CIGRE-598
2023 CIGRE Canada Conference & Exhibition
Vancouver, BC, Sept.25 – 28, 2023

Modern Capacitor Bank Protection Methods

R. Bowersox, J. Schaefer
Florida Power and Light
D. Ransom
GE Vernova
United States of America

daniel.ransom@ge.com

SUMMARY

Capacitor banks add necessary VAr support to the power system, promoting efficient energy transfer and reducing costs of building large transmission lines. It is a significant challenge to protect capacitor banks effectively. This paper discusses various methods to protect capacitor banks, including voltage differential (87V), neutral-voltage unbalance (59NU), phase-current unbalance (60P), and neutral-current unbalance (60N). Included is a discussion on various capacitor-bank arrangements, details of staged protection, and application of differential-slope principles. Real-world examples illustrate these protection concepts.

KEYWORDS

Shunt capacitor bank, protection, auto-setting, self-tuning, unbalance

I. Introduction

Shunt capacitor banks (SCBs) provide capacitive, reactive compensation and power-factor correction. SCBs improve the power-system voltage profile, provide better voltage regulation, reduce system losses, and postpone investments in transmission and generation facilities.

SCBs strengthen the power system, preventing blackouts and adding reactive power VAr support for the increased penetration of distributed generation wind farms. Capacitor banks are valuable assets used daily in system operation and must provide reliable operation through abnormal power-system scenarios.

Protection for SCBs must avoid false tripping for system disturbances while providing sufficient sensitivity to detect capacitor can faults and minimizing SCB damage.

SCBs have numerous, separate capacitor cans in series and parallel connections. A capacitor bank can operate with many capacitor-can failures. Typically, operations personnel continue to run the SCB after one or more capacitor cans have been removed temporarily (bank is scheduled for can replacement to restore the bank to full operation). This situation creates unbalances. Modern capacitor bank protection requires a reliable and sensitive relay that can deliver adequate protection during an inherent unbalance in the protected bank, as well as system unbalances. Relays must protect the bank based upon published standards [1], [2].

Many custom applications and dedicated capacitor-bank protection relays compensate for inherent unbalance based on subtracting historical values from the operating quantities, making the relay respond to incremental, “delta” signals. The modern capacitor-bank protection relay employs dynamic compensation for unbalances among the power-system phase voltages [3]. These differences are constantly changing and can be 2 percent or more during normal conditions, and tens of percent during major system events such as close-in faults. This protection method compensates simultaneously for the bank inherent unbalance and system unbalance, increasing both sensitivity and security of protection.

Modern capacitor-bank protection features auto-setting and self-tuning applications [4]. Auto-setting is calculating new accurate relay constants to account for the inherent bank unbalances following bank repair and is performed in response to the user’s request and under user supervision. Self-tuning is an operation of constantly adjusting the balancing constants to maintain optimum protection sensitivity when bank reactances change slowly (in response to seasonal temperature variations and other conditions). Self-tuning applications require monitoring total changes in the balancing constants to detect slow failure modes and account for small changes that do not trigger alarms.

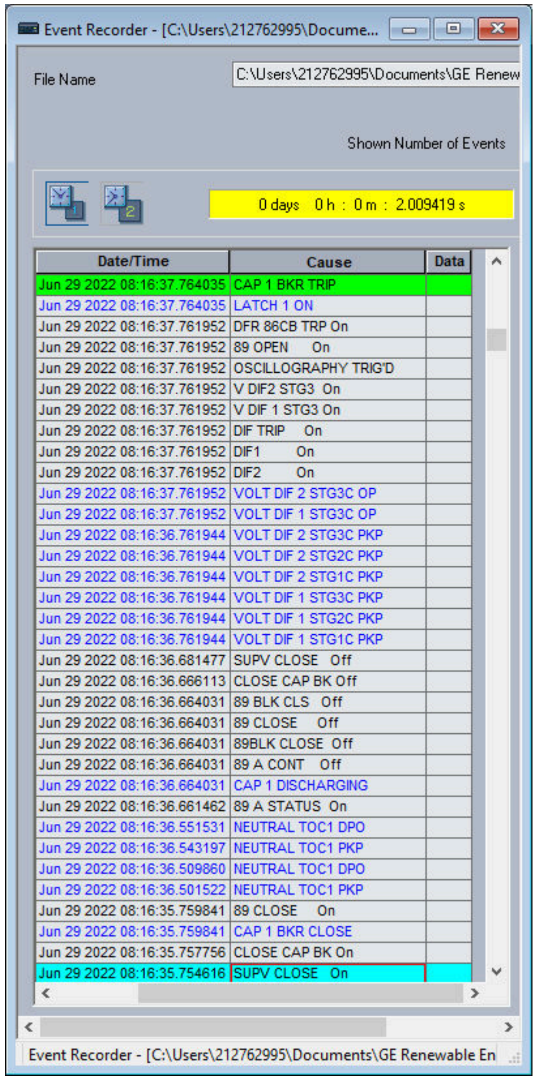
II. Real-world examples

Real-world examples show the value of applying modern capacitor-bank protection principles. The following are actual SCB protection events. Additional information on capacitor-bank protection can be found in IEEE Std C37.99-2012, IEEE Guide for the Protection of Shunt Capacitors Banks [5].

a) Voltage differential trip, 87V

The protection relay tripped the bank on Phase-C, 87V voltage differential upon closure of the bank connection switches. Operations issued a supervisory close at 8:16:35.754616, as shown in the event record of Figure 1. The relay detects some residual charge in the SCB and issues CAP 1 DISCHARGING. This is a programmable delay that inhibits closing after the bank has been switched out of service until the bank has had time to discharge any trapped charge. If the capacitor is closed with trapped charge of opposite polarity from the system voltage at that instant, larger than normal transients can occur. The discharge timer in this case was 5 minutes and the bank had previously been in service, opened and then closed.

The SCB switch closes (89 A STATUS ON), and the 87V VOLT DIF 1, Stage 1, Stage 2, and Stage 3 pickup in 100 ms from the lack of differential balance. This is because there is no cap-bank voltage detected on Phase C, as shown in Figure 2. Settings, shown in Figure 3, list pickups for Stage 1, Stage 2, and Stage 3 at 0.108 and less, so a complete loss of phase picks up these elements. After the programmed 1-second delay for Stage 3, the relay trips the cap bank.



Date/Time	Cause	Data
Jun 29 2022 08:16:37.764035	CAP 1 BKR TRIP	
Jun 29 2022 08:16:37.764035	LATCH 1 ON	
Jun 29 2022 08:16:37.761952	DFR 86CB TRP On	
Jun 29 2022 08:16:37.761952	89 OPEN On	
Jun 29 2022 08:16:37.761952	OSCILLOGRAPHY TRIG'D	
Jun 29 2022 08:16:37.761952	V DIF2 STG3 On	
Jun 29 2022 08:16:37.761952	V DIF 1 STG3 On	
Jun 29 2022 08:16:37.761952	DIF TRIP On	
Jun 29 2022 08:16:37.761952	DIF1 On	
Jun 29 2022 08:16:37.761952	DIF2 On	
Jun 29 2022 08:16:37.761952	VOLT DIF 2 STG3C OP	
Jun 29 2022 08:16:37.761952	VOLT DIF 1 STG3C OP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG3C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG2C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG1C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG3C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG2C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG1C PKP	
Jun 29 2022 08:16:36.681477	SUPV CLOSE Off	
Jun 29 2022 08:16:36.666113	CLOSE CAP BK Off	
Jun 29 2022 08:16:36.664031	89 BLK CLS Off	
Jun 29 2022 08:16:36.664031	89 CLOSE Off	
Jun 29 2022 08:16:36.664031	89BLK CLOSE Off	
Jun 29 2022 08:16:36.664031	89 A CONT Off	
Jun 29 2022 08:16:36.664031	CAP 1 DISCHARGING	
Jun 29 2022 08:16:36.661462	89 A STATUS On	
Jun 29 2022 08:16:36.551531	NEUTRAL TOC1 DPO	
Jun 29 2022 08:16:36.543197	NEUTRAL TOC1 PKP	
Jun 29 2022 08:16:36.509860	NEUTRAL TOC1 DPO	
Jun 29 2022 08:16:36.501522	NEUTRAL TOC1 PKP	
Jun 29 2022 08:16:35.759841	89 CLOSE On	
Jun 29 2022 08:16:35.759841	CAP 1 BKR CLOSE	
Jun 29 2022 08:16:35.757756	CLOSE CAP BK On	
Jun 29 2022 08:16:35.754616	SUPV CLOSE On	

Figure 1. 87V operation event record

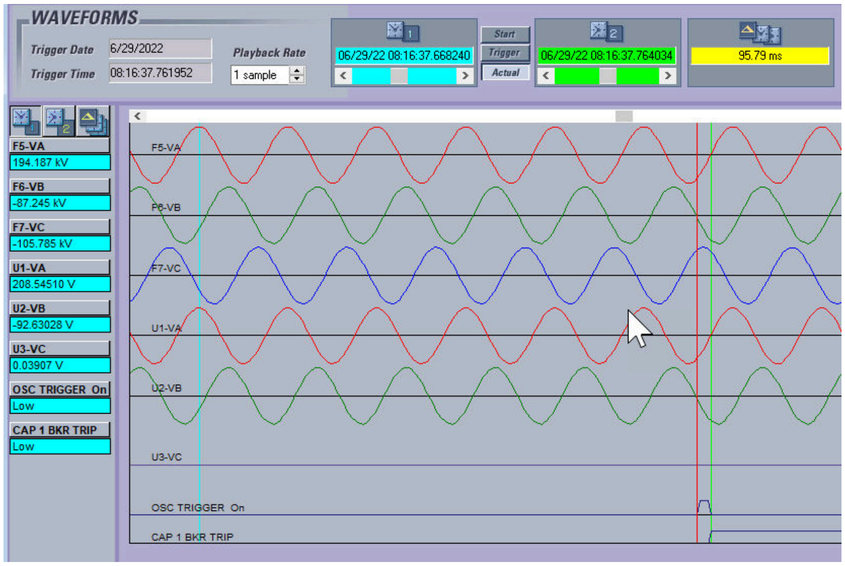
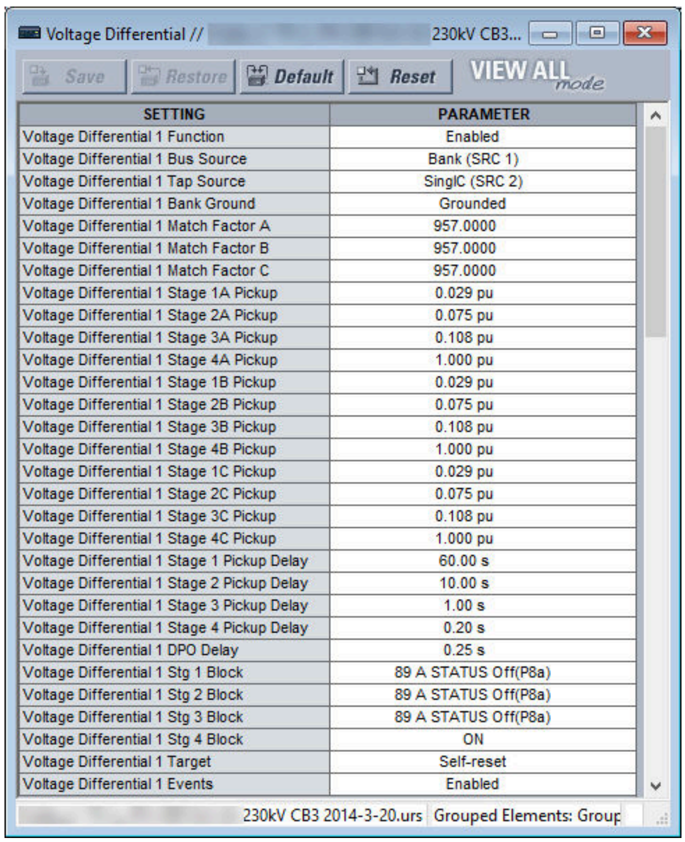


Figure 2. 87V operation from lack of source VC (Phase C voltage)



SETTING	PARAMETER
Voltage Differential 1 Function	Enabled
Voltage Differential 1 Bus Source	Bank (SRC 1)
Voltage Differential 1 Tap Source	SinglC (SRC 2)
Voltage Differential 1 Bank Ground	Grounded
Voltage Differential 1 Match Factor A	957.0000
Voltage Differential 1 Match Factor B	957.0000
Voltage Differential 1 Match Factor C	957.0000
Voltage Differential 1 Stage 1A Pickup	0.029 pu
Voltage Differential 1 Stage 2A Pickup	0.075 pu
Voltage Differential 1 Stage 3A Pickup	0.108 pu
Voltage Differential 1 Stage 4A Pickup	1.000 pu
Voltage Differential 1 Stage 1B Pickup	0.029 pu
Voltage Differential 1 Stage 2B Pickup	0.075 pu
Voltage Differential 1 Stage 3B Pickup	0.108 pu
Voltage Differential 1 Stage 4B Pickup	1.000 pu
Voltage Differential 1 Stage 1C Pickup	0.029 pu
Voltage Differential 1 Stage 2C Pickup	0.075 pu
Voltage Differential 1 Stage 3C Pickup	0.108 pu
Voltage Differential 1 Stage 4C Pickup	1.000 pu
Voltage Differential 1 Stage 1 Pickup Delay	60.00 s
Voltage Differential 1 Stage 2 Pickup Delay	10.00 s
Voltage Differential 1 Stage 3 Pickup Delay	1.00 s
Voltage Differential 1 Stage 4 Pickup Delay	0.20 s
Voltage Differential 1 DPO Delay	0.25 s
Voltage Differential 1 Stg 1 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 2 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 3 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 4 Block	ON
Voltage Differential 1 Target	Self-reset
Voltage Differential 1 Events	Enabled

Figure 3. 87V settings

Analysis showed that there was a problem with the connecting switch knife mechanism in Phase C.

The bank is a split-wye, grounded bank. The split wye is not even, there is a single string per phase (a reference string) and then a multi-string per phase. However, the differential principle applies well, with a multiple-input 87V differential from the bus voltage to each string tap, as shown in Figure 4. The protection relay adds together the single-string and paralleled string voltage transformer (VT) bank sources from each phase to form a differential with the respective bus phase voltages.

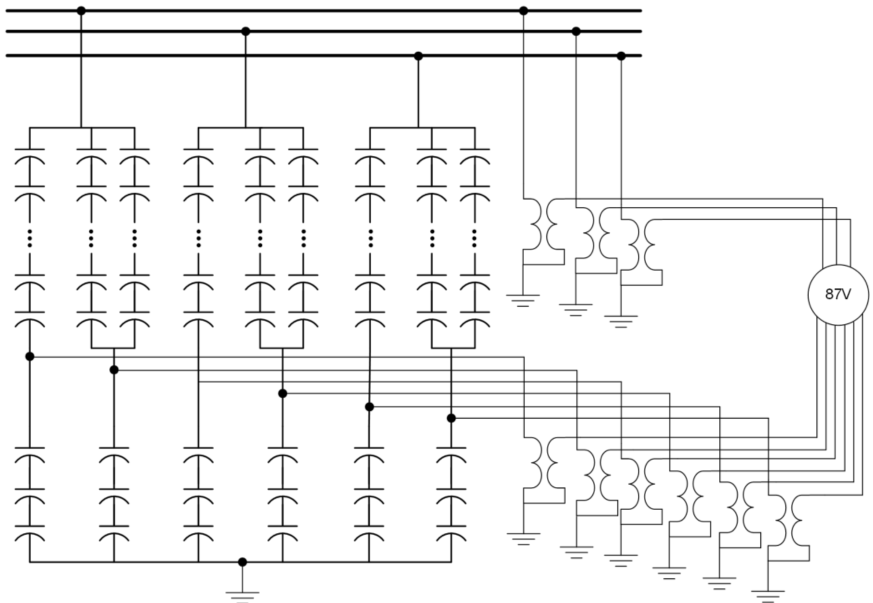


Figure 4. 87V differential connections

a) Voltage differential 87V trip while in service

The protection relay responded to a significant drop in Phase-C voltage while the capacitor bank was in operation, as shown in the oscillograph of Figure 5. This drop activated the Phase-C 87V stage elements and tripped the capacitor bank offline on Stage 4. Inspection showed that too many cans had shorted, reducing the Phase-C voltage. This sensitive and early trip protected the remaining capacitors in the group from a cascading failure.

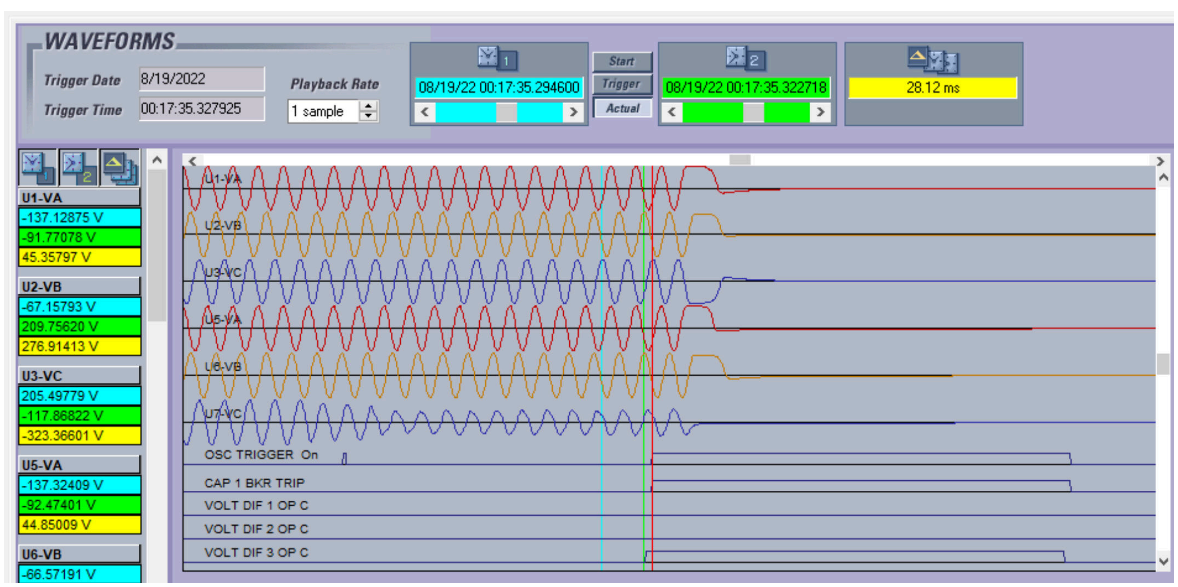


Figure 5. Phase-C voltage drop during operation

This trip was the result of too many failed cans. When there is an alarm on a cap bank, field maintenance technicians take the bank out of service and troubleshoot to find any failed cans. Many times, this work is not the highest priority and operations personnel will continue to use the bank because they need voltage support in the area. Eventually, the unbalance stresses the other cans in the string causing more can failures. Then, protection trips and locks out the bank.

This SCB is a split, wye-grounded bank at 230 kV, rated at 108.5 MVAr. There is a single string per phase (a reference string) on one side of the differential, and a multi-string on the other side of the differential, as shown in Figure 4. It is large, with 216 cans in 8 strings per phase and multiple cans per string below the tap as shown in Figure 6. There are 8 cans per phase below the tap.

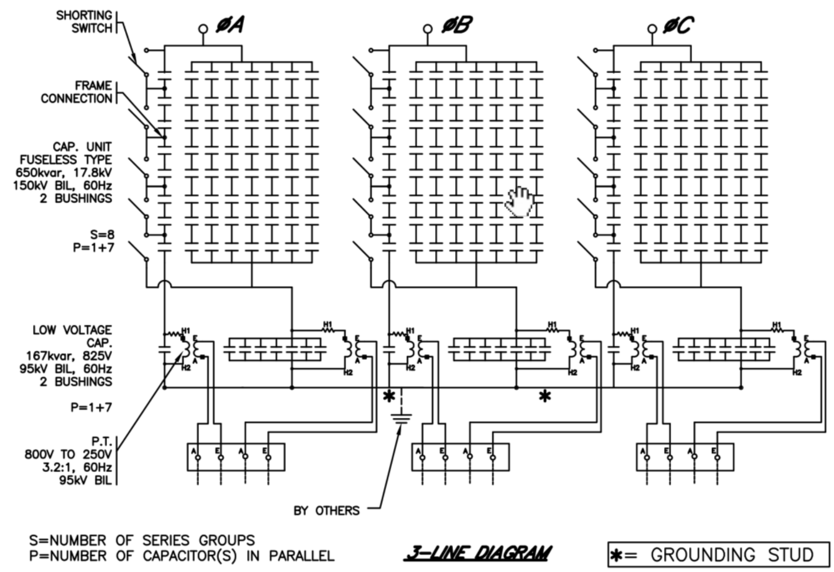


Figure 6. Grounded-wye bank detail

b) Compensated bank neutral voltage unbalance (ANSI 59NU) upon closing

Neutral voltage unbalance 59NU measures an overvoltage condition of the neutral-point voltage. If a capacitor element in the bank fails, then the bank becomes unbalanced and the neutral voltage increases. The example SCB is shown in Figure 7. A resistive potential device provides the neutral voltage to the protective relay input 59N (which has a large impedance and does not ground the bank).

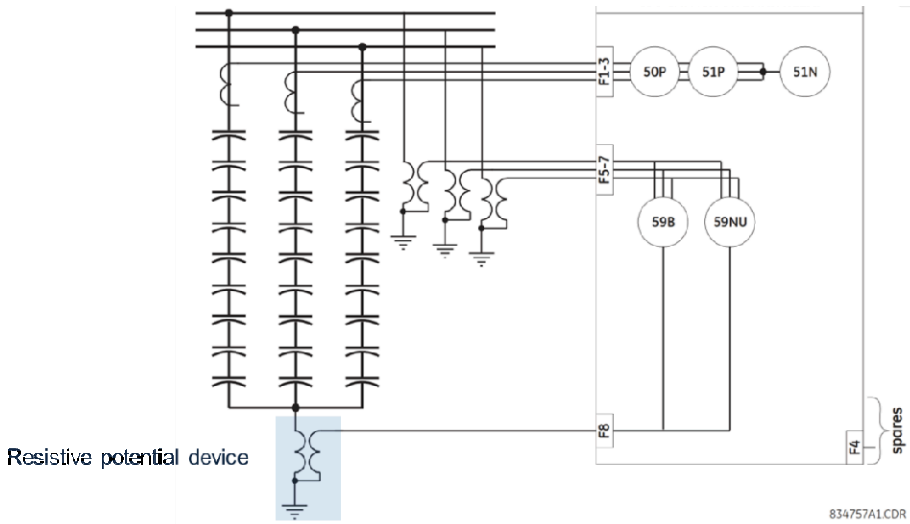


Figure 7. Ungrounded SCB and neutral voltage sensing

Upon closing the SCB a gross overvoltage occurred in the 59NU element, shown in the event record of Figure 8. This NTRL VOLT rise was in Stage 1 through Stage 4 (this application has these set to the same level and delay, as shown in Figure 9). The relay tripped the capacitor bank. After-event investigation revealed a mechanical problem in the circuit switch knife blades that did not make (connect) on Phase C.

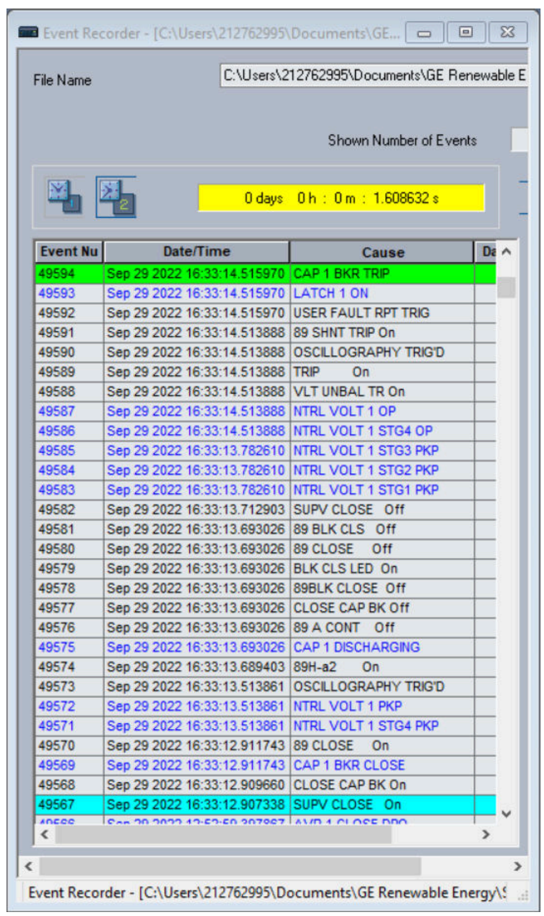


Figure 8. Events for neutral unbalance 59NU

SETTING	PARAMETER
Neutral Current Unbalance 1 Function	Enabled
Neutral Current Unbalance 1 Bank Source	NeutUn (SRC 2)
Neutral Current Unbalance 1 k MAG	0.0000
Neutral Current Unbalance 1 k ANG	0 deg
Neutral Current Unbalance 1 STG1 PKP	0.048 pu
Neutral Current Unbalance 1 STG1 SLOPE	0.0 %
Neutral Current Unbalance 1 STG2 PKP	0.072 pu
Neutral Current Unbalance 1 STG2 SLOPE	0.0 %
Neutral Current Unbalance 1 STG3 PKP	0.072 pu
Neutral Current Unbalance 1 STG3 SLOPE	0.0 %
Neutral Current Unbalance 1 STG4 PKP	0.072 pu
Neutral Current Unbalance 1 STG4 SLOPE	0.0 %
Neutral Current Unbalance 1 STG1 DEL	1.00 s
Neutral Current Unbalance 1 STG2 DEL	0.17 s
Neutral Current Unbalance 1 STG3 DEL	0.17 s
Neutral Current Unbalance 1 STG4 DEL	0.17 s
Neutral Current Unbalance 1 DPO DEL	0.25 s
Neutral Current Unbalance 1 STG1 Block	89H-a2 Off(P8a)
Neutral Current Unbalance 1 STG2 Block	89H-a2 Off(P8a)
Neutral Current Unbalance 1 STG3 Block	ON
Neutral Current Unbalance 1 STG4 Block	ON
Neutral Current Unbalance 1 Target	Self-reset
Neutral Current Unbalance 1 Events	Enabled

Figure 9. Neutral voltage unbalance 59NU settings

c) Bank overcurrent 60N

The modern capacitor-bank protection relay has many settings. Gathering bank data and running studies informs the settings values. Occasionally, errors occur when creating settings that make it past reviews and commissioning. This is the case with a bank trip, shown in the oscillograph in Figure 10.

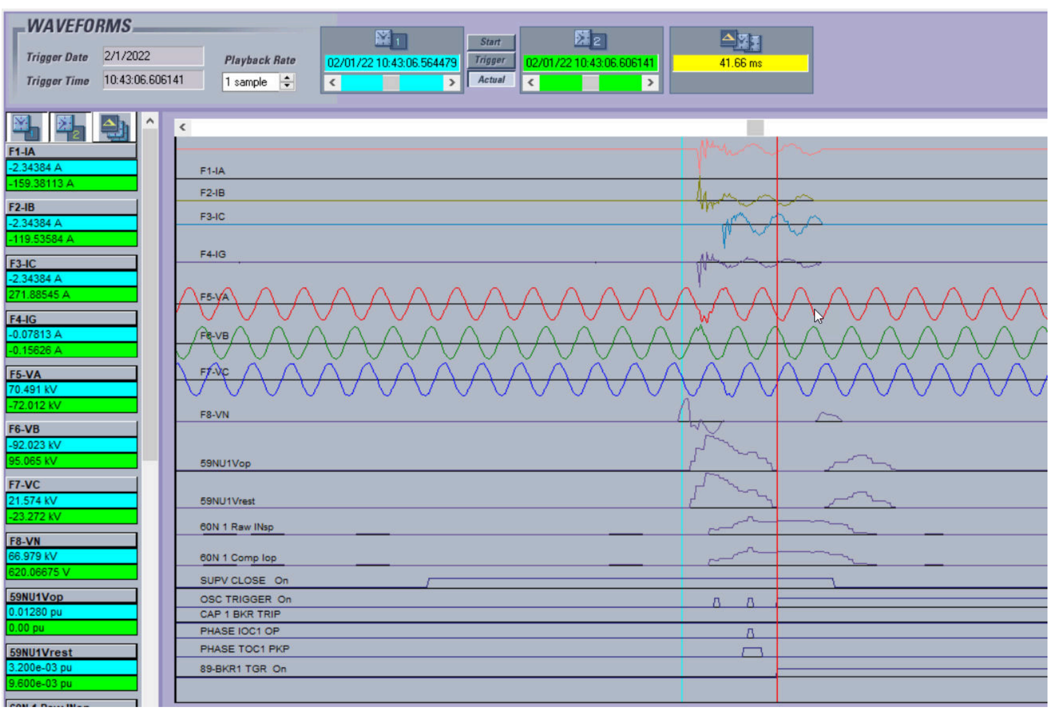


Figure 10. Closing SCB event

This capacitor bank is a split wye, ungrounded bank at 115 kV. The bank rating is 34 MVAr with 20 cans per phase. The bank arrangement is shown in Figure 11.

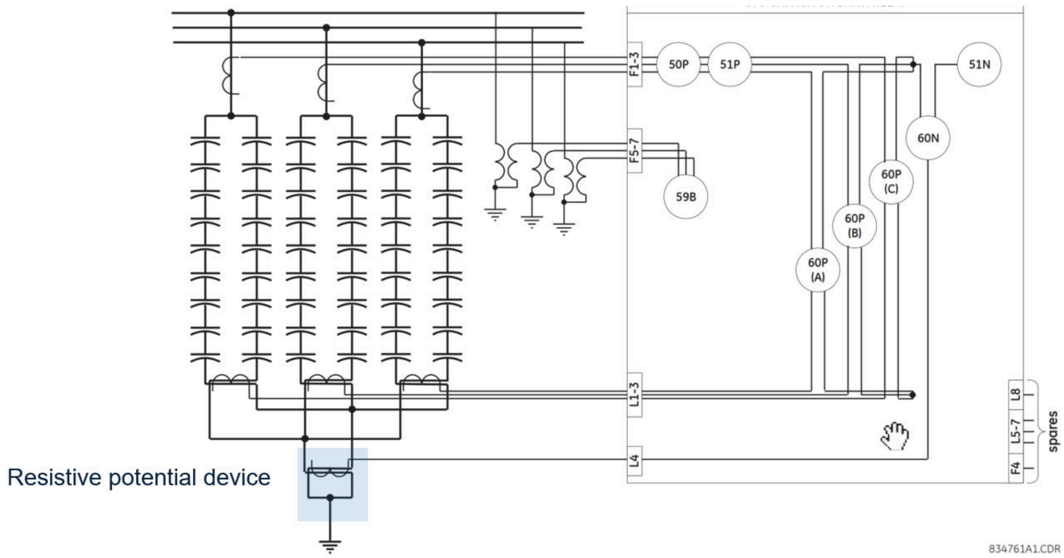


Figure 11. Current balance protection 60N and 60P

Operations closed the SCB, and surge charge current caused the bank to trip. Note that the neutral current unbalance 60N becomes active, and the bank opens as seen in the 89-BKR1 TGR On status. This was normal operation, not a trip. Settings were increased to ride through this event.

d) Bank phase overvoltage 59B settings

Abnormal system conditions can cause overvoltage stress to the capacitor bank. It is good practice to evaluate the capability of the bank to withstand transient overvoltages, according to the IEEE 1036-1992 standard or to manufacturer specifications. For example, consider the following manufacturer overvoltage tolerance limits to protect against overvoltage transients stressing the capacitor insulation:

- 2 pu overvoltage for 0.25 second
- 1.5 pu overvoltage for 15 seconds
- 1.25 pu overvoltage for 5 minutes

Account for these tolerance limits conservatively when calculating the relay settings, approaching to within 10 percent of the limit (set to 90 percent) and at half the time. Three overvoltage trip stages are applied using a factor of 0.9 for the stage pickup overvoltage levels and half of the allowable time outlined (to prevent exceeding the lifetime limit).

Table 1. Bank phase overvoltage 59B settings

59B	Amplitude calculation	Pickup setting	50 percent of maximum time (s)
Stage 1	0.9 • 1.25	1.125 pu	150
Stage 2	0.9 • 1.5	1.35 pu	7.5
Stage 3	0.9 • 2	1.80 pu	0.125

The resulting relay settings are these for the three stages (Figure 12):

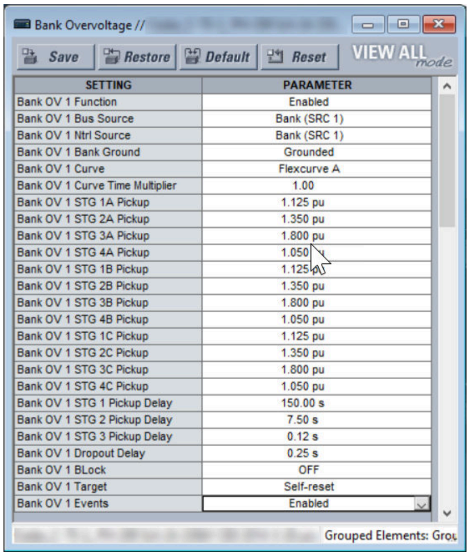


Figure 12. Bank phase overvoltage 59B stages settings

III. Conclusions

Protecting capacitor banks is a significant challenge. Effective protection methods include voltage differential (87V), neutral-voltage unbalance (59NU), phase-current unbalance (60P), neutral-current unbalance (60N) and bank phase overvoltage (59B). These methods are applied depending on the capacitor-bank arrangement and measuring points. The modern capacitor-bank protection relay compensates for unbalances among the power-system phase voltages through auto setting and self-tuning, increasing both sensitivity and security of protection. Real-world examples showed the applications of the protection methods.

BIBLIOGRAPHY

[1] IEEE Std 18-2012, IEEE Standard for Shunt Power Capacitors

[2] IEEE Std 1036-2020, Guide for the Application of Shunt Power Capacitors

[3] Fundamentals of Adaptive Protection of Large Capacitor Banks – Accurate Methods for Canceling Inherent Bank Unbalances; B. Kasztenny, J. Schaefer, E. Clark; Georgia Tech Protective Relay Conference, 2006

[4] Shunt Capacitor Bank Fundamentals and Protection; G. Brunello, B. Kasztenny, C. Wester; Conference for Protective Relay Engineers, Texas A&M University, 2003

[5] IEEE Std C37.99-2012, IEEE Guide for the Protection of Shunt Capacitors Banks