WIRELESS CURRENT SENSING FOR IMPROVED DISTRIBUTION CAPACITOR BANK CONTROL

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SEL

Introduction

Switched capacitor banks are used on utility distribution systems to maintain system voltage and control the flow of reactive power, all with the goal of increasing efficiency for the utility and increasing power quality for utility customers. Switched capacitor banks, equipped with intelligent controls and current sensing, are a key component in a changing grid. These devices can provide better switching decisions as well as system visibility.

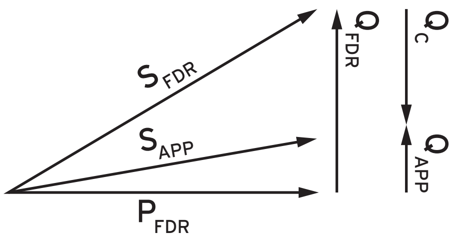
This paper describes the function of capacitor banks in the distribution system and describes common methods for controlling capacitor banks, including their benefits and challenges. It also introduces a new method for controlling capacitor banks by using wireless current sensors in place of traditional line post sensors.

Theory of Reactive Power in Distribution Systems

Electric power distribution systems deliver electric power from the bulk electric system to consumers. Distribution feeder circuits must physically connect to numerous consumers in a geographical area. A single distribution feeder may stretch for miles and connect a variety of consumer types (residential, commercial, industrial, etc.) distributed along its length. Because of the inductive characteristic of the feeder's impedance, and because of the inductive demand of some load types, there is a significant reactive power demand distributed along the length of the distribution feeder.

Reactive power is not converted to other forms of energy used by consumers and is therefore typically not metered, which means the utility has no mechanism to recover costs associated with reactive power. But there is a cost to the utility to generate and distribute reactive power. For the same amount of active power (P) delivered, a higher level of reactive power (Q) results in a higher level of apparent power (S). This results in higher current on the distribution feeder and, therefore, higher thermal losses and more voltage drop.

Utilities are, therefore, generally motivated to reduce reactive power demand along the feeder and operate as close to a unity power factor ($P = S$, $Q = 0$) as possible. This is commonly accomplished by installing shunt capacitor banks at multiple locations on a distribution feeder, as described in [1]. Each bank effectively reduces the apparent inductive demand of consumer loads downstream by its rating in VARs. Figure 1 shows that a capacitor bank's compensation (Q_C) reduces the reactive demand from the feeder loads (Q_{FDR}) to a smaller apparent reactive demand (Q_{APP}), which in turn reduces the apparent power of the feeder loads from S_{FDR} to S_{APP} and brings the apparent power factor (PF_{APP}) closer to unity.

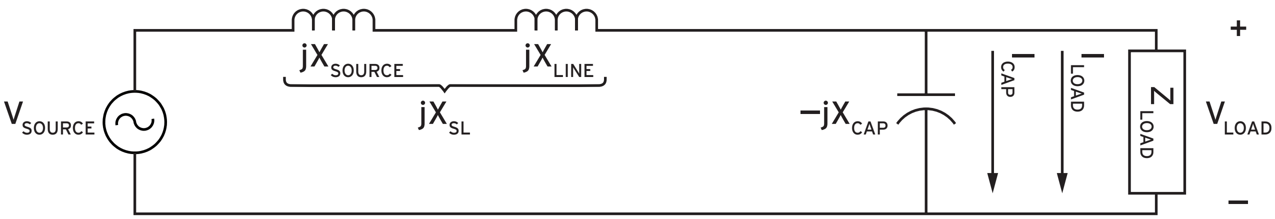


$$PF_{FDR} = \frac{P_{FDR}}{S_{FDR}}$$

$$PF_{APP} = \frac{P_{FDR}}{S_{APP}}$$

Figure 1—Capacitor bank contribution to power triangle.

Capacitor banks also reduce the inductive voltage drop upstream caused by active power demand on the feeder (see Figure 2). These properties result in less thermal loss and less voltage drop along the distribution feeder, maximizing the use of the utility's assets to transmit profitable active power. Many attempts have been made over the years to quantify the savings afforded by the installation of capacitor banks and optimize their placement to maximize these savings [2] [3].



$$V_{LOAD} = \frac{(V_{SOURCE} - I_{LOAD} \bullet jX_{SL})}{1 - \left(\frac{X_{SL}}{X_{CAP}}\right)}$$

$X_{CAP} = \infty$	$V_{LOAD} = (V_{SOURCE} - I_{LOAD} \bullet jX_{SL})$
$X_{CAP} > X_{SL}$	$V_{LOAD} > (V_{SOURCE} - I_{LOAD} \bullet jX_{SL})$
$I_{LOAD} = 0$ and $X_{CAP} > X_{SL}$	$V_{LOAD} > V_{SOURCE}$

Figure 2—Capacitor bank contribution to voltage.

The Role of Capacitor Banks

Consumers connected to a distribution system typically present cyclical and seasonably varying loads. Over the course of each year, and even each day, reactive demand on a distribution feeder can vary widely. During lightly loaded conditions, there is typically some minimum level of reactive demand on a distribution feeder or on a substation bus. Because of this, it is beneficial to leave some capacitor banks connected at all times. These are referred to as fixed banks and form a baseline of minimum reactive compensation. But, if a utility installs enough fixed banks to compensate for peak inductive demands, there can be too much capacitance at times of light load, resulting again in excessive and unprofitable reactive demand [1] [4].

To minimize reactive demand at all times, capacitive compensation on the distribution feeder can be dynamically adjusted to closely match the inductive demand of the feeder in real time. This can be accomplished with switched capacitor banks that can be connected to the feeder as inductive demand increases and disconnected from the feeder as inductive demand decreases. Switched banks typically operate automatically using a capacitor bank control (CBC) that determines when the feeder's reactive demand requires more or less capacitance and connects or disconnects the bank accordingly. Today, there are multiple control algorithms available, and they all determine the need for reactive compensation from different types of inputs.

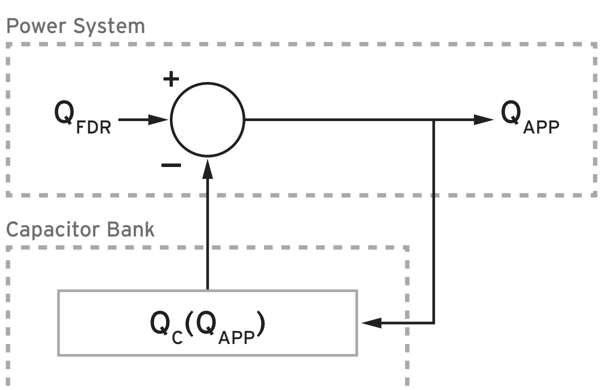
CBC Methods

CLOSED-LOOP CONTROL METHODS

Closed-loop control methods use the desired output as an input to the control scheme and respond directly to the desired output. For a capacitor bank, the desired output may be to minimize VAR demand, hold a target power factor (PF), or regulate voltage. Utilities can examine the effect of each different control method on the power system by modeling the power system with a control block diagram. This tool can also help evaluate how to set a CBC using each method to produce the desired output.

VAR CONTROL

VAR control is a simple and stable control method. The connection and disconnection of a capacitor bank to the power system has a direct additive effect on apparent VAR demand, and the effect can be measured directly with no influence from other uncontrolled factors [1]. In Figure 3, the apparent VAR demand of the feeder (Q_{APP}) is the result of the native VAR demand of the feeder (Q_{FDR}) minus the capacitor bank's VAR contribution (Q_C). Q_C is a function of Q_{APP}. The CBC measures Q_{APP} as a feedback input to determine when to connect and disconnect the capacitor bank. When connected, the capacitor bank contributes Q_C equal to the bank rating (Q_{RATED}), and when disconnected, it contributes Q_C equal to 0. The $Q_C(Q_{APP})$ function shown in Figure 3 demonstrates the typical settings for a VAR-controlled CBC.

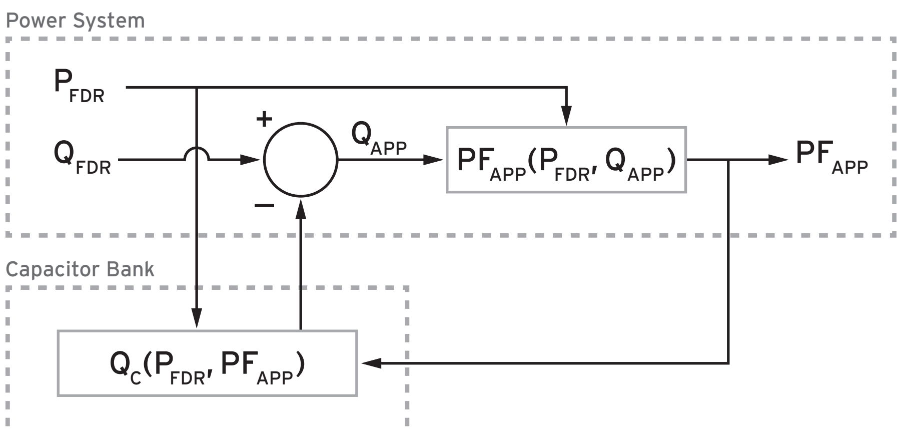


$$Q_C(Q_{APP}) = \begin{cases} Q_{RATED} \text{ if } Q_{APP} > 0.67 \cdot Q_{RATED} \\ 0 \text{ if } Q_{APP} < -0.50 \cdot Q_{RATED} \end{cases}$$

Figure 3—VAR control block diagram.

POWER FACTOR CONTROL

PF control is a typical option for capacitor banks to maintain a target PF. This may be more common at a metering point where a PF penalty could be applied. Because of the trigonometric relationship between active and reactive power, the capacitor bank's contribution (Q_C) does not provide a simple additive contribution to the apparent PF (PF_{APP}). In other words, the power factor with the bank switched on (PF_{ON}) is not equal to the power factor with the capacitor bank switched off (PF_{OFF}) plus the capacitor bank's contribution (Q_C). In fact, at a very light load, the connection of the capacitor bank could make PF_{APP} worse by creating an excessive leading PF [1]. For this reason, a PF-controlled CBC will typically also employ active power as a feed-forward input to create minimum active power supervision (P_{MIN}), as shown in Figure 4.



$$PF_{APP} = \frac{P_{FDR}}{\sqrt{P_{FDR}^2 + Q_{APP}^2}}$$

$$Q_C(P_{FDR}, PF_{APP}) = \begin{cases} Q_{RATED}, \text{ if } PF_{APP} < 0.97 \text{ LAG} \\ 0, \text{ if } PF_{APP} < 0.97 \text{ LEAD} \\ 0, \text{ if } P_{FDR} < P_{MIN} \end{cases}$$

Figure 4—PF control block diagram.

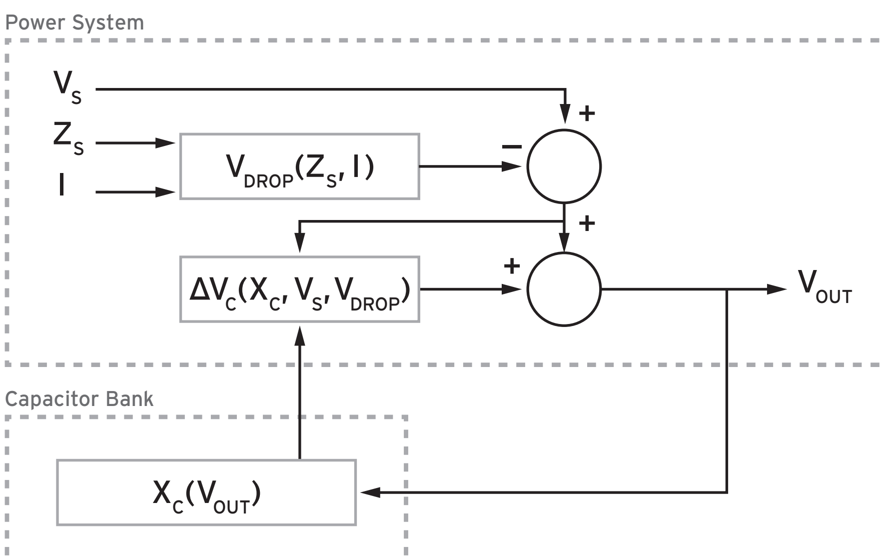
OPEN-LOOP CONTROL METHODS

In the absence of available current measurements, two common open-loop control methods are voltage control and time-and-temperature control. The settings for these methods must be developed empirically, often leading to a trial-and-error approach that may take several load seasons to stabilize.

VOLTAGE CONTROL

Utilities may use a switched capacitor bank for gross voltage regulation and, as such, can use voltage as a closed-loop feedback input with no current measurements [1]. It is easier to study the effects of the capacitor bank on voltage by considering its reactive impedance (X_c) rather than its reactive power contribution. However, the X_C of the capacitor bank is only one of many inputs used to determine the output voltage (V_{OUT}) at the capacitor bank. Other inputs influencing the output are the source voltage (V_S), load current (I), and source impedance (Z_S). Because a voltage control does not measure these inputs, this form of control is still predominantly open-loop.

Therefore, voltage control is useful for operation over a wide deadband, such as the example in Figure 5. It may be used as an override control in conjunction with a VAR or PF control to block or recover from operations that result in excessive voltage excursions. It may also be used where current measurements are simply unavailable or may not relate to the feeder's VAR demand, such as when a capacitor bank is installed at the end of a feeder or on a lateral.



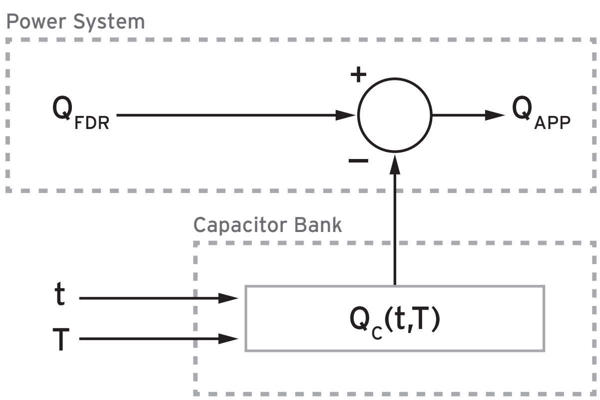
$$X_C(V_{OUT}) = \begin{cases} \dfrac{V_{RATED}^{\,2}}{Q_{RATED}}, \text{ if } V_{OUT} < 0.97 \text{ PU} \\ 0, \text{ if } V_{OUT} > 1.03 \text{ PU} \end{cases}$$

$$\Delta V_C(X_C, V_S, V_{DROP}) = \frac{(V_S - V_{DROP})}{\left(\dfrac{1 - Z_S}{jX_C}\right) - (V_S - V_{DROP})}$$

Figure 5—Voltage control block diagram.

TIME-AND-TEMPERATURE CONTROL

Time (t) and temperature (T) can be used as rough indications of the reactive demand on a distribution feeder. On residential and commercial feeders, reactive demand will typically increase with temperature due to the air conditioning compressor load, and daily peaks can often be predicted by normal hours of business or residential occupancy. However, the relationship between VAR demand and time or temperature is not quantitatively predictable. At best, it can be modeled empirically and could be unique to each distribution feeder. Time-and-temperature control is a completely open-loop control method that can only be set by trial and error or by empirical modeling, such as in [4]. A typical control scheme using time and temperature is shown in Figure 6. This scheme is an entirely open-loop method with no feedback signal and no means of self-correction.



$$Q_C(t,T) = \begin{cases} Q_{RATED}, \text{ if } t_{ON} < t < t_{OFF} \\ Q_{RATED}, \text{ if } T > T_{ON} \\ 0 \text{ if } T < T_{OFF} \end{cases}$$

Figure 6—Time-and-temperature control block diagram.

SELECTION OF CBC METHOD

The most obvious input values to use in a CBC are voltage and current, which enable the direct measurement of the reactive demand that the capacitor bank compensates. Voltage is readily available to CBCs because of the ac voltage supply that must be provided to power the control. Current measurement can be more difficult to acquire because an additional current transformer or current line post sensor must be installed, which can be expensive and difficult. As a result, there have typically been two basic solutions in the industry. One solution has been to make the best of the open-loop control methods in lieu of current measurements. Another solution has been to continue improving current measurement technologies by developing lower-cost current sensors that are easier to install than previous sensors or current transformers. The latter solution enables the closed-loop control methods that offer superior control and are easier to set.

<table>
<tr><th>CONTROL TYPE</th><th>STRENGTHS</th><th>WEAKNESSES</th></tr>
<tr><td>Voltage</td><td>Easy to implement using the same PT that powers the control.</td><td rowspan="2">These are open-loop methods. They provide rough indications of reactive demand and offer minimal feedback for switching decisions, which can lead to improper switching and inefficient distribution systems. Measuring successful switching operations is difficult.</td></tr>
<tr><td>Time and Temperature</td><td>Easy to implement as this type of control requires no power system inputs. Only time and temperature are needed.</td></tr>
<tr><td>Power Factor</td><td rowspan="2">These methods enable direct measurement of reactive demand on the distribution system, meaning that you can operate your capacitor bank switch with confidence and measure the results of the operation in a closed-loop manner.</td><td rowspan="2">These methods require current sensing, which can be difficult to install and expensive. Low-cost sensors or new wireless sensors can mitigate this difficulty.</td></tr>
<tr><td>VAR</td></tr>
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Table 1—CBC Method Strengths and Weaknesses

Simple Closed-Loop Control With Wireless Current Sensing

The SEL-734W Capacitor Bank Control and LINAM Wireless Current Sensor (WCS) solution (shown in Figure 7) offers low-cost wireless sensors that offer the benefits of current-enabled control without the difficulty of expensive and hard-to-install line post sensors.

Figure 7—SEL-734W and LINAM WCS solution makes the transition to closed-loop control much easier.

The solution consists of two parts: the sensor and the control. The sensor is entirely line-powered, meaning personnel will never need to replace a battery. It measures current over a period of several cycles and reports an rms value to the control. It also transmits harmonic values as a percentage of the fundamental current value.

The control receives the message from the sensor without the need for any separate receiver device. It translates the frequency and rms value of the current into a waveform, and from there it behaves like a traditional capacitor control. The SEL-734W is a versatile device that can be equipped with custom control logic to fit any CBC application and includes simple-to-set, preconfigured control schemes. The control lets utilities improve power quality and address customer concerns with advanced monitoring features, such as harmonic measurements, load profile trending, and voltage sag, swell, and interruption (VSSI) recording.

The SEL-734W and LINAM WCS solution addresses the following common problems experienced by distribution engineers trying to support CBC.

INSTALLING TRADITIONAL SENSORS IS COSTLY AND TIME-CONSUMING

CBCs can improve the efficiency of the power system and save the utility money. Historically, the efficiency gains from current-enabled capacitor control could not always justify the costs of installing the required line post sensors or additional current transformers, and utilities often opted for cheaper and less-effective alternatives, like voltage control or time-and-temperature control. Wireless sensors can reduce the total cost of a capacitor bank installation, making closed-loop control much more attractive. The LINAM WCS installs on an overhead distribution line with a single hot stick. There is no need for an outage or significant hot-line work, which keeps customers happy and utility personnel safe.

Figure 8 shows a cost comparison of the traditional method of current-based control compared to the SEL CBC and WCS solution.

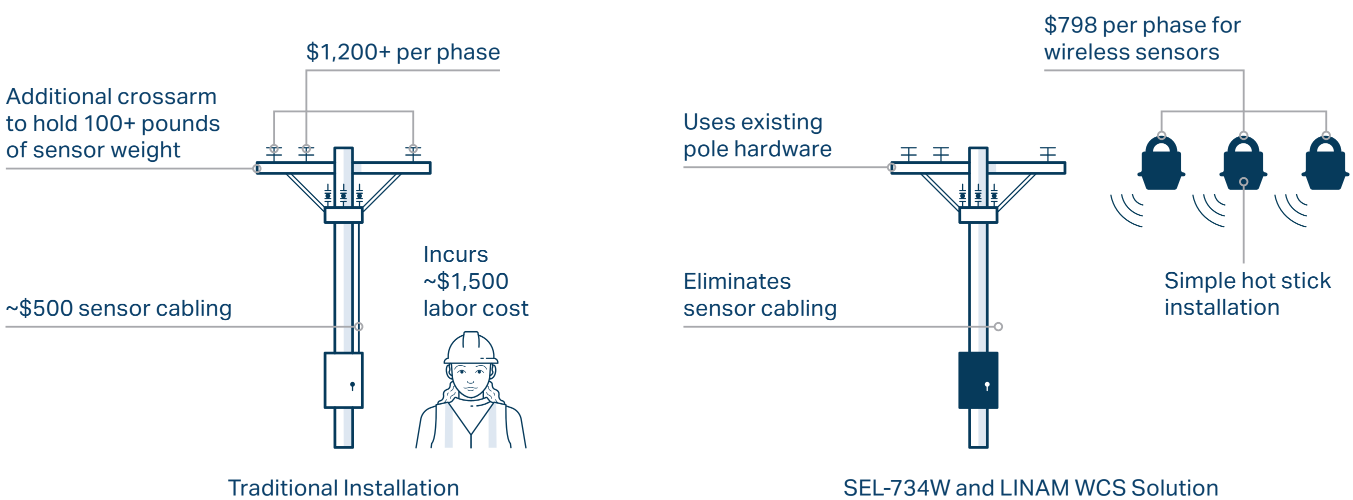

Figure 8—Cost comparison between a traditional installation and the SEL-734W and LINAM WCS solution.

With the LINAM WCS, there is no need for extra pole hardware or expensive and complicated sensor cabling. There is no need to identify the right cables to interface between the control, junction box, switch, and sensors. With wireless sensors, the only necessary connection is the control cable to the switch itself, along with the voltage to power the control. And instead of purchasing different-sized sensors based on the line voltage, utilities can purchase just one sensor and apply it at any distribution voltage up to 38 kV. Factoring in the costs for the labor, sensors, junction box, and possible pole hardware, the wireless solution could save thousands of dollars, possibly more than the entire cost of the control!

INSTALLING TRADITIONAL SENSORS CAN BE UNSAFE FOR DISTRIBUTION LINE PERSONNEL

Utilities generally have two choices when installing a CBC with sensors. They can choose an outage, during which they will have to reconfigure their power system and possibly shut off power for their customers, or they can install the sensors on an energized power line. Typically, the utility will choose to do the hot-line installation to avoid the outage. Any hot-line work can be dangerous for line personnel.

Installing line post sensors can be especially dangerous due to the weight of the sensors. Traditional line post sensors can be as heavy as 50 pounds. Carrying more than 50 pounds of sensor up the line and installing it with thousands of volts nearby can be unsafe for personnel.

Installing the lightweight LINAM WCS using a hot stick is much safer because it places line personnel farther away from the high-voltage power lines. The job can be finished in minutes, greatly reducing the risk of electrocution, falls, and other injuries.

CAPACITOR BANKS ARE NOT ALWAYS IN THE OPTIMAL LOCATION

For capacitor banks, control and switching typically occur at the same physical location. The sensor, the control, and the capacitor bank are usually co-located. With wireless current sensing, this is no longer required. Personnel can make a measurement at one location and use that measurement to make a control decision at a different location.

This is useful because sometimes the control and the capacitor bank are in the wrong spot. For example, because of right-of-way concerns, maybe a control was installed on a feeder tap instead of on the main line. That control is compensating for some upstream inductive load on the main feeder, but at the control position, the PF is perfectly fine. With the LINAM WCS, utilities can measure the inductive load on the main feed but still make control decisions at another location.

With the SEL-734W and LINAM WCS, utilities can now use the capacitor bank at one point on the system while controlling another point on the system. They can mount the wireless sensors up to 1,500 feet away from the capacitor bank installation, closer to inductive loads where VAR demand is a better indicator of the need for compensation (depending on the line of sight), as shown in Figure 9.

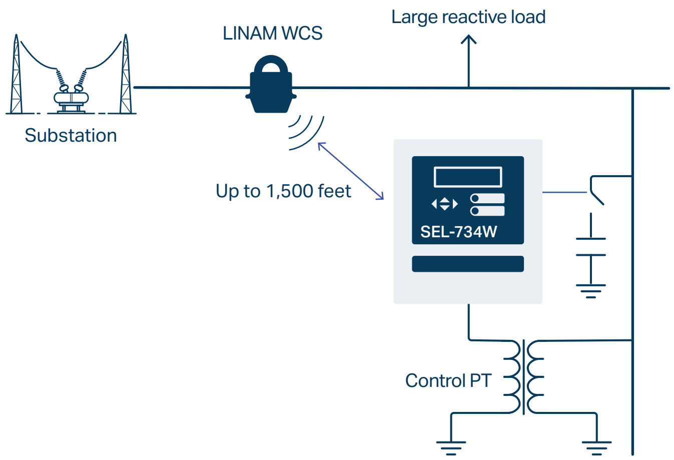

Figure 9—The LINAM WCS provides current measurement of feeder to SEL-734W installed on lateral tap.

Conclusion

Previous generations of CBCs did not measure load current and made switching decisions based on factors like time and temperature. Modern controls are capable of measuring load current using line post sensors, allowing those controls to switch capacitor banks based on reactive power or power factor. However, these line post sensors are very bulky and difficult to install.

Today's CBCs must be equipped with current sensing, both to make better switching decisions and to give better visibility into an increasingly smarter and more complex electrical grid. Using the SEL-734W and LINAM WCS solution takes the pain out of this transition and provides the following benefits:

- Easy installation.
- Cost savings—both for the sensors and the associated cables and pole hardware.
- Simple stocking for sensors—utilities can purchase one sensor type for all distribution voltages up to 38 kV.
- Measurement at a distance to enable new capacitor control applications.

CBCs optimize system efficiency and control line voltage. With the new wireless solution, utilities can achieve these goals and optimize their distribution systems with better accuracy and less costs, both in terms of money and time.

References

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Biographies

Ben Rowland received his BS in engineering management with an emphasis in electrical engineering from Gonzaga University in May 2014, after which he began working for Schweitzer Engineering Laboratories, Inc., as an associate application engineer. Ben has worked in the fields of precise timing, wireless communications, distribution controls, and sensors. Ben currently holds the position of product line owner for capacitor bank controls and voltage regulator controls.

Jeremy Blair, P.E., joined Schweitzer Engineering Laboratories, Inc., as an application engineer in 2013. Previously, he worked for Entergy Corporation as a distribution planning engineer with responsibilities in distribution system planning, protection, power quality, and automation in Baton Rouge, LA. He also managed Entergy's Automatic Load Transfer and Sectionalization Program over its four-state territory. Jeremy earned his BSEE from Louisiana Tech University and his MSECE from Georgia Institute of Technology. He is a licensed Professional Engineer in the state of Louisiana.

Kei Hao, P.E. (M 2011), received his PhD in electrical engineering from the University of Wisconsin—Madison, his MSEE from the University of Wisconsin—Milwaukee, and his BSEE from La Universidad de la Republica, Uruguay. He joined Schweitzer Engineering Laboratories, Inc., in 2010 and has worked as an automation and protection engineer in the Engineering Services division. He is presently a development lead engineer in research and development. He has experience in the fields of control and automation systems, wireless communications systems, and power system automation and protection. He is a member of IEEE and a registered Professional Engineer in the state of California.

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