

Aspects of 230 kV Shunt Capacitor Bank Failures

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Presented at the
Energy Association of Pennsylvania
Spring 2007 Electrical Equipment and Protection Committee Meeting
Reading, PA
March 8, 2007

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Summary

The use of substation shunt capacitors has been on the rise at FirstEnergy Company (FE) as well as at most utilities across North America. These capacitors are becoming a much greater factor in the reliable operation of transmission, sub-transmission, and distribution systems. Utilities are becoming more dependent on these capacitors to reduce losses and improve voltage regulation. FE has approximately 700 substation shunt capacitor banks and 10,500 MVAR of installed capacity at voltages ranging from 2.4 kV to 500 kV. The loss of any one of these shunt capacitor banks can create local system problems if the loss occurs during periods of heavy loading or when adjacent lines or equipment are out of service. This condition can become even more exaggerated when considering individual transmission capacitors banks. Some of these banks can be rather large and potentially create problems proportional to their size. Based on these factors, it is becoming increasingly important for utilities to insure that all installed substation shunt capacitors are highly reliable and remain available for service during critical operating periods. At FirstEnergy, this became very apparent at Hosensack Substation in 2006, when the loss of two, 230 kV capacitor banks equated to the loss of 285.6 MVAR for an extended period of time.

Background

On June 21, 2005 at approximately 0401 hours, Cap Bank 1 at Hosensack substation failed violently during an unsolicited open operation. The failure resulted in significant damage to the individual capacitors of both B and C phase of section 1, due to a combination of electrical stress, fire, and projectiles. An oil-filled neutral CT on that section also failed violently. The damage to the capacitor bank was repaired and the switching device was serviced during an extended outage. During the re-commissioning process of Cap 1 in May 2006, it was discovered that the operational integrity of the switching device was likely compromised, thus prolonging the outage. On October 04, 2006 at approximately 09:50 hours, Cap Bank 2 at Hosensack Substation tripped off line immediately after a solicited close operation. The initial inspection revealed no identifiable problems; therefore, an attempt was made to immediately restore the bank. An arc was observed on only the A phase of the circuit switcher during the close operation, which was then immediately followed by an open operation. A second attempt was made to close the bank after another inspection was performed with similar results.

Cap 1 & 2 Configuration

The capacitor banks at Hosensack substation are a grounded double wye configuration each rated at 142.8 MVAR and operated at 230 kV. Each phase of a bank is separated into two distinct sections with all three phases of each section connected to ground through a unique CT. Each capacitor bank consists of 714 individual capacitors rated at 19,920 volts, 200 kVAR and they are equipped with individual 15 kA expulsion fuses. Each phase within a section is made up of seven groups of capacitors connected in series with each group containing seventeen capacitors arranged in parallel. Each phase of each section has a potential transformer (PT) that is used to determine phase imbalance. The PTs are connected between the third and fourth group up from the neutral bus. The capacitor banks are located directly next to each other and are connected in

parallel via a short length of bus. Each bank is switched with an S&C Mark V circuit switcher. There are also two circuit breakers (C182 & C12) along with a reactor in series between the circuit switchers and the substation bus. The breakers provide fault protection and the reactor limits transient current between the capacitors and the 230 kV bus. (See Figure 1) The Cap 1 circuit switcher uses pre-insertion inductors and the Cap 2 circuit switcher uses pre-insertion resistors to limit high frequency transient currents and voltages associated with back-to-back capacitor switching. Circuit switchers are designed to insert these devices during closing for 7 to 12 cycles depending on the system voltage [1].

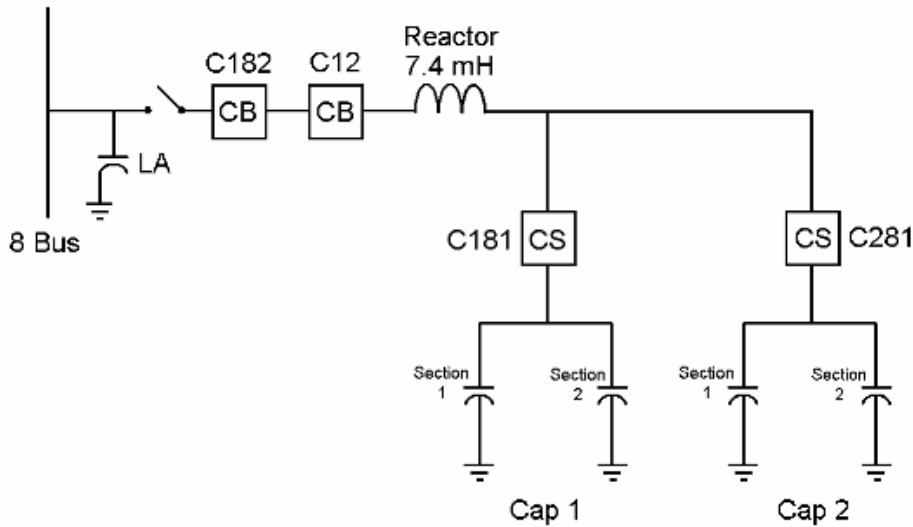


Figure 1
Basic Configuration of the Hosensack 230 kV Shunt Capacitor Banks

Protection and Control

The capacitor banks are placed in service and removed from service by supervisory control as warranted by system conditions. S&C type GP relays are used for potential imbalance control and Westinghouse type CO over current relays are used for neutral current imbalance control. Both imbalance schemes are set to alarm for a one can per phase imbalance and trip for a two can per phase imbalance. A 230 kV S&C Mark V Circuit Switcher is used for normal and imbalance capacitor switching. Separate over current protection is provided using General Electric IAC and Westinghouse CO relays with lockouts, which simultaneously operates the two series-connected 242 kV, 63 kA, ABB PMG circuit breakers.

Operational History

These capacitor banks were originally installed in 1982 to support importing power from the Three Mile Island Nuclear Power Plant to the Jersey Central Power and Light Company (JCP&L) which owned a 50% share of the plant at the time. The capacitor banks were installed at the Hosensack substation which is a shared facility between Pennsylvania Power and Light Company (PP&L) and Metropolitan Edison Company (Met-Ed). Met-Ed, a sister company of JCP&L, has operated and maintained the capacitor banks since their installation.

Prior to this set of events, another significant failure was documented involving Cap 2. On 09/13/96 a violent failure occurred that caused 5 individual capacitors to be destroyed and required 52 capacitors to be replaced due to tolerance issues. In that incident, a can failure alarm

was received and within one second Cap 2 was cleared through the operation of C182 and C12 due to an over current condition.

Failure Investigations

Cap 1

The formal investigation of the Cap 1 failure was actually conducted almost ten months after the incident because the operating company addressed this event as just another routine capacitor failure similar to the many that have plagued the company over the years. The investigation and root cause analysis was conducted by the Substation Maintenance department when they were contacted to re-commission Cap 1. FirstEnergy's Substation Maintenance department had already been formally investigating numerous capacitor failures across the entire FE system in an effort to identify the root cause of the various capacitor failures and to recommend appropriate modifications to capacitor bank design, operation and maintenance. Piecing together the circumstances of the Cap 1 failure was accomplished by obtaining information from a combination of personnel interviews, operational records, recorded relay targets, pictures, emails, and a manufacturer's report. The following is a summary of significant information related to the cap bank failure:

1. The Cap 1 circuit switcher (C181) opened due to an imbalance condition on B and C phases consistent with relay targets obtained. The C12 and C182 circuit breakers also opened in the same scan period, but no relay targets were obtained.
2. Damage was excessive on phases B and C of section 2. Many capacitors were blown apart and there was significant fire damage to other capacitors, the bus, and other components. The section 2 CT failed violently causing the lid to blow off. Many other fuses were blown throughout both sections of the cap bank. All capacitors that were damaged and/or out of tolerance were replaced.
3. There was an open coil on the neutral current imbalance relays that are connected to both the section 1 and 2 neutral CT's. Additionally, there were burn marks on the back of the relay and the relay case. The relay was replaced.

During the investigation it was discovered that there had been prior incidents involving this capacitor bank. Previously, a coil on the neutral current imbalance relay had been burned open and the HV lead of one of the neutral CTs was burned off inside the tank. These items were discovered during routine maintenance. It was also revealed that other failures involving these banks had occurred over the years. In addition, it had also been discovered that the Cap 1 circuit switcher, C181, was modified during the late 1990's. Six new pre-insertion inductors were installed to replace the original pre-insertion resistors.

During the re-commissioning process the C181 circuit switcher was tested to insure acceptable operating characteristics. Testing was completed with satisfactory results for timing, contact resistance, pre-insertion inductor impedance, and open interrupter resistance. The C181 switch live parts displayed excessive wear and in need of replacement in the near future. The entire protection scheme -- including associated alarms -- was also tested with satisfactory results. The pre-insertion contact arms were measured for mechanical tolerances since their operation is essential for the proper functioning of the pre insertion inductors. All three phases were discovered to be out of tolerance.

Cap 2

The investigation into the Cap 2 incident began immediately after the problem was discovered. Analysis of the digital fault recorder (DFR) at the site revealed that during all the attempts to

switch the capacitor into service, only A phase actually carried current. This was consistent with the eye witness account of the circuit switcher arcing on only one phase during the close operation. Subsequent testing of the C281 circuit switcher revealed that the contact resistance and open interrupter resistance were satisfactory, however, the pre-insertion resistance value on one of the A phase poles indicated an open condition. The C281 switch live parts were observed to have excessive wear which would require replacement in the near future. The operational problem where B and C phases did not close could not be reproduced during extensive testing. S&C was contracted to perform field service on the C281 circuit switcher which revealed that there was broken parts in the A phase brain and a significant amount of mechanical slop in the drive mechanism.

Analysis

Cap 1

In reviewing the problems related to the June 2005 failure and the other reported problems that had been occurring with Hosensack Cap 1, it became apparent that there was likely more than one single problem. The violent failure occurred while the circuit switcher was attempting to trip for an imbalance condition. The magnitude and pattern of the damage described was typical of a re-strike condition. A re-strike is caused by the inability of the interrupting device to adequately clear and thus open the circuit. The withstand voltage of the interrupter thus becomes very important in that it must always exceed the transient recovery voltage during a trip operation. If the withstand voltage is no longer high enough to perform this task, then a re-strike is likely to occur. Many factors can reduce the withstand voltage of an interrupter. They can include such conditions as contact surface abnormalities (burrs and pits) from wear, reduction of the dielectric strength of the insulating medium or non-standard operation of interrupting contacts during trips (speed and location). Because of these factors, each interrupter has a factory recommended life based on utilization and number of operations. According to S&C Inspection Recommendations, the operational limit of these interrupters for capacitor applications at the rated current can be approximated at 3261 operations. This value was determined utilizing the shape-preserving interpolation method [2]. The operation counter on this circuit switcher is currently 3262.

Secondly, the damage experienced on the Cap 1 neutral circuit and on the secondary circuits is all reminiscent of inrush problems related to close operations. According to the relay crews, this has been an ongoing problem over the last several years. The pre-insertion contact arm gaps must be within specification or they will only be partially effective during close operations. The damage described can occur when high frequency voltages and currents are present due to the partially effective (or completely ineffective) operation of the pre-insertion inductors during back-to-back capacitor switching operations. In general, the use of these pre-insertion inductors may not be as reliable as other switching devices, since they rely on an air gap and several other mechanical tolerances to be completely effective.

Cap 2

The failure of the Cap 2 circuit switcher (C281) to close properly was due to the inability of the B and C phase interrupters to properly reset during the last open operation. The problem associated with the circuit switcher operation appeared to be the direct result of mechanical wear. The operating mechanism is attached to the A phase pole and mechanically linked to the B and C phase poles. The mechanical slop identified in the drive mechanism is capable of producing the observed intermittent misoperations. Similar to Cap 1, the published operational limit of the circuit switcher interrupters for capacitor applications is 3261 operations. The operation counter on this circuit switcher is currently 3212.

During the investigation, the 09/13/96 failure of Cap 2 was examined. The initial investigation and report did not seem to offer any potential root cause analysis and/or draw any conclusions other

then a suspected can failure. The record seems to indicate that the failure did not involve the operation of the circuit switchers. The actual description was more reminiscent of a single can failure and associated alarm followed by a fault condition. In this scenario, one likely cause of the fault may be the result of improper fuse clearing following a single can failure. During the examination of this capacitor bank, as well as many others on the FirstEnergy system, it was revealed that often the expulsion fuse leaders were not properly threaded into the spring mechanism. This condition will enable the leader to whip out toward the side and inhibit proper clearing thus effecting nearby cans in a potentially catastrophic manner.

Corrective Actions

Based on the number of operations on both the Cap 1 and Cap 2 circuit switcher interrupters and switch live parts, it was determined that at a minimum these components had to be replaced. Both circuit switchers also required a complete overhaul of their major components including the power train, switch operator, shunt trip device, and brains. The recent incidents associated with these capacitors and the evidence uncovered during the investigation indicates that there have been pre-strike and re-strike problems associated with these circuit switchers. FirstEnergy’s Planning and Protection department recommended replacing the circuit switchers with synchronous closing circuit breakers and installing a fixed 500 μH reactor between the two new breakers. (See Figure 2) This recommendation was consistent with FirstEnergy’s current effort to greatly improve the design, operation and maintenance procedures on all of the company’s substation shunt capacitor banks.

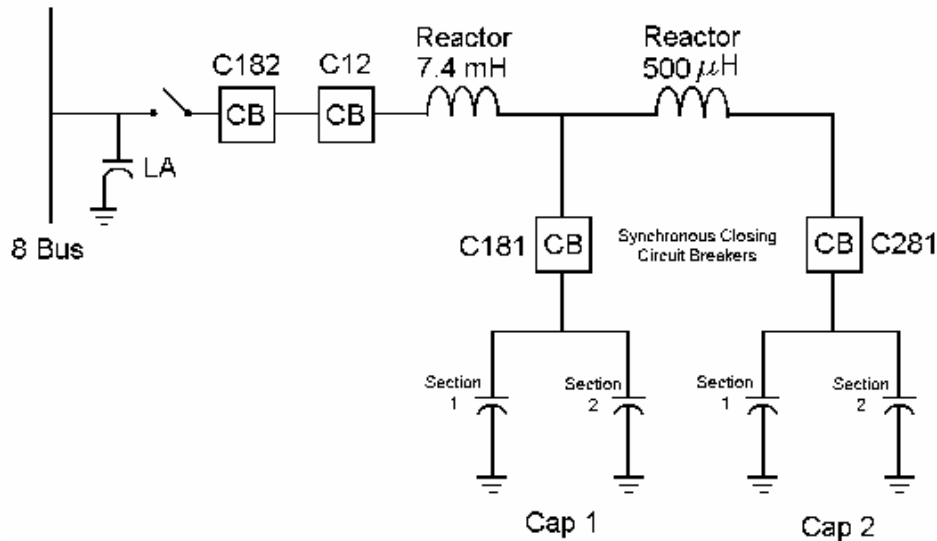


Figure 2
Modifications to the Hosensack 230 kV Shunt Capacitor Banks

The design of new capacitor installations as well as upgrades to existing banks already installed on the system will be thoroughly studied to determine required operating characteristics. New and upgraded installations will be designed and constructed based on these characteristics. The operation of these banks will also be studied to determine the most effective manner of capacitor control. (See Figure 3) Many new capacitor banks are being equipped with automatic voltage controls which will remove the system operator from the equation and ensure the banks are removed from service before experiencing any over voltage conditions. Conversely, it will also ensure that capacitors are switched in service promptly as voltage drops occur.

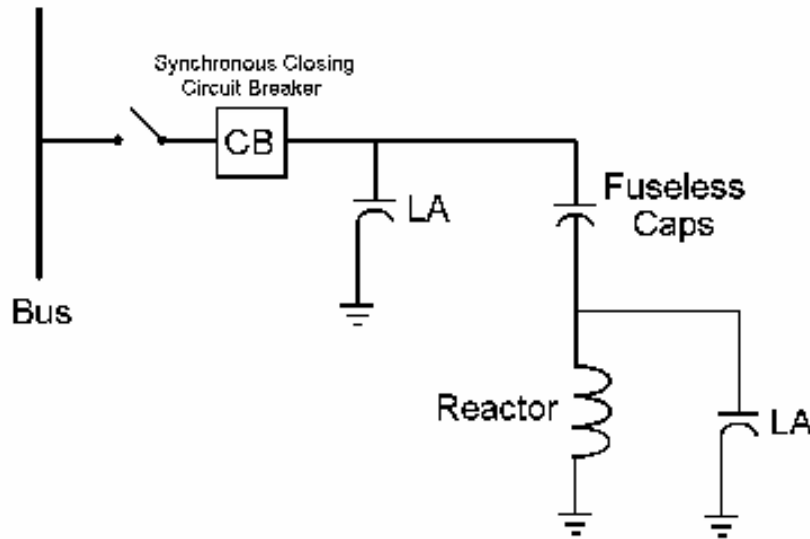


Figure 3
Basic 230 kV Capacitor Design for New Installations

An equally important element to the improvement in capacitor bank reliability is the maintenance associated with all the components of these installations. Procedures are routinely being developed and published by the FirstEnergy Substation Maintenance department to support regional substation operations in the testing and maintenance of capacitor banks. These procedures address the many capacitor types, bank configurations, switching devices, and protection techniques employed over the years at all seven of the FirstEnergy operating companies.

Practical Lessons

All substation shunt capacitor bank failures require a follow up investigation and root cause analysis. Too often in the past, capacitor failures were viewed more as routine annoyances that just had to be endured. The trend today is to approach each capacitor failure as the potential result of a design, operation or maintenance flaw. An in depth forensic investigation should be conducted by an investigator familiar with the capacitor bank and performed before any potential evidence is disturbed. Once the root cause of the failure is determined, the information can then be passed on to the responsible department(s). Relevant information can be obtained and shared through this process and appropriate changes can then be made where applicable.

Conclusion

Substation shunt capacitor banks are becoming increasingly important in the reliable and economic operation of electric systems throughout North America. The experiences associated with the increased use of these capacitor banks at FirstEnergy has made it apparent that these static devices are extremely vulnerable to a multitude of system anomalies. It is imperative to fully understand the operating characteristics of shunt capacitors and to apply good engineering principles in their design, operation, and maintenance. The various problems identified at Hosensack substation illustrate that there are many potential sources that can lead to or cause capacitor failures. It is therefore essential that each substation shunt capacitor failure be thoroughly investigated so that a root cause can be identified and the resulting information used to improve the reliability of both the current and future capacitor banks.

References

- [1] E. H. Camm, "Shunt Capacitor Overvoltages and a Reduction Technique," presented at the 1999 IEEE/PES Transmission and Distribution Conference and Exposition, New Orleans, LA, April 14, 1999.
- [2] S&C Electric Company, Instruction Sheet 711-590, June 3, 1991.

Biography

Lawrence P. Hayes is a Senior Engineer in the Relay and Controls section of the Substation Maintenance department at FirstEnergy Corporation. Larry has over 23 years of experience in the construction, maintenance and operation of substation electrical equipment and has held numerous engineering and management positions in the FirstEnergy family of companies. Larry has a BSEE from Drexel University in Philadelphia, PA and is a registered Professional Engineer in New Jersey and Pennsylvania.