Capacitor Bank Protection for Simple and Complex Configurations

Roy Moxley, Jeff Pope, and Jordan Allen
Schweitzer Engineering Laboratories, Inc.

This paper was presented at the 65th Annual Conference for Protective Relay Engineers and can be accessed at: http://dx.doi.org/10.1109/CPRE.2012.6201251.

For the complete history of this paper, refer to the next page.

Presented at the
65th Annual Conference for Protective Relay Engineers
College Station, Texas
April 2–5, 2012

Previously presented at the
11th Annual Clemson University Power Systems Conference, March 2012

Originally presented at the
38th Annual Western Protective Relay Conference, October 2011

Capacitor Bank Protection for Simple and Complex Configurations

Roy Moxley, Jeff Pope, and Jordan Allen, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Economical operation of modern power systems requires more distributed voltage support than ever before. Load and distributed generation characteristics have both changed to require increased VAR support throughout the power system. Substation capacitor banks are the most economical form of adding VARs to the system, yet because of harmonics, grounding, and operational concerns, there are many different types of capacitor banks. Capacitor banks also form the heart of filter banks necessary for the application of high-voltage direct current (HVDC) and other flexible ac transmission systems (FACTS) devices. These filter banks also come in a variety of connection types.**

Microprocessor-based relays make it possible to provide sensitive protection for many different types of capacitor banks. The protection methodology is dependent on the configuration of the bank, the location of instrument transformers, and the capabilities of the protective relay. This paper details the protection methods applied to traditional grounded and ungrounded banks, as well as a number of novel banks with connections that are far from traditional.

This paper discusses the application, sensitivity, and speed of the applied protection schemes. Bank configurations studied include traditional as well as C-type filter banks, capacitively grounded banks, and double H banks. Applications beyond protection, such as capacitor fault location, are also discussed to provide added benefits to substation personnel.

I. Introduction

Capacitor banks are designed with many configurations to meet system design constraints, and the protection engineer must be prepared to protect any of these configurations. The inputs available to the relay are voltage and current, with the instrument transformer location determined by the bank configuration. This paper describes three significantly different types of banks and uses real-time simulation to evaluate protection effectiveness and stability for each application. The banks studied include both fuseless and internally fused designs. The same principles apply to an externally fused bank as to an internally fused bank. But, typically, externally fused capacitor banks have higher failure voltages and currents than fuseless or internally fused banks because an external fuse blowing causes the loss of an entire unit. As a point of reference, fuseless capacitor banks have a unit construction, as shown in Fig. 1 [1].

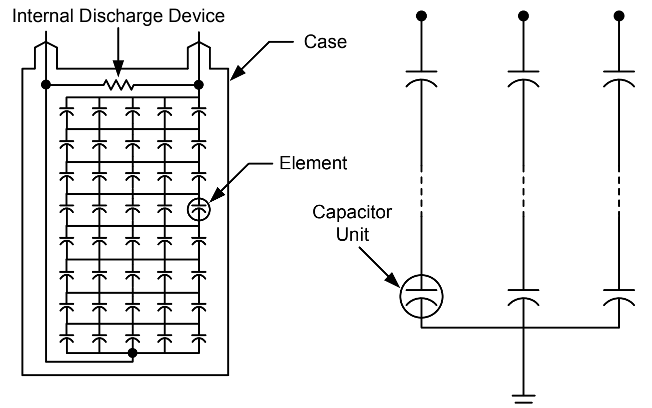

Fig. 1. Fuseless unit in a wye-connected bank

Note that in fuseless construction, when a single element fails, it shorts out those units in parallel with it, increasing the voltage stress on the remaining series units.

An internally fused bank has fuses on each individual element, as shown in Fig. 2.

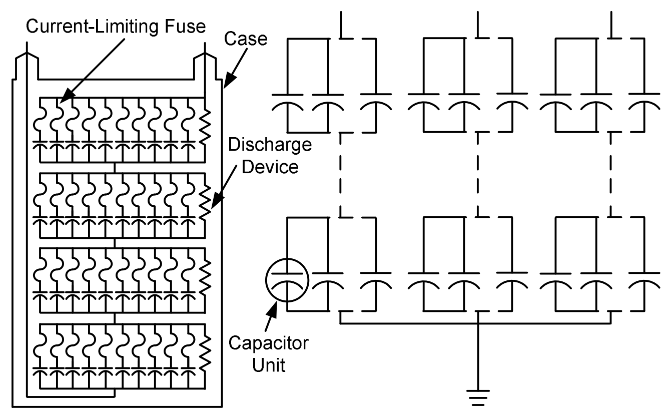

Fig. 2. Internally fused unit in a wye bank

In the case of an element failure in an internally fused bank, when the fuse to the failed element blows, the voltage stress is increased on the elements remaining in parallel with the failed element.

The objective of bank protection is, ideally, to detect individual element or fuse failures and give enough advance indication of problems within the capacitor bank to prevent a cascading collapse when too many individual elements fail.

For all the banks studied, it is assumed that overcurrent protection is provided on the line side of the bank for tripping in case of a phase-to-phase or phase-to-ground fault. The objective of the capacitor bank protection is to alarm on the failure of some minimum number of elements or units and trip on some higher number of failures. It is, of course, desirable to detect any element failure.

II. Element and Unit Failures Examined

A. Double-Wye Bank

The first bank to be examined is a standard double-wye bank with a grounding unit, as shown in Fig. 3. The numbers given are the capacitance of each portion of the bank in microfarads. This bank is rated 2 MVAR, 69 kV.

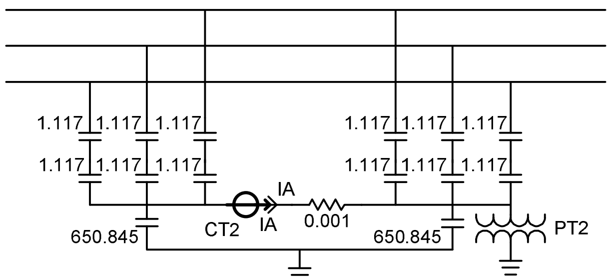

Fig. 3. Double-wye capacitor grounded bank

In this configuration, it is common to only use the current balance to provide the bank protection. We are interested in looking at the sensitivity comparison between the voltage differential element and the current balance protection. Voltage differential is derived from potential transformer (PT) PT2 and a high-side PT (not shown). Current balance is measured at current transformer (CT) CT2. CT1 (not shown) is used for bank overcurrent protection.

Converting to reactance values, the total reactance above the wye point is –j4799 ohms. The reactance below the wye point is –j4.076 ohms. PT2 uses the voltage developed across the reactance below the wye point as an input. This becomes a significant sensitivity issue when we consider that each capacitor bank has multiple series sections and we want to detect the failure of just one series section.

Fig. 4, Fig. 5, and Fig. 6 show currents and voltages for failures of one, two, and three series elements. In these figures, the differential current flowing in CT2 is shown in the upper trace. Differential voltage, the difference between PT2 and the high-side PT, is shown on the lower trace. Relay element pickups are shown at the bottom. The 87 elements are voltage-based, and the 60 elements are current-based. Relay elements were set as recommended by the manufacturer, with alarm delays for low-level failures and higher-speed operation for severe failures.

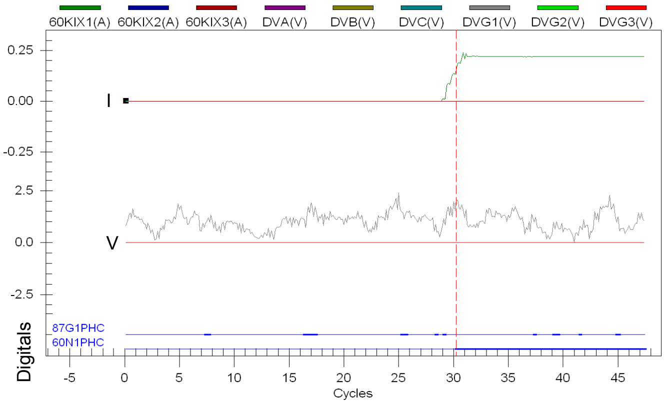

Fig. 4. Double-wye bank, single element failure

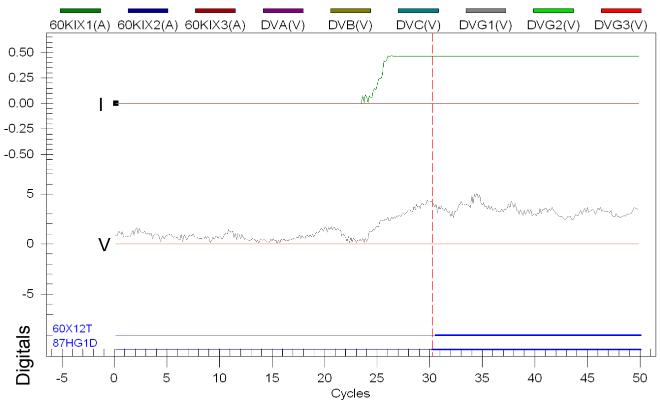

Fig. 5. Double-wye bank, two elements failed

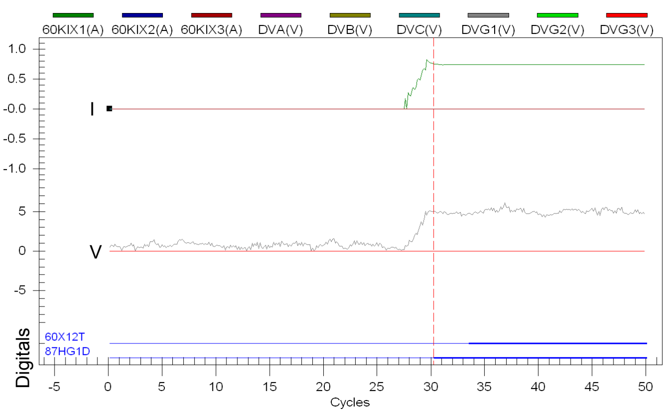

Fig. 6. Double-wye bank, three elements failed

Note that in Fig. 4, the differential current rises at the time of failure, while the differential voltage remains at a very noisy 0.5 to 2.5 V level. None of the voltage elements has a stable operation. For two failed elements (Fig. 5), the voltage signal still has a very low signal-to-noise ratio with about a 2 V noise signal before and after the fault, with a differential voltage of just under 5 V after the element failure. However, it can be reasonably seen that the voltage goes up along with the current. In this case, the 87HG1D (time-delayed voltage) element operates at essentially the same time or even slightly before the 60X12T current element. By the third element failure (Fig. 6), we can see that the voltage signal is strong and stable, having almost the same signal quality as the current signal.

We were concerned about the noise observed in the differential voltage circuit. By looking at the high-side voltage and the differential voltage (Fig. 7), we can see the issue. The magnitude of the differential element is virtually the same before and after a single element failure (Cycle 30), varying as much as 2 V because of the low signal-to-noise ratio on the circuit. The primary voltage at the same time is 40 kV, peak to peak. Even considering scaling of PT circuits, the differential voltage generated by a single element failure in the wye bank is so small compared with the primary voltage that a meaningful detection of a single element failure by a voltage element is not possible. We are of the opinion that in an actual substation, the same problem is highly likely to occur.

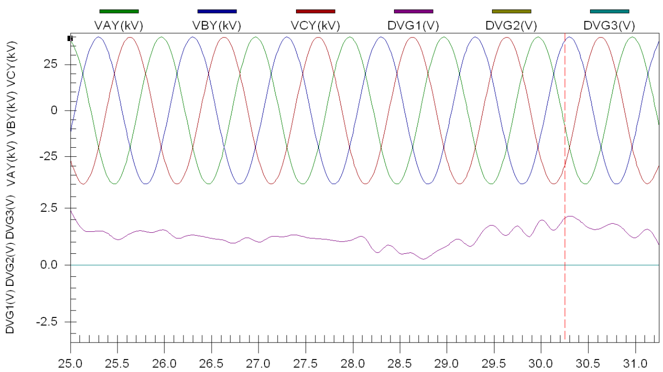

Fig. 7. Double-wye bank, primary voltage and differential voltage before and after a single element failure

B. Double H Bank

The second bank studied was installed for power factor correction in an area where high fifth-harmonic voltage, caused by overfluxing of the station transformers, was a concern. In this case, a tuning reactor and resistor were added to protect the bank during this condition, as shown in Fig. 8.

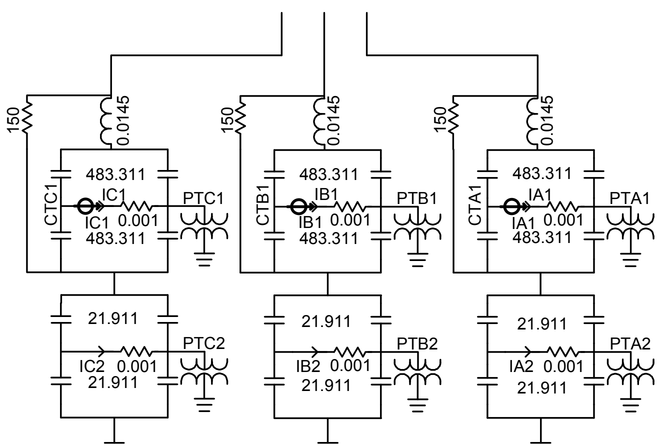

Fig. 8. Double H bank with tuning reactor and resistor

This bank uses internally fused capacitors, meaning that the failure of a single element only removes the failed element, not the elements in parallel, as in the case of a fuseless bank (faulty element shorts out all parallel elements). This means that individual element failures are much more difficult to detect. The objective of the protection was to operate for a failure of 1 percent of the elements and trip on element failures that would result in a voltage rise on healthy elements in excess of 110 percent of the rated element voltage. The user stated that the preferred protection was a voltage differential measurement comparing the intermediate voltage in each H section with the primary bus voltage. Current balance measurement using CTs connected between branches was available as backup protection if the voltage protection was not sensitive enough. Primary bank failure protection included negative-sequence directional overcurrent and bank overvoltage, as well as the current- and voltage-based protection to detect failed elements and units, as shown in Fig. 9, Fig. 10, and Fig. 11.

The first test was to fail one element in the main portion of the bank and verify that this could be detected. The main portion of the bank is identified as that portion with only capacitance and no resistive or inductive components. Fig. 9 shows both voltage and current elements resulting from the failure.

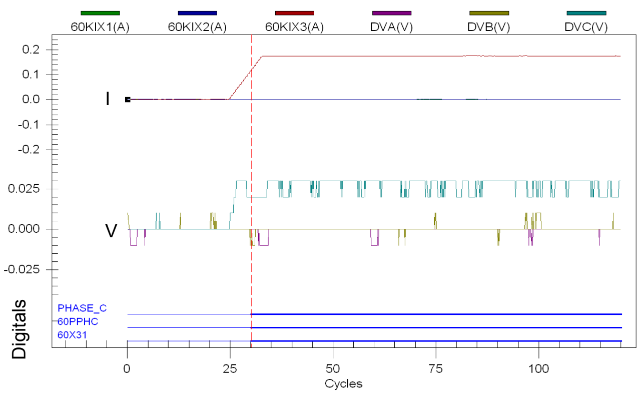

Fig. 9. Double H bank, single element failure

In Fig. 9, the current measurement is the top trace and the voltage measurement is the middle trace, with the relay digital element pickups shown on the bottom traces. While there was an increase in the differential voltage, the magnitude change of 25 mV is only marginally larger than the noise. The current element going from very near 0 to 0.2 A provides a much better signal.

The failure of two elements, as expected, shows a doubling of the operating signals, without an increase in the noise in the voltage measurement (Fig. 10).

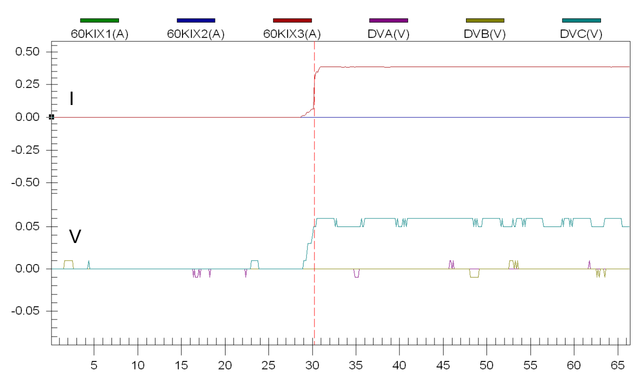

Fig. 10. Double H bank, two failed elements

In Fig. 10, we see that the current signal (top trace) is much more stable than the voltage signal (bottom trace). The voltage rise is slightly faster than the current rise, but with normal alarm time delays of 5 to 10 seconds, this is not significant.

Finally, we investigated a complete unit failure. Fig. 11 shows the results, with the generated unbalance current shown on the top trace and the differential voltage on the bottom trace.

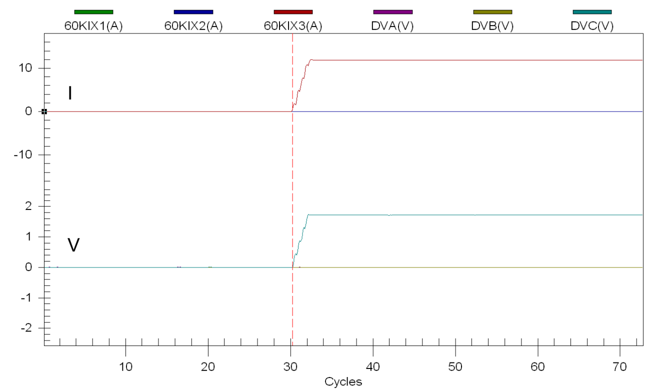

Fig. 11. Double H bank, failed unit

In this case, the voltage element has a strong and solid operating signal with a rise time almost precisely the same as the current element.

C. C-Type Filter Bank

The last bank protection tested was a C-type filter bank. In this case, the construction is very similar to the double H bank in Fig. 8, with different resistors selected for the desired frequency response. The circuit is tuned so the fundamental current flows through the capacitors while harmonic current flows through the resistors. Part of the protection was current elements on the resistors to protect against overheating. This protection was part of the overall bank protection but not included in our tests because it depends entirely on the harmonic voltages present at the bank location (Fig. 12). This bank is a fuseless bank, so the failure of a single element results in the shorting of all elements in parallel with the failed element. The protection of the actual bank did not use mid string voltage differential protection, only current balance protection. We simulated mid string PTs to investigate their performance as compared with current-based protection.

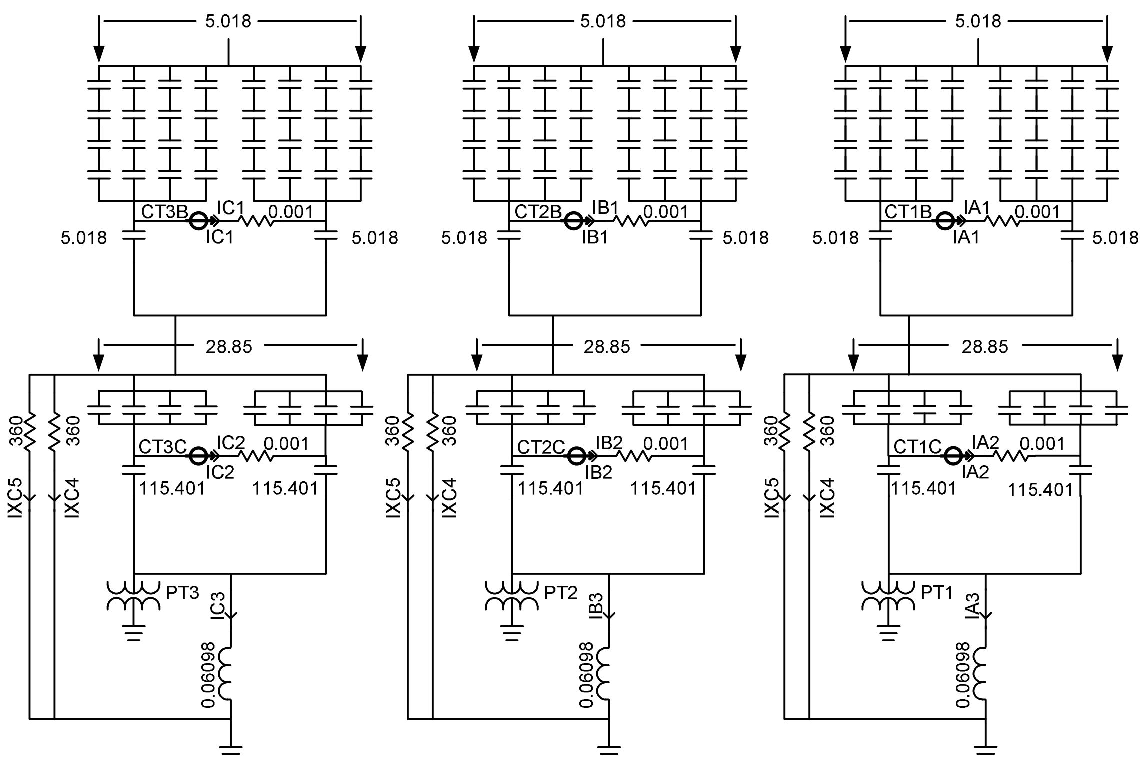

Fig. 12. C-type filter bank model (numbers refer to individual capacitor values applied in failure tests)

The protection must detect failures in either the main portion of the bank (upper graph in Fig. 13) or the tuning portion of the bank (lower graph in Fig. 13).

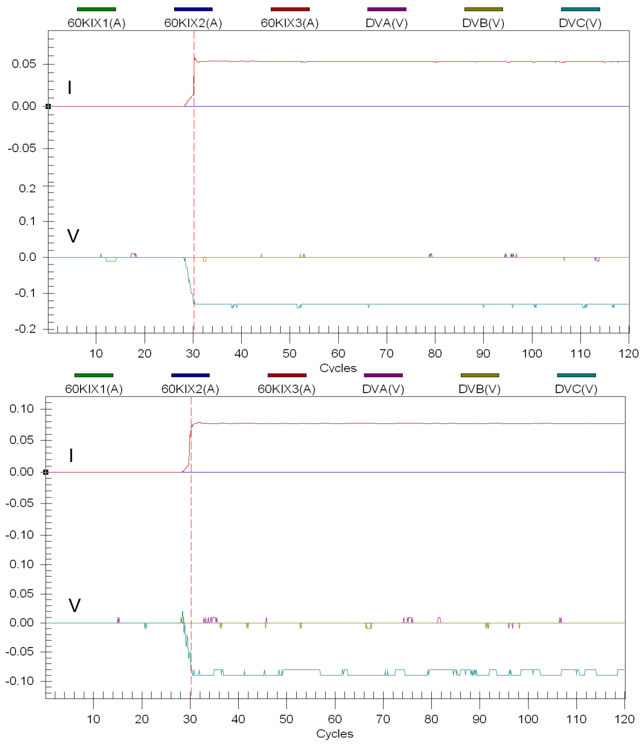

Fig. 13. C-type filter bank, single element failure in main (upper graph) and tuning bank (lower graph)

As in the other bank examples, there is significantly more noise in the voltage differential measurement than in the current unbalance. In the case of an element failure in the tuning portion of the bank, the voltage element has somewhat more noise than the main portion failure but still provides good sensitivity and a reasonable backup to the current-based protection. As is expected, the failure of two elements provides measuring quantities twice as large as a single failure with no increase in the noise, resulting in a much better signal-to-noise ratio and a more stable operating characteristic.

D. Faulted Element Location

In an externally fused bank, it is trivial to find the faulted capacitor unit. The spring-loaded fuse pops out when a failure occurs, requiring only visual inspection to find the faulted fuse. An internally fused or fuseless bank does not provide this indication. Modern, all film, capacitors do not bulge (caused by internal gassing) when a failure occurs. The question is then asked, “How do we find the faulted unit when an alarm is given?” The faulted element location is indicated in the following two steps:

- Phase identification is given in each of the three-phase banks in these examples. If a neutral balance system is used, then there is no identification. Individual protection elements, per phase, are preferred.
- Voltage elements provide indication if the faulted element is above or below the measurement point. Consider the voltage trace in Fig. 13, –0.1 V, and that of Fig. 10, +0.05 V. This identifies if the failure is above or below the PT connection point.

In a double H bank construction, with PTs and CTs on each leg, the number of units to be checked for an alarm will be as low as 1/24 of the total number of capacitor units. This can save hours or days of testing, depending on bank size.

III. Complicating Factors

The simulations performed used banks with balanced capacitors in each leg. This is a best-case condition, and real-world factors must be considered when evaluating and setting protective relays. Anything that causes a steady-state or transient unbalance condition should be considered. Modern protective relays typically provide advanced compensation logic to nullify any standing unbalance in order to maximize the sensitivity of the voltage differential and current unbalance elements.

A. Manufacturing Tolerances

Standards recognize that manufacturing tolerances can lead to variation in capacitance among individual units of the same rating [2]. To meet standards, the rating must be from minus 0 to plus 10 percent. Capacitor bank manufacturers generally place units into a bank to limit the unbalance to less than 0.5 percent [3]. Steady-state unbalances of this size can be zeroed out in a voltage or current balance system by adjusting the compensation when it is known (or presumed) that all elements or units are healthy. Note that this needs to be done whenever a unit is changed, because the replacement unit may or may not have the same capacitance as the unit it replaces.

B. Solar Radiation Impact

A special case of unbalance caused by differences in unit capacitance is caused by the sun shining on one side of a capacitor bank and not the other, as shown in Fig. 14. Here, we see the sun shining on the right side of the bank, while the left side sits in the shade.

Fig. 14. Capacitor bank with sun on right side

The change in capacitance from solar heating can come from three different causes:

- The dielectric film (usually polypropylene) changes with temperature.
- The dielectric fluid (mineral oil or other fluid) changes with temperature.
- Heating of the dielectric fluid causes expansion, better permeating the film.

Solar heating varies depending on location, orientation of the bank, and other factors, such as wind or nearby equipment. One study showed a 10°C variation simply from the bottom of an outdoor cabinet to the top on a sunny day [4]. Relay operations have been observed on capacitor banks when the rising sun hits one side, causing heating.

The traditional way to compensate for unequal heating and the unbalance it causes is to increase pickup settings. Accurately addressing transient changes in capacitance requires more sophistication than compensating for a fixed difference between bank strings. A temperature input, or two inputs, can be brought into the relay to change settings groups or increase pickup values. The relay uses the value of temperature, or the temperature difference, to modify pickup values. A single temperature measurement above a threshold value can be used to raise pickup settings. If multiple temperatures are provided, the settings can be dynamically changed to compensate for the change in capacitance on one side of the bank. Logic can be implemented within the capacitor protective relay to combine temperature inputs with alarm values, blocking alarms if unbalance slowly changes. The challenge of detecting transient changes in capacitor bank impedance is being able to reliably distinguish between an actual failure within the capacitor bank and the transient conditions described previously. Relay logic can distinguish between sudden changes from element failures and gradual changes due to temperature shifts or even unit aging.

One possible drawback of any of these possibilities is that, depending on bank construction, failures may start small, with one element failing, followed by another failure and another failure. Experience may provide the best guide for a given location.

IV. Conclusion

The many variations in capacitor bank design mean there is no one-size-fits-all solution to bank protection. The basic concepts of short-circuit protection and element failure detection remain unchanged, regardless of bank design. We recognize that different protection types are useful for different conditions. The lessons learned from these failure tests on complex capacitor banks include the following:

- Failure of even a single element can generally be detected by voltage or current protection elements, even on internally fused banks. Reliable detection of element failures in very large banks may require more failures because the signal-to-noise ratio may prohibit reliable detection of individual element failures.
- Current measurements are generally more sensitive than voltage measurements for capacitor bank unbalance. Low-level current measurements exhibit less noise than low-level voltage measurements.
- Voltage-based protection elements are as fast or faster than current-based elements, making them suitable for protecting against catastrophic failure.
- To meet the need for complete protection, voltage, current, additional input capability, and flexible logic should be available and applied.

V. References

[1] M. Dhillon and D. Tziouvaras, "Protection of Fuseless Capacitor Banks Using Digital Relays," proceedings of the 26th Annual Western Protective Relay Conference, Spokane, WA, October 1999.

[2] IEEE Standard for Shunt Power Capacitors, IEEE 18-2002.

[3] E. Price and R. Wolsey, "String Current Unbalance Protection and Faulted String Identification for Grounded-Wye Fuseless Capacitor Banks," proceedings of the 65th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2011.

[4] F. Gutierrez, R. Moxley, D. Kopczynski, and D. Holmes, "Relays in the Hot Box," proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

VI. Biographies

Roy Moxley received his B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2000 as market manager for transmission system products. He is now marketing manager for all protection products. He has authored and presented numerous papers at protective relay and utility conferences. Prior to joining SEL, he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the state of Pennsylvania and a member of IEEE and CIGRE. He was awarded a patent in the area of wide-area measurements.

Jeff Pope is the senior product engineer for the transmission product group at Schweitzer Engineering Laboratories, Inc. Jeff is a member of the IEEE Power Engineering Society and has been involved with the commissioning, control, protection, monitoring, and automation of power system apparatus for 20 years. Jeff received his BSEET in 1986 from the DeVry Institute of Technology and his Masters of Engineering from University of Wisconsin-Madison in 2005.

Jordan Allen received his A.A.S. in Electronics Engineering Technology and B.S. in Computer Engineering from Brigham Young University, Idaho. Jordan is a member of IEEE and currently interning at Schweitzer Engineering Laboratories, Inc., while working on his Masters of Engineering in Electrical Engineering at the University of Idaho.

Previously presented at the 2012 Texas A&M
Conference for Protective Relay Engineers.

20120217 • TP6505-01