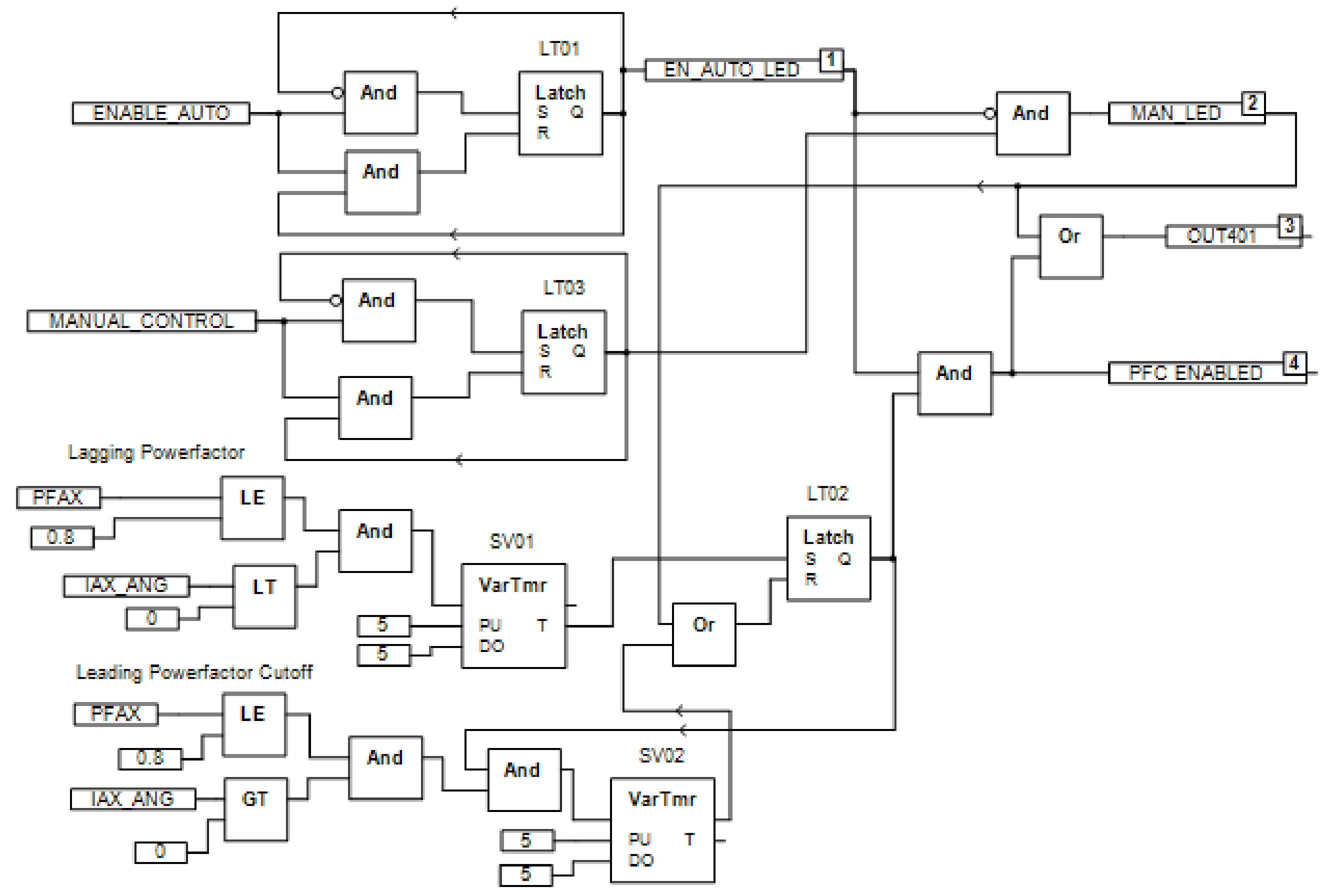
- Monitoring AC system
  - Lab AC meters rated ±0.5%
  - AC Voltage Monitoring
    - AC Meter Card Specification ±0.08%
    - Average Error = -0.15%
  - AC Current Monitoring
    - AC Meter Card Specification ±0.5%
    - Average Error = 0.39%
  - AC Power Factor Monitoring
    - AC Meter Card Specification ±1%
    - Average Error = -0.098%

Results

- Monitoring AC system
  - SEL-2411 Programmable Automation Controller
    - Display information of the AC system
      - Cycles information on two screens
      - Displays Voltage, Current, Phase Angle, and Power Factor

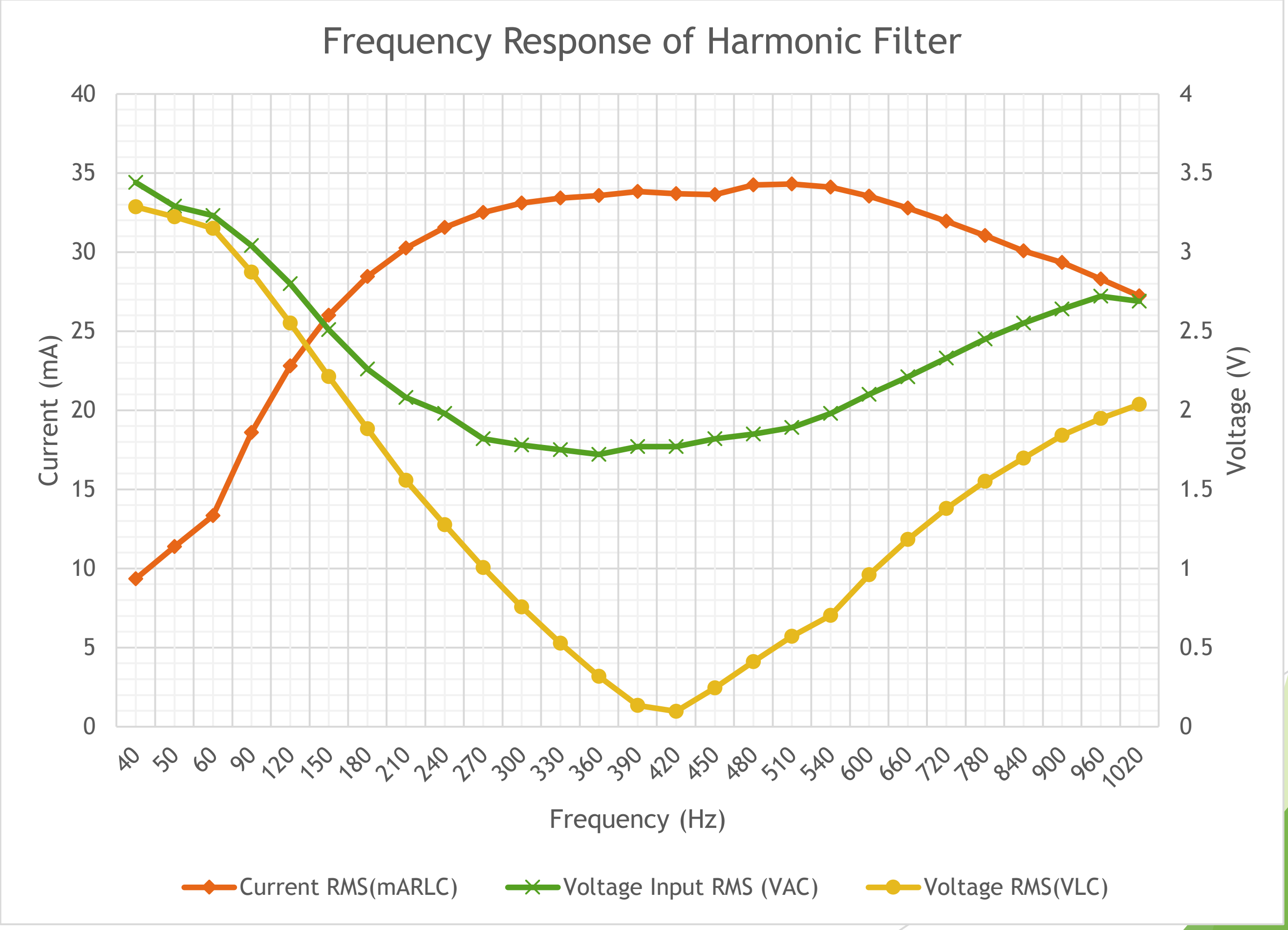
Results

- Monitoring AC system
  - Logic Diagram from ACSELERATOR QuickSet® Software



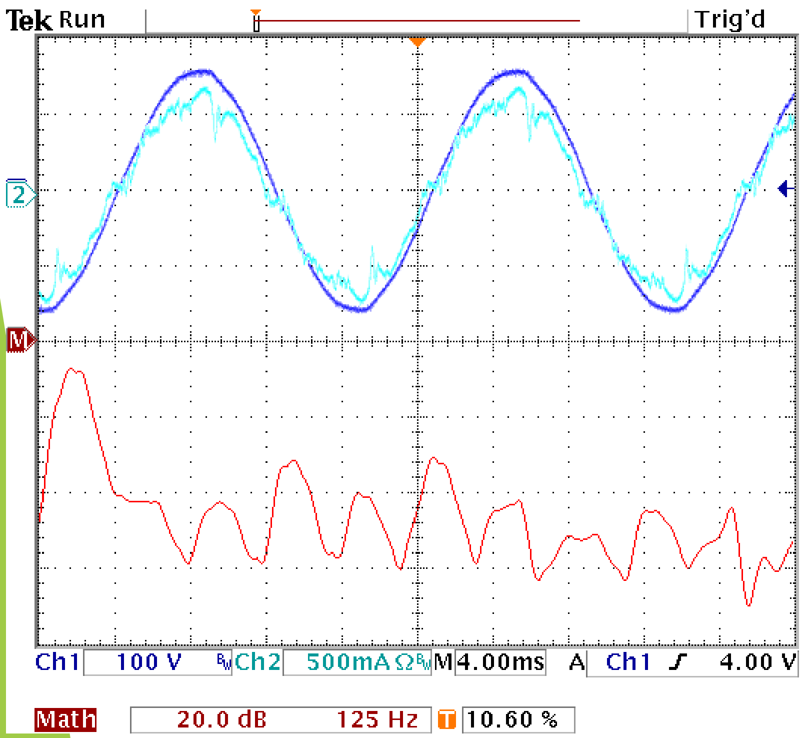
Results

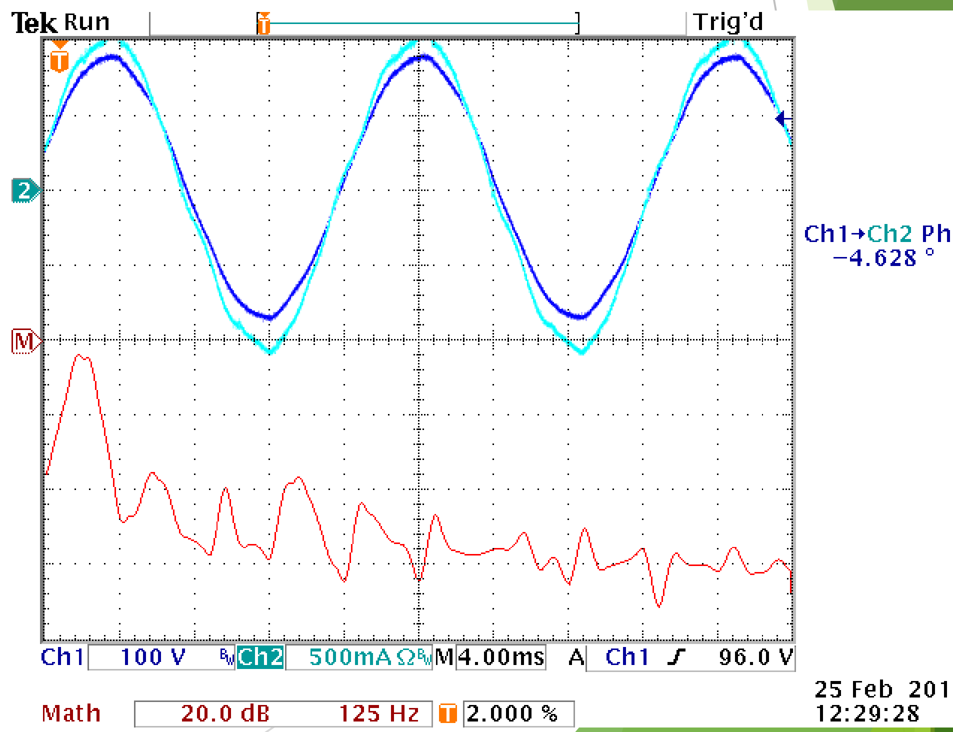
- Harmonic Filter Frequency Response



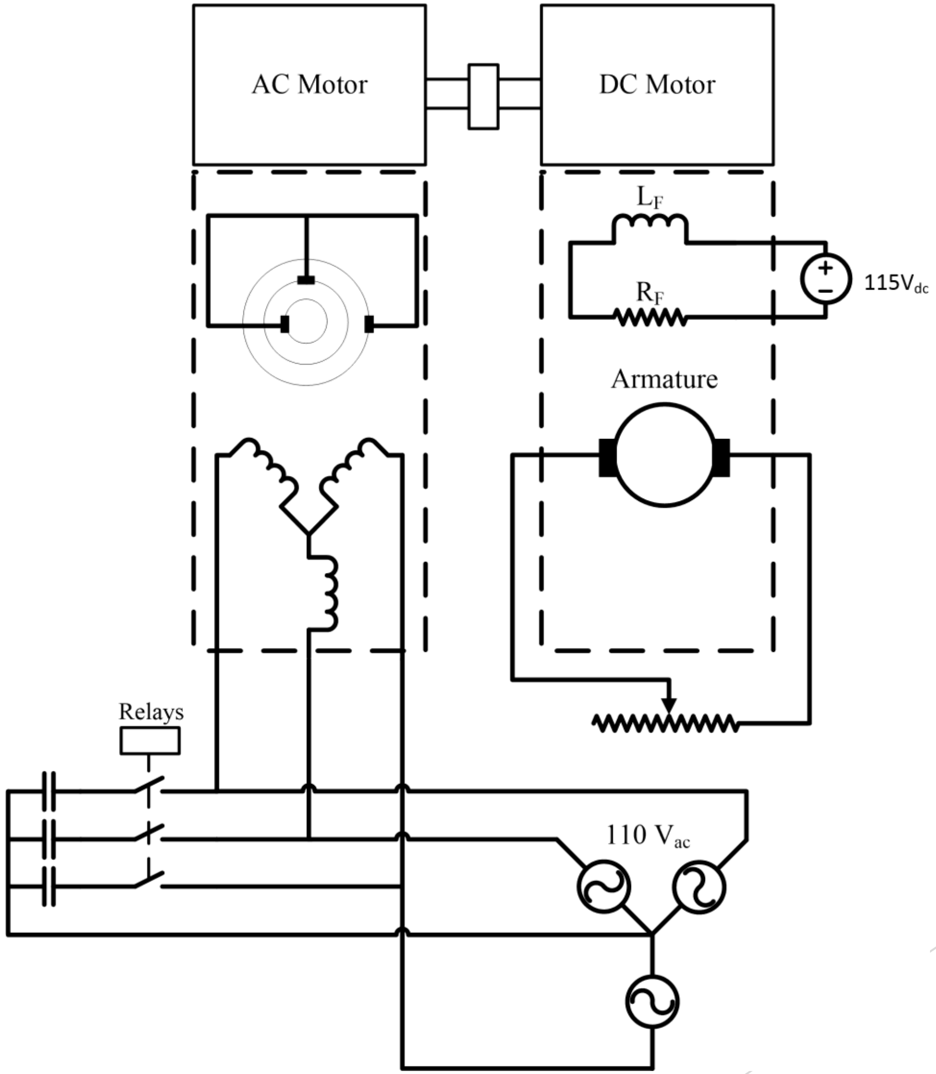
Results

- Harmonic Filtering
  - Reduced current distortion
  - Resulted in higher current
  - No increase of efficiency with PF correction



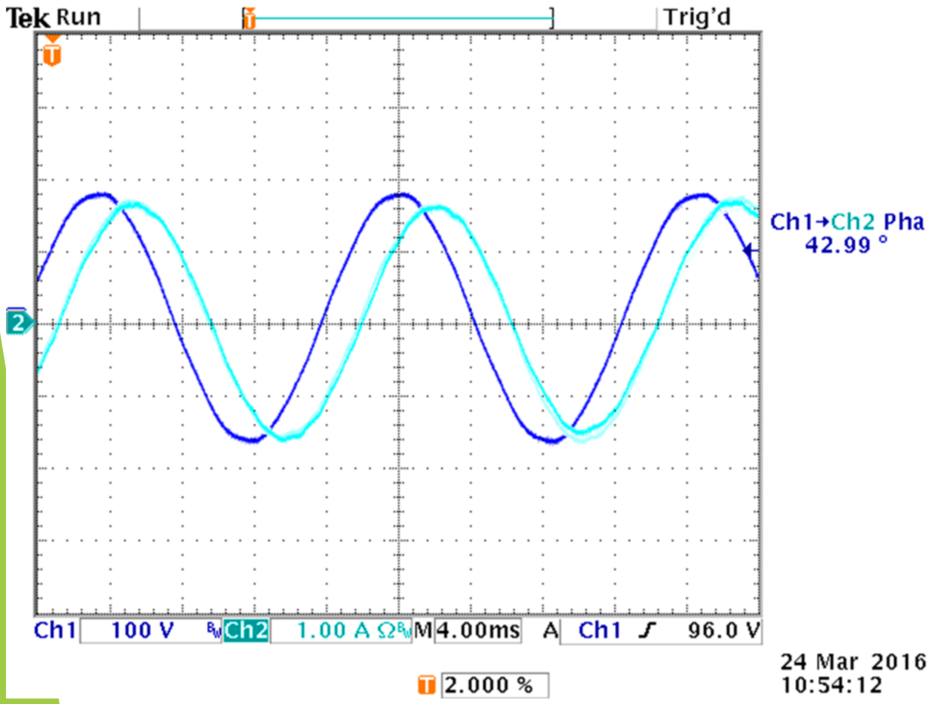


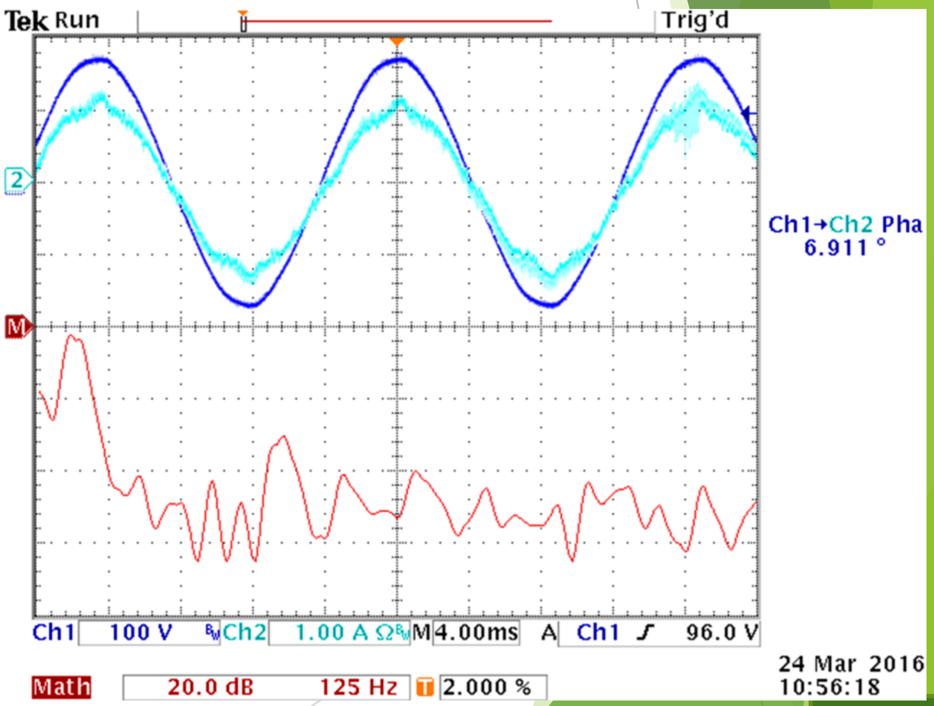
AC Power Factor Correction AC Motor Load Alternate Load Test



Results

- AC Power Factor Correction
  - Harmonics reduced in 3-phase machine power factor correction
  - 39 Watt reduction in power usage





Conclusion

- Successfully implemented SEL-2411 to monitoring AC system
- Performed power factor correction
  - Sized capacitance needed for loads
- Explored solution to current harmonic distortion
  - Performing power factor correction causes current harmonic distortion
  - Using RLC tuned harmonic filter does provide way to reduce the harmonic distortion
  - Using harmonic filtering reduces power saving with power factor correction
- Testing with 3-phase motor load
  - Success in correcting the power factor

Q & A

Detailed Results

- Monitoring AC System
  - 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%**

Detailed Results

- Monitoring AC System
  - AC Current Monitoring

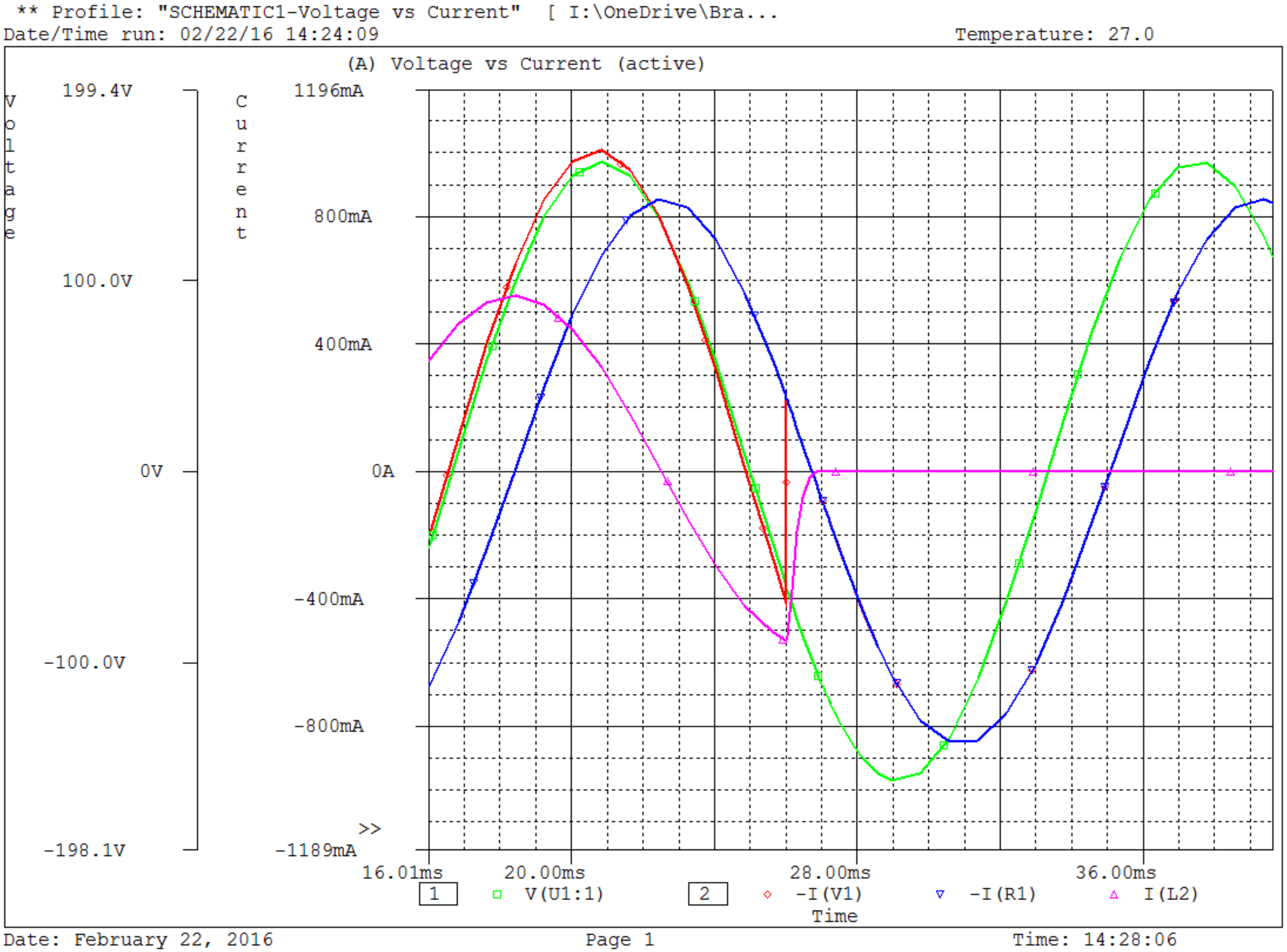
Actual Current (mA_{rms})	Read Current (mA_{rms})	Current Reading Error
160	162	-1.25%
230	230	0.00%
310	302	2.58%
385	378	1.82%
455	447	1.76%
518	514	0.77%
600	601	-0.17%
675	678	-0.44%
710	710	0.00%
748	746	0.27%
792	796	-0.51%
832	833	-0.12%
	Average Reading Error	**0.39%**

Detailed Results

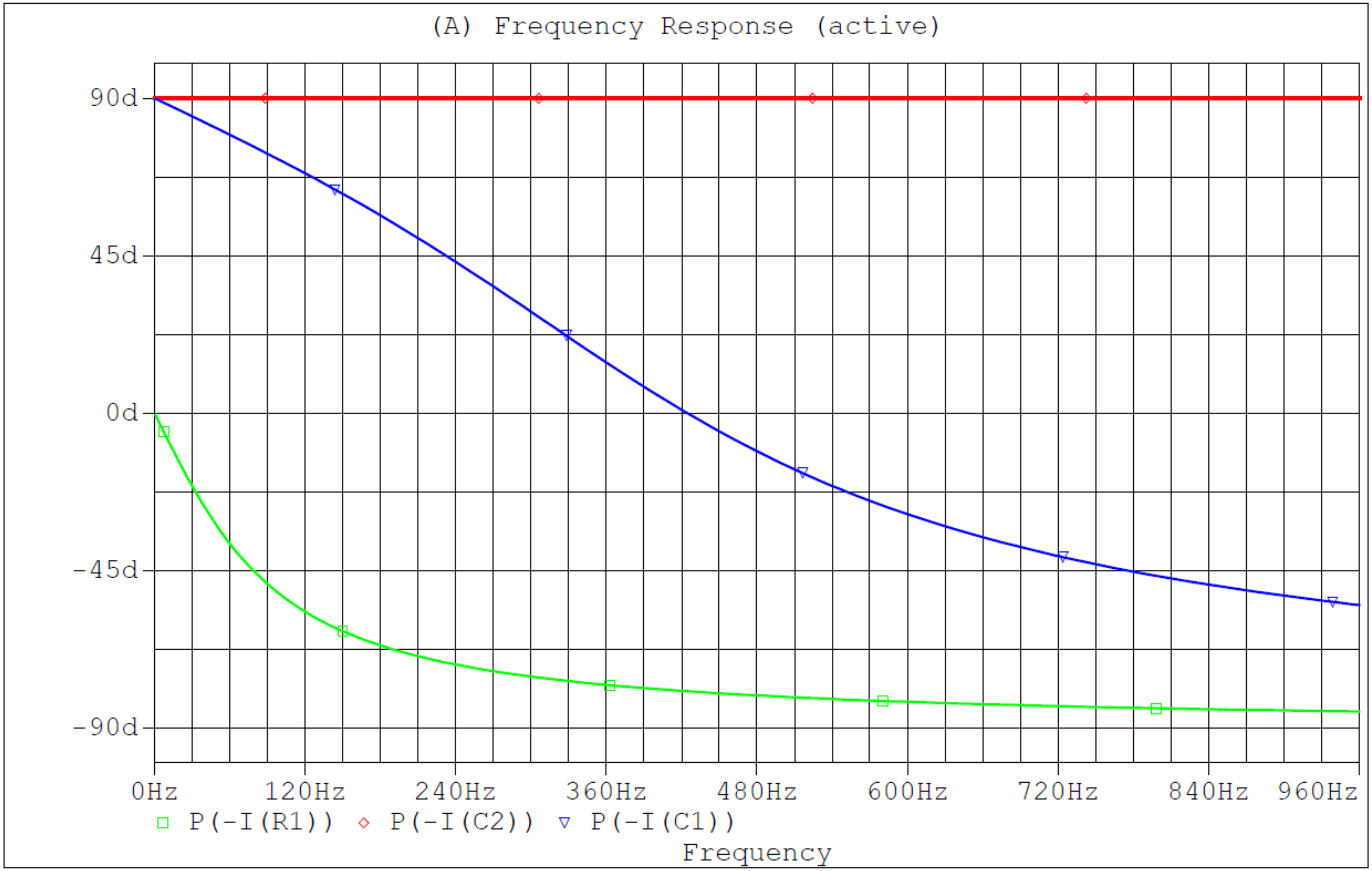
- Monitoring AC System
  - AC Power Factor Monitoring

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%**

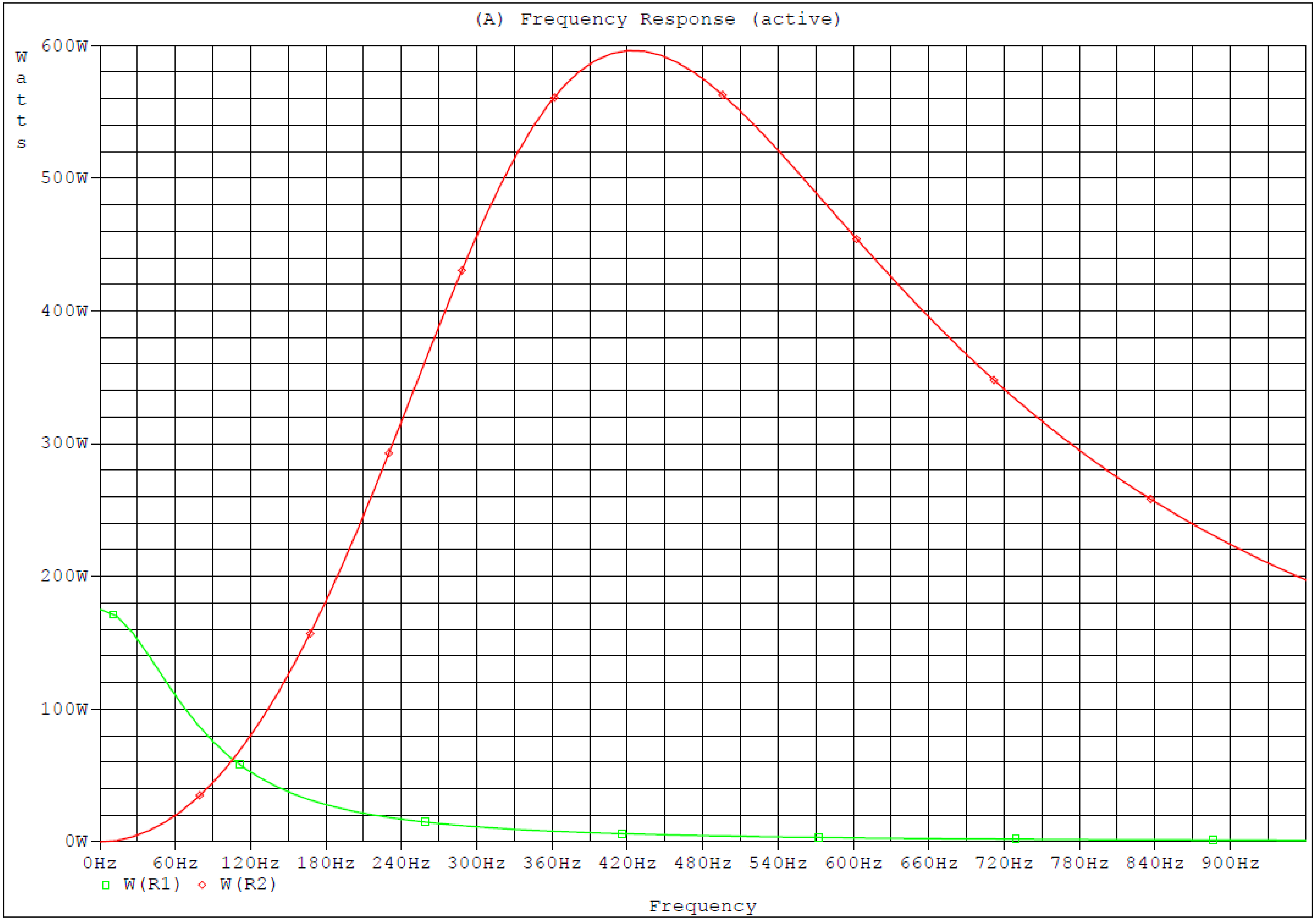
Simulation in OrCAD adding 2µF capacitor



Simulation Phase Shift



Simulation Response



Derived Capacitance Calculation

$$\bar{Q} = \bar{S}\ \sin\theta \qquad (1)$$

$$\bar{Q} = V_s I_s \sin\theta \qquad (2)$$

$$\bar{Q}_{cor} = -\bar{Q} \qquad (3)$$

$$\bar{S}_{cor} = \bar{Q}_{cor} \qquad (4)$$

$$\bar{I}_{cor}{}^{*} = \frac{\bar{S}_{cor}}{\bar{V}_{cor}} = \frac{\bar{S}_{cor}}{\bar{V}_s} \qquad (5)$$

$$\bar{X}_{cor} = \frac{\bar{V}_s}{\bar{I}_{cor}} = \frac{\bar{V}_s \cdot \bar{V}_s}{\bar{S}_{cor}} = \frac{\bar{V}_s{}^2}{\bar{Q}_{cor}} \qquad (6)$$

$$C_{cor} = \frac{1}{2\pi f \bar{X}_{cor}} \qquad (7)$$

$$C_{cor} = \frac{\bar{Q}_{cor}}{2\pi f \bar{V}_s{}^2}\left[\frac{VAR}{V^2}\right] \qquad (8)$$