2 Design Lab II: An Automatic Power Factor Correction System

(Dr. Rajesh Karki, Sept. 2009)

2.1 Safety Advisory:

The activity prescribed in this laboratory will be conducted in an environment where hazardous electrical potentials exist. The student should be aware of normally expected electrical laboratory hazards and follow procedures to minimize risk. Please refer to general safety precautions in the Laboratory Manual and those posted in the labs.

This laboratory exercise presents the following specific hazards:

- **Shock:** Collapsing fields in inductors, transformers and motors can produce extremely high potentials even with low input source voltages; allow for appropriate discharge paths and insulate yourself appropriately when contacting leads or components.

- **Burn:** Circuit elements under load, especially abnormal load caused by circuit or design errors, can reach temperatures which will cause burns to skin if contacted. Do not attempt to determine the temperature of elements with your fingers! Approach potentially overheated elements with caution and allow sufficient time for cooling when necessary. In some cases, elements may burst into flames. This is usually very isolated and does not normally create a fire hazard. If overheating to flames do occur, immediately remove power and determine and correct the cause before re-energizing!

- **Explosion:** Modern capacitor designs using metal cases with pressure relief mechanisms have proven very safe and should be used in all new designs. However, capacitors that are subjected to potentials exceeding their rating can, on very rare occasion, rupture their cases. This especially applies to electrolytic capacitors commonly used as power supply filter elements. Electrolytic capacitors are typically polarized, and if they are connected with the polarity reversed, even below rated voltage, can overheat quickly. Make certain that all electrolytic capacitors are connected with the proper polarity before energizing the circuit. If in doubt, re-check the polarity of the voltage rails without the filter capacitor and then mount the element correctly.

- **Rotating Shaft Hazard:** There is an electric motor with a rotating shaft. Although small, the shaft and mounted sensor disk may pose a slight abrasive hazard if contacted. Caution should be exercised when the motor is running even though the risk of serious injury is negligible.
Some additional procedures for dealing with high potential equipment are included below. Please familiarize yourself with these and follow them when appropriate.

**Turning Power ON, Taking Readings and Turning Power OFF**

- Make sure everyone is clear of the circuit and equipment. Announce your attention to turn the power on. Turn on the **table breaker** first to avoid accidental human contact with the energized terminals on the table breaker. Turn on the **100-amp breaker at your work station (bench panel breaker)** second to energize the circuit.

- **Take meter readings immediately. Do not delay.** Only one member of the group should take readings from the meters. Place both hands behind your back. Call out the readings. Be careful not to contact any part of the circuit or equipment. Another member of the group should record the readings called out. The recording person should be positioned a safe distance from the circuit. All other members of the group should stay clear of the circuit and the meter reading person. **Turn power off immediately after the readings are taken. Do not delay.**

- Turn the **100-amp breaker at your work station (bench panel breaker)** off first, followed by the **table breaker**. Always turn both breakers off. Have the circuit rechecked if **Any** changes are made to the circuit.

**Circuitry of High Power Ratings ( > 100V ):**

- Work only with one hand; keep the other in a pocket or behind your back when working with powered equipment and circuitry. This will reduce the chance of touching two powered points at the same time and will greatly reduce the extent of injury if something should happen.

- **ALWAYS** disconnect power to the circuit when not in use and when changing connections

- Place all meters nearest to the edge of the circuitry nearest to you so that your do not have to lean over powered circuitry to make readings

- Keep wiring as neat as possible so that you can easily determine how the circuitry is connected without having to grab wires to determine where connections go.

- Use wires that are a short as possible to make connections to equipment, but not so short that they are stretched to their limit (use good judgment)

- In a learning lab environment **ALWAYS** have your circuit checked by an instructor before powering the circuit
2.2 Background: Reactive Power and Power Factor Correction in Power Circuits

The average power drawn by a load connected to an energized power circuit is also known as the active power or real power, and is calculated using Equation (1).

\[
P = V \cdot I \cdot \cos \theta \quad (1)
\]

where, \(V\) is the RMS voltage across the load, \(I\) is the RMS current drawn by the load, and \(\theta\) is the phase angle between the voltage and the current waveforms. For given voltage and current levels, the average power is maximized when the value of \(\cos \theta\) (which is known as the power factor) is maximized, i.e. equal to 1. It is, therefore, desired that electrical loads operate close to unity power factor in order to increase the efficiency of the power system.

\[
\text{Power Factor (p.f.)} = \cos \theta \quad (2)
\]

where, \(\theta\) is known as the power factor angle, and is the phase angle between the voltage and the current waveforms. When the current waveform lags the voltage, the power factor is said to be lagging power factor. This occurs when the load has inductive reactance. A load with lagging power factor is considered to draw reactive power from the circuit. On the other hand, when the current waveform leads the voltage, the power factor is said to be leading. This occurs when the load has capacitive reactance. A load with leading power factor is considered to inject reactive power into the circuit. Equation (3) shows one method to calculate reactive power, \(Q\).

\[
Q = \sqrt{A^2 - P^2} \quad (3)
\]

where, \(A\) is the apparent power and \(P\) is the average (or real) power of the load. The apparent power is the product of the RMS voltage and current of the load. Power factor is also defined as the ratio of the average power and the apparent power.

Power factor can also be calculated from the impedance, \(Z\) of the load. If \(Z\) is expressed in the polar form, the angle of the impedance is the power factor angle, \(\theta\). If \(Z\) is purely resistive, \(\theta\) is zero, and therefore, power factor is unity.

Most residential and industrial loads are of inductive nature, and therefore, will cause lagging power factor. Power factor correction (PFC) is usually done by connecting a capacitor of appropriate rating to inject reactive power and bring the power factor close to unity. When the reactive power injected is equal to the reactive power drawn by the inductive load, the power factor is corrected to unity. The capacitance required to inject reactive power \(Q\) can be calculated using Equation (4).

\[
C = \frac{Q}{(2\pi f V^2)} \quad (4)
\]

where, \(V\) is the RMS voltage across the capacitor and \(f\) is the frequency.

It is obvious that the capacitance required for power factor correction of a power utility customer will vary as the number and type loads vary throughout the day. It becomes important to avoid resonance type situations when capacitors are used to neutralize the lagging effect of inductors in a circuit, or else, some parts of the circuit may be subjected to very high voltages or currents. Care must be taken to ensure the circuit components are able to withstand the resulting currents or voltages.

It is important to maintain a steady RMS voltage at the load terminal, since residential as well as industrial loads are rated to operate at a specific voltage level. When a load is
connected, the voltage at the load terminals will however decrease due to a voltage drop in the circuit upstream to the load terminals. Corrective actions, such as transformer tap-changing or reactive power injection, must be taken if the voltage at the load terminal drops significantly. It should be noted that the corrective actions should be removed or altered when the load is changed or disconnected, or else the voltage at the load terminals can be excessive. These factors require careful attention when designing a PFC system for a typical power consumer. PFC system can be static as well as dynamic through automatic switching.

2.3 **Part 1- Power Factor Calculation and Measurement**

1(a):
- Connect a resistor in series with an inductor to form an inductive load.
- Calculate and measure the total impedance to obtain a power factor of 0.8.
- Use a variac to energize the load with a suitable voltage, so that the current through the circuit components (including the connecting cables) are within allowable limits.
- Measure the phase angle between the voltage and the current waveform using an oscilloscope and calculate the power factor.
- Connect a power analyzer and measure the power factor. It should be noted that a negative reading indicates leading power factor, and a positive reading indicates lagging power factor.

1(b):
- Connect the circuit as shown in the single-line diagram in Figure 2.1.
- This represents a power supply system to a residential/industrial customer. The inductor coil represents the upstream circuit impedance. Make sure that the components are able to withstand the operating voltages.
- Connect a 60 W incandescent lamp at Load 1 terminal in series with a switch. You should have an estimate of the current that will flow in different parts of the circuit, and make sure that the components and cables are able to carry the current.
- Measure the voltage at the load terminal, the current, active and reactive powers and the power factor.
- Replace the 60 W lamp with a 23 W compact fluorescent lamp (energy efficient lamp), and take the readings.
2.4 Part 2 – Voltage Drop and Control

2(a) – Voltage Drop Measurement:
- Energize the above circuit without connecting a load, and measure the no-load voltage at the Load terminal.
- Switch-on a 150 W incandescent lamp at the Load Terminal.
- Measure the voltage at the load terminal, the current, active and reactive powers and the power factor.
- Calculate the voltage drop (reduction in voltage) at the load terminal from the measured voltages.
- Verify with calculations that \( V_{\text{no-load}} - V_{\text{drop@coil}} = V_{\text{load}} \).

2(b) – Voltage Control Using Transformer Tap-changing:
- Calculate the level of voltage increase that can be obtained through tap changing of the transformer.
- De-energize the circuit by opening the breakers.
Perform tap-changing at the primary winding of the transformer to increase the load voltage across the 150 W load.
- Measure the voltage at the load terminal.
- Disconnect the load. What is the voltage at no load?
- Discuss on-line and off-line tap changing with team members and instructor.
- De-energize the circuit and switch back to the original transformer taps.

2(c) – Voltage Control with Reactive Power Injection:
- Connect a 150 W lamp at the load terminal and measure the voltage, current, real and reactive power.
- Connect a capacitor bank in series with an ammeter at the load terminal.
- Gradually increase the reactive power injection, and monitor the current through the capacitor, the reactive power injected, and the voltage at the load terminal.
- Obtain a load voltage close to the original no-load voltage, and measure the connected capacitance.
- Also take the readings from the power analyzer.
- Switch off the 150 W load and measure the voltage at the load terminal.
- De-energize the circuit and change the switch position, so that both the load and the capacitor bank are controlled by the same switch.
- Measure the no-load and load voltage.
- De-energize the circuit and disconnect the capacitor bank.

2.5 Part 3 – Power Factor Correction
3(a):
- Connect an inductor in series with a variable resistor at the Load Terminal in Fig. 1. Also connect an ammeter to measure the current drawn by the load. You should have an estimate of the current that will flow in different parts of the circuit, and make sure that the components and cables are able to carry the current.
- Vary the resistance and/or inductance to obtain a lagging power factor of 0.7.
- Energize the circuit and measure the voltage at the load terminal, the current, active and reactive powers and the power factor.
- Calculate the capacitance required to correct the power factor close to unity.
- Connect the desired value of the capacitor bank to the Load Terminal through an ammeter. Estimate the current that will flow through the capacitor bank and make sure the circuit can handle that current.
- Measure the Voltage at the load terminal, the current, active and reactive powers and the power factor.
- Compare the currents drawn by the capacitor, the load and the total current shown by the power analyzer.
- Verify that the total current drawn from the source is the summation of the current through the capacitor and the load.
- Disconnect the resistor/inductor load and measure the voltage at the Load Terminal.
- Discuss appropriate switch positions for the load and capacitor bank with your group and your instructor. Also discuss the applications of static and automatic power factor correction systems.
3(b) – Automatic Power Factor Correction
- Obtain 3 different power factor levels for resistor/inductor load by changing the value of the resistance and/or inductance.
- Calculate the capacitance required to correct the power factor close to unity.
- Connect the desired value of the capacitor bank to the Load Terminal through an ammeter.
- Measure the Voltage at the load terminal, the current, active and reactive powers and the power factor.
- Disconnect the resistor/inductor load and measure the voltage at the Load Terminal for each case.

2.6 Part 4 – Design of a PFC System
- Consider an industrial power customer that is supplied through a 5 kV distribution feeder. The customer has different types of loads (such as ovens, air-conditioners, motors, etc.) that have different power factors.
- Draw a single line diagram of the system.
- Design a power factor correction system for the customer, taking into consideration the power factor correction range, maintaining acceptable voltage at the customer terminal at all times, and using components with proper ratings to withstand operating voltages and currents.