Analyzing Transmission Capacitor Bank Events

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Presented to the
Georgia Tech
Fault and Disturbance Analysis
May 5-6, 2003

Introduction

This paper is intended to demonstrate some of the techniques involved in analyzing transmission capacitor bank operations. In particular, this paper will cover operations of banks that have microprocessor relays utilizing the voltage differential protection scheme. Examples of several unique events are included. While these events may be unusual, the same analysis can be applied to most, if not all, capacitor bank operations. There will first be a short description of the types of banks and then real life examples of some of the more unusual events that have occurred at Dominion.

Description of Capacitor Banks Utilizing Voltage Differential Protection

The transmission capacitor banks on the Dominion system are connected grounded WYE. There is a point somewhere in the bank on each phase where the voltage is measured. This tap point voltage is then compared against the source voltage of the bank. Figure 1 is a functional diagram of a fuseless bank. Figure 2 shows a diagram of a fused bank.

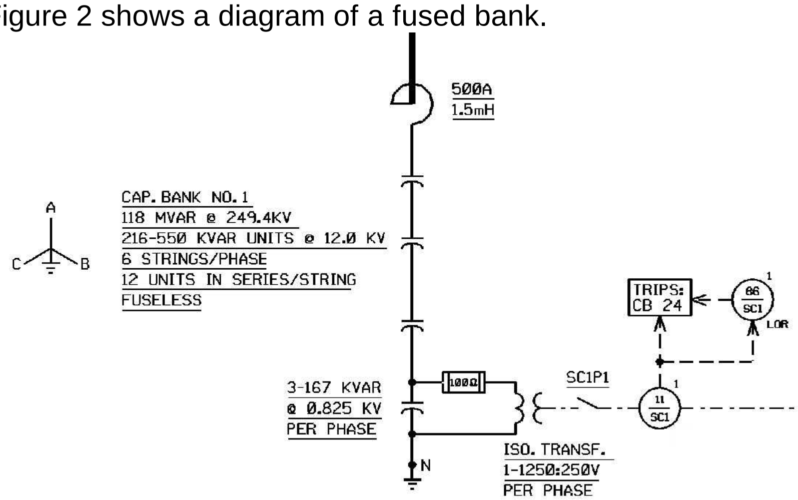

Figure 1 - Fuseless Capacitor Bank Diagram - 230 KV

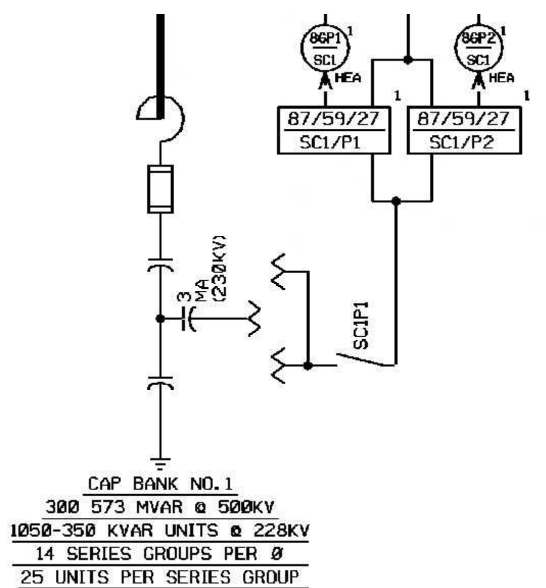

Figure 2 - Fused Capacitor Bank Diagram - 500 KV

The Parts of a Capacitor Bank

Each bank consists of capacitors (cans) connected in a series - parallel combination. Each can is constructed with capacitor packs, also connected in series - parallel combinations. Figure 3 and Figure 4 below give a detailed look at how the cans are constructed and how they fit into the bank.

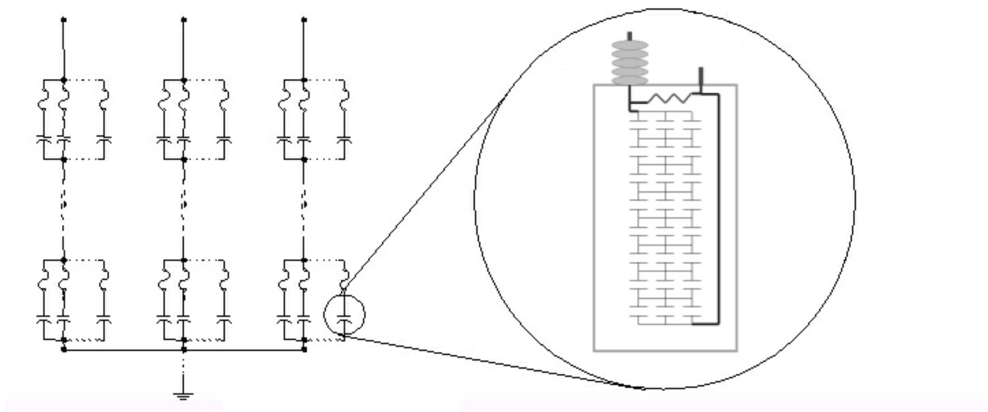

Figure 3 - Fused bank detail

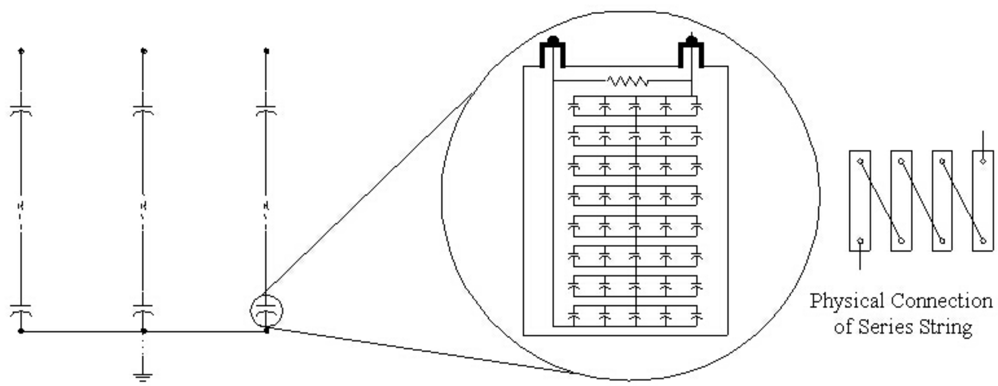

Figure 4 - Fuseless bank detail

Description of voltage differential protection scheme

The voltage differential scheme compares the bus voltage with the voltage at the tap point of the capacitor bank. The tap point voltage is measured by a PT with a smaller ratio than the source PT. For example, on the 500 KV bank in Figure 2, the tap point PT is a 230 KV device. The tap point voltage is usually different than the bus voltage, therefore a multiplication factor is needed. This factor is determined by the PT ratios used and construction of the bank, and then actually measured once the bank is placed in service. The measured value often varies from the calculated value due to slight variations in the capacitance of the individual cans. Once the proper factor is determined, this is used to null the difference in secondary voltages between the bus and the tap point of the bank. Under normal operating conditions, the differential voltage is very close to zero. A capacitance change in any of the cans results in a change in the differential voltage. The formula for calculating differential voltage is:

$$V_{Diff} = V_{Bus} - (V_{Tap} \times K)$$

For example, given a K factor of 1.46, bus voltage of 119.02 and tap voltage of 81.67

$$119.02 - (81.67 \times 1.46) = -0.2182$$

The differential value is -0.2182. Trip values are typically in the 1.5 - 2 volt range, therefore this is an acceptable value. The trip value is based on the number of packs in a can all failing at once. This setting is designed to trip for a ruptured can. The polarity of the voltage can give an indication of where the capacitance has changed - above or below the tap. The value of the differential voltage indicates how much the capacitance has changed. These will be discussed in the following analyses of events.

It can be seen from the above formula that the differential voltage follows the bus voltage and changes inversely with the tap voltage.

Fused Banks

These banks have each capacitor can individually fused. When a capacitor can fails, the fuse blows and takes that can out of service. Usually there will be more than one can in the string that is taken out of service when a fuse blows. The result is slightly lower capacitance on the bank.

When a can fails and blows a fuse above the tap (between the tap and the bus) there will be lower capacitance in that half of the bank so the voltage drop across that portion will be higher. This results in a lower tap voltage. Therefore, the differential voltage will go in a positive direction. When a can fails below the tap then the differential voltage will move in a negative direction. Remember that less capacitance means higher impedance, and therefore, a higher voltage drop.

At Dominion, most of the fused banks have about 60% of the bank above tap and the remaining 40% below tap.

Fuseless Banks

These banks do not have fuses on individual cans. The failure mode of these capacitors is to short. What happens is that packs inside the can short, not necessarily the whole can. The result is that the capacitance of that series string of cans will go up and each can will have an increased voltage drop across it. If the voltage across any of the cans gets too high, the cans can overheat and fail. The relay needs to protect against overstressing any of the capacitor cans.

When a can fails above the tap the capacitance of that portion of the bank will go up resulting in a higher tap voltage (less voltage dropped across the above tap portion) which will mean the differential voltage will move in a negative direction.

Most fuseless banks have a large portion (over 80%) of the bank capacitance above the tap with only a few large capacitors between the tap and the center of the Y connection. This means that most of the time you will see a negative change in voltage when there is an operation. A positive change will indicate other, unique problems. These will be discussed in the later analyses.

Table 1 shows the differential voltage movement for the failure modes of each type of bank. **The only reason for the difference in voltage change between the two types of banks is that the fuse removes part of the bank from service.** The failure mode of the cans is the same: they short.

	Fused Bank	Fuseless bank
Failure Above Tap	Up	Down
Failure Below Tap	Down	Up

Table 1 - Differential Voltage Movement

Other types
There are other types of banks, internally fused and unfused for example. This paper will not discuss these types since the author does not have any analysis experience with them.

Dominion Relays
The relays used by Dominion do not provide a differential voltage reading at the time of the trip, and the event reports do not show differential values leading up to the trip. The differential values must be calculated. One of our calculations engineers wrote a DOS program that will read the event reports and then produce a text file containing RMS values and differential values for every line in the event report. This program reads the "K" factor and calculates the differential voltage. We have since added a Windows® front end for that program. Using this tool, we can evaluate capacitor bank events much more quickly. The same task could be accomplished using Excel or another spreadsheet program, although it is a little more time consuming. All of the event reports shown in this paper have been "processed" by this program.

We can quickly look at not only the trip event, but also any events leading up to the trip. The change in differential voltage is the key to analyzing these capacitor bank events.

Our Circuit Calculations department produces a spreadsheet for each capacitor bank. This sheet shows the differential values expected when a given number of cans are bad in the bank. It also lists partial cans out because each can is made up of capacitor packs that can fail, resulting in a can that remains in service, but has altered capacitance.

Morrisville, May 10, 2001
This event is from the Morrisville 500KV fused bank. This is one of the few "normal" capacitor bank events. (The date on the relay was not correct)

```
MORRISVILLE PRIMARY #1                    Date: 4/10/1      Time: 07:42:18.125

     Bus Voltage                Tap Voltage            Differential Voltage

  VAX     VBX     VCX       VAY     VBY     VCY        dVA     dVB     dVC

 122.46  120.35  122.80    114.15  112.30  114.58     +0.32   +0.19   +0.31
 122.46  120.35  122.80    114.15  112.30  114.58     +0.32   +0.19   +0.31
 122.46  120.35  122.83    114.15  112.30  114.55     +0.32   +0.19   +0.37
 122.46  120.38  122.82    114.15  112.30  114.55     +0.32   +0.22   +0.37

 122.46  120.38  122.86    113.37  112.29  114.58     +1.16   +0.23   +0.38
 122.46  120.42  122.86    112.27  112.32  114.58     +2.34   +0.24   +0.38
 122.52  120.43  122.82    110.09  112.33  114.55     +4.72   +0.24   +0.37
 122.59  120.39  122.82    107.37  112.30  114.55     +7.71   +0.23   +0.37

 122.63  120.40  122.76    105.64  112.31  114.51     +9.59   +0.23   +0.35
 122.68  120.38  122.77    104.96  112.29  114.51    +10.38   +0.23   +0.35
 122.65  120.38  122.74    104.85  112.27  114.55    +10.46   +0.24   +0.28
 122.59  120.38  122.74    108.12  112.30  114.55     +6.90   +0.21   +0.28

 122.55  120.38  122.77    110.36  112.30  114.58     +4.47   +0.21   +0.28
 122.51  120.38  122.77    112.59  112.30  114.58     +2.04   +0.21   +0.29
 122.49  120.36  122.83    115.04  112.30  114.58     -0.61   +0.20   +0.35
 122.46  120.39  122.82    114.73  112.30  114.58     -0.30   +0.23   +0.34

 122.46  120.39  122.82    114.73  112.30  114.58     -0.30   +0.23   +0.34
 122.49  120.39  122.82    114.89  112.30  114.58     -0.44   +0.23   +0.34
 122.47  120.40  122.82    115.15  112.30  114.58     -0.74   +0.24   +0.34
 122.47  120.38  122.82    115.04  112.30  114.58     -0.63   +0.21   +0.34
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Note the sudden voltage change on A phase and return to a more normal differential voltage. This is a fuse blowing. In this case, the bank did not trip. For the brief instant that the capacitor went bad and before the fuse blew there is a big change in differential voltage in the positive direction. The increase in voltage occurs when the portion of the bank became shorted due to capacitor failing. Once the fuse blew, the differential voltage settled out to around -0.7 volts, compared to +0.32 volts prior to the failure. The fact that the voltage went down after the problem cleared indicates that there was a failure below the voltage tap point. The increase in differential voltage during the shorted condition reinforces that the failure was below the tap point.

Lanexa, July 15, 2001

Here are two cycles of the processed event report from a trip at Lanexa substation.

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LANEXA CAPBANK SC132                       Date: 7/15/1      Time: 10:26:19.925

     Bus Voltage              Tap Voltage           Differential Voltage

  VAX     VBX     VCX       VAY     VBY     VCY        dVA     dVB     dVC

 116.98  116.33  117.06    107.03  106.38  106.79     -0.76   -0.80   -0.73
 116.99  116.33  117.06    107.03  106.35  106.78     -0.75   -0.77   -0.72
 108.85  116.32  117.03    107.01  106.35  106.75     -8.85   -0.77   -0.72
 114.85  116.38  116.99    107.02  106.35  106.75     -2.87   -0.71   -0.75

  84.28  116.35  116.40    107.02  106.35  106.78    -33.44   -0.75   -1.38
  88.17  115.66  116.74    107.05  106.38  106.78    -29.59   -1.47   -1.04
  70.68  115.65  116.68    107.02  106.38  106.83    -47.05   -1.47   -1.15
  63.56  115.34  116.82    107.02  106.35  106.81    -54.16   -1.74   -1.00
```

Note the very large change in the A phase differential voltage. That is what we first noticed and what were about to report to the substation department, until we noticed that *the tap voltage never changed*. Notice that the A phase bus voltage takes an alarming dip. Of course, if the tap voltage doesn't move and the bus voltage dips over 30 volts, the problem must be somewhere in the bus potential device, or the secondary circuit.

The lesson we learned from this event is that the differential voltage does not always tell the whole story. Pay attention to which voltage, bus or tap, is causing the differential to appear.

Whealton 9/10 and 9/17, 2001

The Whealton capacitor bank is a fuseless bank. The tap voltage comes from a potential transformer paralleled across the large capacitor near the bank neutral. (See Figure 1) On September 10th the bank tripped with B and C differential targets. The differential voltage changed from +0.75 on B phase and +1.25 on C phase to +1.6 and +2.2, respectively, at the time of the trip. We compared the differential voltage change to the calculations spreadsheet and conveyed the number of cans to look for to the substation department. All the cans were tested on B and C phases and no bad cans were found. Here are excerpts of event reports from the September 10th event. These events are 10 seconds apart and there are four other event reports between these two that show an increasing differential voltage. Notice the difference in the differential voltage on B and C phases.

WHEALTON CAPBANK SC142 Date: 9/10/1 Time: 20:49:40.741

Bus Voltage			Tap Voltage			Differential Voltage		
VAX	VBX	VCX	VAY	VBY	VCY	dVA	dVB	dVC
117.50	116.97	118.01	107.97	106.43	107.18	-0.50	+0.75	+1.19
117.50	116.95	118.05	107.94	106.41	107.25	-0.47	+0.75	+1.15
117.52	116.95	118.01	107.95	106.44	107.21	-0.47	+0.72	+1.15
117.52	116.94	118.03	107.93	106.42	107.25	-0.44	+0.73	+1.13

WHEALTON CAPBANK SC142 Date: 9/10/1 Time: 20:49:50.608

Bus Voltage			Tap Voltage			Differential Voltage		
VAX	VBX	VCX	VAY	VBY	VCY	dVA	dVB	dVC
117.68	117.11	117.90	108.00	105.78	106.11	-0.36	+1.60	+2.25
117.63	117.16	117.86	107.97	105.83	106.11	-0.38	+1.59	+2.21
117.63	117.13	117.87	108.02	105.80	106.11	-0.44	+1.60	+2.21
117.60	117.18	117.87	107.98	105.85	106.11	-0.42	+1.59	+2.21

On September 17th the bank tripped again with the same targets and roughly the same differential voltages. This time we took a more critical look at the voltage change and realized that for failure of any cans above the tap (where most of the bank is) the differential voltage should change in a negative direction, not a positive direction as was found. This led us to look more closely at the large capacitors at the center of the Y and also at the potential transformer. The transformer and capacitors tested good. We then “discovered” that there is a 100 ohm resistor in series with the primary of the transformer. We were blissfully unaware of the existence of the resistor in fuseless banks before this event. The substation department then took a closer look at that resistor. When they did, a considerable amount of corrosion was found on the connections to that resistor. The connections were taken apart, cleaned and reconnected. When the bank went back in service, the differential voltages were -0.09 and +0.13, much better than the previous in service readings!

Shawboro June 20, 2000

Shawboro capacitor bank #2 locked out 5 minutes after it was energized. The relay had an A-phase differential target. The same phase was involved in a June 15 trip of this bank. The differential trip setting is 1.5 volts and the relay record of the trip indicates a differential voltage of around 1.3 – 1.4 volts. No bad cans were found. The bank was returned to service, and voltage differential readings were taken from the differential relay at that time. The relay showed differential readings varying from 0.5 to 1.1 volts in a matter of seconds. This amount of fluctuation is not normal. We have observed fluctuations on the order of a few hundredths of a volt on most banks and consider that to be a normal variation.

Many items were investigated as the possible cause of the fluctuations. Among the tests performed:

- Parallel the “bus” and “tap” voltage inputs to the relay and check the steadiness of the differential voltage
- Jumper out “P” (potential knife blade) switches and observe differential steadiness
- Jumper across secondary fuses and observe differential steadiness
- Run separate conductor from the potential device to the relay
- Parallel another relay with the existing one.
- Check all wiring, terminations and test switches for loose connections

None of the above resulted in the voltage jitters going away.

One test that was performed did cause the voltage jitters to disappear. We used a different set of 230KV potential devices for the “bus” voltage input to the relay. This points to a problem with the potential devices.

This problem appears to have lessened in severity, and further testing has not been performed due to the time and expense involved. One possibility that has surfaced during the research of this paper that has not been checked is the condition of the primary grounding of the bus potential devices. A bad ground in that portion of the switchyard could cause the jittery voltages seen during this event. This would also rule out the potential devices, which are relatively new, as the culprit.

Morrisville January 3, 2001

The following is an event that we have never fully explained. B phase differential voltage goes very high, very quickly. The magnitude of the voltage indicates that the entire half of the bank was bad, but only three blown fuses were found. The change in voltage is negative, which would indicate all the fuses below the tap were blown *or* that the half of the bank above tap was shorted.

MORRISVILLE PRIMARY #1 Date: 1/2/1 Time: 21:32:18.183

Bus Voltage			Tap Voltage			Differential Voltage		
VAX	VBX	VCX	VAY	VBY	VCY	dVA	dVB	dVC
122.21	120.37	121.43	113.86	112.65	113.22	+0.37	-0.16	+0.39
122.27	120.34	121.43	113.93	112.62	113.22	+0.36	-0.16	+0.39
122.27	120.48	121.45	113.91	119.80	113.25	+0.39	-7.70	+0.39
122.23	120.41	121.51	113.88	120.14	113.32	+0.37	-8.14	+0.37
122.00	121.04	121.49	113.70	139.80	113.30	+0.34	-28.55	+0.38
122.06	121.01	121.46	113.74	141.14	113.26	+0.35	-30.01	+0.39
121.80	121.54	121.44	113.52	155.52	113.23	+0.34	-44.87	+0.39
121.93	121.57	121.35	113.62	156.73	113.15	+0.36	-46.14	+0.40
121.88	121.57	121.37	113.57	158.89	113.16	+0.36	-48.45	+0.40
121.91	121.55	121.34	113.62	159.20	113.13	+0.33	-48.79	+0.40
121.86	121.55	121.36	113.57	159.50	113.16	+0.34	-49.12	+0.40
121.88	121.53	121.34	113.69	159.41	113.16	+0.23	-49.04	+0.37
121.79	121.62	121.36	112.55	159.55	113.18	+1.36	-49.10	+0.37
121.85	121.59	121.39	112.38	159.55	113.18	+1.61	-49.13	+0.40
121.79	121.65	121.40	112.06	159.55	113.20	+1.89	-49.08	+0.40
121.89	121.62	121.38	111.89	159.55	113.14	+2.17	-49.09	+0.43

As was stated earlier, only 3 blown fuses were found. What makes this event more mysterious is that it happened again a few hours later and the differential voltages were exactly the same. Given the large differential voltage, one would think that the problem would be obvious. However, we had the substation department look over the bank several times, but they did not report any unusual flash marks, or any other signs of damage. Our current theory is that a flash occurred when the fuses blew that caused arcing across several groups of capacitors.

The Dominion Mount Storm 500KV capacitor bank

This bank is actually four fuseless banks operated in parallel. Each of the four banks has its own differential relay. The banks are connected in such a way that there are two sets of two banks, and if needed, only half the bank can be switched in service. The banks are named SC1A, SC1B, SC1XA, and SC1XB. Total rating of the bank is 343.4 MVARS. This bank is critical in providing voltage control in the northwestern part of our system.

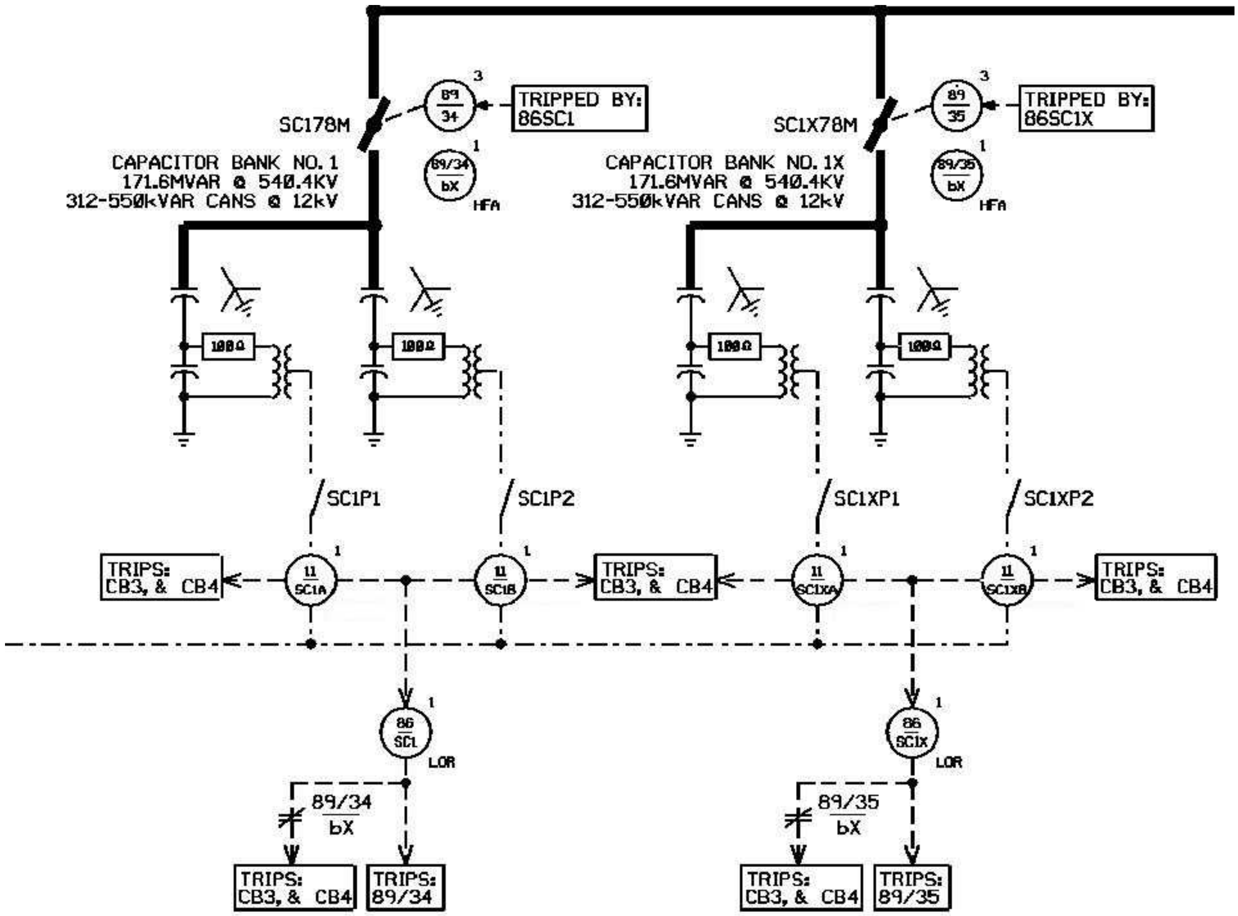

Figure 5 - Mount Storm Capacitor Bank One Line

Mount Storm event May 14, 2002 08:50

The bank tripped out 4 minutes after being energized. It was determined that the SC1A relay had a C phase differential target. The first cycle of the processed event report from bank SC1A is shown below.

Bus Voltage			Tap Voltage			Differential Voltage		
VAX	VBX	VCX	VAY	VBY	VCY	dVA	dVB	dVC
118.44	119.94	120.65	112.06	113.56	114.74	-0.79	-0.77	-1.67
118.42	119.94	120.67	112.03	113.56	114.77	-0.79	-0.77	-1.67
118.43	119.94	120.61	112.08	113.53	114.74	-0.82	-0.74	-1.70
118.43	119.95	120.61	112.03	113.54	114.76	-0.77	-0.74	-1.73

It can be seen that the differential voltage on C phase is much higher than the other phases. The trip setting is 1.84 volts. We have the relay set to generate an event report at voltage levels below the trip point so that we may get an idea of how long the problem has been occurring. For this particular operation, the relay had ten events in the preceding two minutes. Each event had the high differential voltage on C phase. By viewing the preceding events, we could see that the differential voltage went from -1.62 to -1.8 at the time of the trip. We informed the operating center that the problem was on the C phase portion of the SC1A bank. We also expressed some concern about the value of differential voltages on A and B phases, noting that they were indicating some partially bad cans. Partially bad cans are cans that have some shorted packs.

At the time of the trip we looked at the value of measured differential voltage and compared it to the spreadsheet values done when the settings were calculated. A value of 1.8 volts indicated one bad can. That is the information we gave to the substation department. Their testing found a few marginal cans, but no “smoking gun”.

The operating center decided to split the bank and energize the half of the bank that was not affected. Unfortunately, the bank did not stay in very long.

Mount Storm event May 14, 2002 15:52

When the alleged good half of the bank was switched in (from the previous trip), it stayed energized for 20 minutes and then also tripped with a C phase differential target on the SC1XA portion of the bank. Examination of the differential voltages leading up to the trip showed the same differential voltage, around -1.8 volts.

The immediate fix to the bank was to increase the trip setting to 2.06 volts until we could figure out what was causing the bank to trip. Again, one questionable can was found on the C phase section of the bank. Heat scans were performed on the bank after it went back in service. The scans did show some heating of cans, especially in C phase. The hot cans were replaced and sent to the manufacturer for testing. The manufacturer found that there was a problem with the way the crimping was performed inside the cans, which resulted in the heating.

Further investigation of differential voltages on all phases of all portions of the bank showed that most of the differential voltages were higher than expected. This caused us to take steps to monitor the differential voltages of this bank.

Follow-up to Mount Storm Events

Because of the critical nature of this bank, it was decided to start monitoring the differential voltages as soon as possible. We already had a relay autopoll in place that we used periodically to automatically dial relays and retrieve status and also to set the time. That polling was modified to dial the Mount Storm differential relays and retrieve the meter information every two hours. This was intended to be a temporary system until something could be worked out to gather the differential voltages without making long distance calls a dozen times a day. We eventually were able to get the data automatically sent to SCADA, and we now have the differential voltage readings taken every 30 minutes and archived.

We are now able to get the SCADA differential voltage data imported into a spreadsheet and then graph the differential voltage over time. The graph showed some trends that were useful in discovering what was going on. The differential voltage spikes in a negative direction shortly after energizing and then settles out. Heating by sunlight also causes a noticeable change in the differential voltage. We are currently watching these trends to see if they affect the relay trip point enough for us to take action. Figure 6 is a graph of the differential voltage of the “1A” portion of the bank for a ten day period in the summer of 2002. The negative dips after energizing are very noticeable, and you can also see the change due to heating and cooling at the end of the graph. The very high voltages are when the bank was not in service.

We also saw that the capacitors change their capacitance over the first few months of service. As a result of this, we are starting a program to re-null some banks on a periodic basis by resetting the K factor.

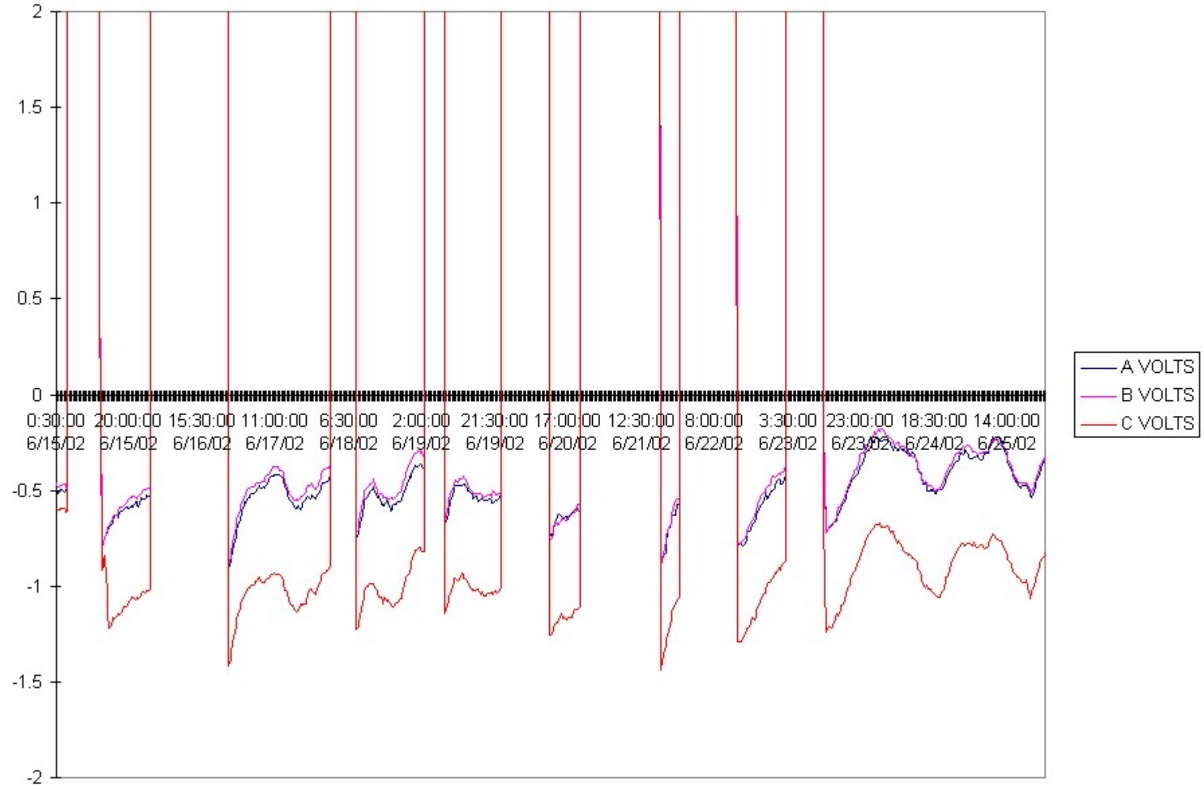

Figure 6 - Differential Voltage over a 10 day period

Summary
We have learned many things over the past several years that help us to understand and analyze capacitor bank operations.

- The differential voltage at the time of the trip doesn't really help. You need to determine the change in magnitude and direction of the differential voltage that caused the event.
- Use the data in Table 1 to determine which portion of the bank has the problem. Knowing this and the affected phase will reduce the suspected trouble area to 1/6 of the bank.
- Troublesome or critical banks may require that the differential voltage be monitored more closely so that problems can be taken care of before they cause the bank to trip.

Capacitor bank operations are much less frequent and somewhat more complex than normal line, bus or transformer operations. We have used our experience to develop a "cheat sheet" form that we can fill out when a capacitor bank event occurs.

Some items to check when an operation occurs:
- Type of bank, fused or unfused.
- Which phase was involved.
- Which relay element operated (time or inst).
- Magnitude and sign of differential voltage at time of trip.
- Magnitude and sign of differential voltage before the trip, if available.
- Which voltage input changed, bus or tap.

If you are able to answer all the above questions then you will be well on the way to quickly finding the cause of the bank operation.

References
Edmund O. Schweitzer III, Jolene Schafman "Unified Shunt Capacitor Bank Control and Protection" presented at the 45th Annual Georgia Tech Protective Relay Conference

IEEE Power System Relaying Committee And Capacitor Subcommittee of the Transmission and Distribution Committee, IEEE Power Engineering Society "Application and Protection of shunt capacitor banks" presented at Texas A&M, April 8, 2002