INTRODUCTION

During 2003, Jersey Central Power and Light Company (JCP&L), a wholly owned subsidiary of FirstEnergy Corp (FE), began to experience a series of seemingly unrelated and unexplained 34.5 kV capacitor bank failures. These failures all involved a group of capacitor banks that had recently been upgraded from 10.8 MVAR to between 15 and 18 MVAR, by installing larger individual capacitor units. Most of the failures were sudden and catastrophic in nature. The failures occurred over a time span of 18 months and seemed to be associated with switching operations. By the spring of 2004, there had been a total of nine failures associated with these capacitor banks which accounted for a failure rate nearing 50%. The additional capacitance they represented was required for the high load periods normally experienced during the late spring and summer months. As a result of the failures, the company was forced to implement very restrictive work rules while these capacitor banks were in service. This restrictive policy was necessary to guarantee the safety of employees who were in the substation; however, it greatly restricted normal operations at the affected sites. Meanwhile, a concerted effort to identify and correct the capacitor problems was launched in late 2003 when it became apparent that the failures might be related.

BACKGROUND

JCP&L is a summer peaking utility with maximum loads exceeding 6000 MW. The system is spread out over nearly half the landmass of New Jersey and it serves over 1,000,000 customers. The JCP&L sub transmission system serving the majority of this load is operated at 34.5 kV and consists of over 1750 miles of lines interconnecting more than 350 distribution substations. During heavy demand periods, voltages on the 34.5 kV system would routinely drop to levels nearing 29.5 kV. In addition, most of the Load Tap Changers (LTC’s) on the distribution power transformers fed from this system were operating exclusively in the high end of the raise (boost) zone. Many LTC’s were routinely going to the 16R position with additional voltage correction still required.

An effort to address the voltage problems associated with the 34.5 kV system began in late 2002. A study of the 34.5 kV system revealed that additional capacitance was required to offset sub transmission system losses during high load periods. It was determined that the addition of 224 MVAR of capacitance to the 34.5 kV system was required to alleviate the low voltage conditions. This represented a capacitance increase of 9.3% over the approximate 2400 MVAR of capacitance that was already installed on the 34.5 kV system.

It was further determined that the most expeditious means to install that much capacity prior to the heavy demand period was to increase the size of certain existing capacitor banks at key sites around the system. Proceeding in that manner would eliminate all the inherent construction delays associated with obtaining required building permits. Twenty-eight sites that were already equipped with 10.8 MVAR outdoor capacitors were selected. These units were selected based on the ability of the affected 34.5 kV buses to handle the capacitance increase without producing a flicker problem during switching.
Design of Capacitor Banks

The majority of capacitor banks used on the JCP&L 34.5 kV system are connected in a double ungrounded wye configuration and typically rated at either 5.4 or 10.8 MVAR. Normally, capacitor bank arrangements consist of individual capacitors (cans), power fuses, reactors (if required), and a switching device. These banks are typically a mix between enclosed and outdoor units. In most applications the banks consist of two parallel racks of single, externally fused 300 kVAR cans rated at nominal phase voltage. The two racks are connected to a common neutral with a CT between them used to detect current imbalances. A relay scheme is used to trip the switching device for unbalanced neutral currents. (See Figure 1)

![Original Capacitor Bank Design](image)

Original Capacitor Bank Design

FIGURE 1

The following steps were taken to increase the size of the capacitor banks from 10.8 MVAR to 18.0 MVAR while utilizing existing foundations and control schemes.

1. **Increase individual capacitor size to 500 kVAR.** The existing racks were arranged to accommodate six cans per group per phase. The two racks connected in parallel contain a total of 36 cans for a rating of 18 MVAR. Other variations were used at times to increase or decrease the amounts in 3MVAR increments. The capacitors and racks were purchased from Cooper Power Systems. The upgraded 500 kVAR capacitors are type CEP185B4FA and rated at 19,920 volts, 150 kV BIL with one bushing and external expulsion fuses.

2. **Upgrade the switching device as required.** Some of the capacitor installations used 1200 amp circuit switchers and required no upgrades. The majority of the existing outdoor capacitor banks being modified utilized a 300 amp Joslyn type VBM fault interrupter for switching. A minimum 400 amp VBM switch was required to switch the new upgraded capacitors. Nineteen new 400 amp Joslyn VBM switches were purchased to replace the existing 300 amp units. Four installations already had VBM switches rated at or greater than 400 amps and therefore were not replaced.

3. **Increase the Reactor size as required.** Many of the upgraded capacitors were situated at substations where other adjacent capacitor banks were located. Reactors were installed between adjacent capacitor banks to reduce the inrush current contributions during both switching and fault conditions. The reactor size was upgraded as required.
4. Increase fuse protection to 400 amps. Most of the 10.8 MVAR capacitor banks were protected with 250 amp fuses. The primary fuse protection was increased to 400 amps, which was accomplished utilizing two 200 amp fuse sets per phase.

These modifications allowed for the most expeditious construction schedule possible and closely mirrored the original design. (See Figure 2)

![Upgraded Capacitor Bank Design](image)

**Initial Failures and Problems**

JCP&L experienced the first failure of these upgraded capacitor banks in early 2003 at the Franklin Substation. A violent failure occurred during an open operation. Some individual cans were destroyed, some had deformed tanks and many had blown fuses. At the time, this was considered an isolated incident with the capacitors themselves being the primary suspect. A second violent failure occurred at the Larrabee Substation about a month later. In that incident Cap 6 had failed to open properly during a supervisory operation. The capacitor bank was found with two poles of the new 400 amp Joslyn VBM switch in the open position while the third remained in the closed position. The failure occurred after the crew was called to the scene and opened the remaining pole manually with a switch stick. This incident prompted an investigation into the operation of that particular VBM switch. Joslyn was contacted and suggested at the time that the operation of the VBM switch was hindered due to high control wire resistance. This resistance was thought to be the result of the long distance between the batteries and the VBM switch itself. Joslyn stated that the total round trip line resistance for the application being used could not exceed 0.31 ohms. Control cables were then increased in size and/or paralleled in an effort to achieve the recommended values.

A third violent failure occurred at the Englishtown Substation in the summer of 2003. Cap Bank 2 was discovered with numerous blown capacitors, which occurred during an earlier open operation. In January 2004, two more violent failures involving newly installed 500 kVAR capacitors occurred at the Readington and Gillette Substations. It was originally thought that only one of these failures occurred during switching while the other occurred during a steady state condition.

**Initial Investigation and Conclusions**

The initial investigation into these problems focused on the capacitors themselves. Several were shipped back to Cooper Power Systems for analysis. One group was from a known switching failure (Gillette Substation) and the other from a suspected steady state failure (Readington Substation). The results indicated that all the failed capacitors were subjected to excessive electrical stress associated with high voltage conditions. This caused the dielectric breakdown and subsequent failures of the capacitors. No manufacturing defects or abnormal conditions were observed during the disassembly of the units. It was
the opinion of Cooper Power Systems that both sets of capacitors experienced similar high voltage conditions and thus failed in a similar manner. Cooper Power Systems also noted that the expulsion fuse leaders on the individual cans were not properly routed through the flipper assemblies. It was pointed out that this condition could result in the improper clearing of a fuse such as for a single can failure. The investigation next focused on the suspected steady state failure. Based on the results from the analysis performed by Cooper Power Systems all the potential sources for over voltage during steady state operation were considered. Resonance problems due to harmonics, remote switching transients and system over voltage conditions were all examined. The investigation into a potential resonance problem and the potential effects of system switching transients identified no problems. The study into potential system over voltage conditions lead to the realization that the System operators were responsible for manually switching the 34.5 kV capacitor banks in and out of service as warranted by system conditions. It was soon discovered from interviewing the system operators that they had occasionally witnessed system voltages that approached 38.0 kV before they were able to remove capacitor banks from service. The system voltage records were examined and they proved that voltages ranging between 105% and 110% of nominal had occurred during the period leading up to the two failures. Cooper Power Systems was contacted regarding these findings and they indicated that occasionally operating the 500 kVAR capacitors at 110 % of rated voltage (37,952 volts) was allowable and within normal design specifications. [1] They further indicated that the damage observed on the capacitors that they examined was not indicative of operating the capacitors in that manner.

The Cooper Power Systems findings prompted a more detailed look into the failure modes of both of the capacitor banks that they examined. It was again confirmed that the failure of the Gillette capacitor bank correlated directly to an open operation of the VBM switch that was solicited by the system operators. It was also confirmed that the failure of the Readington capacitor bank was not associated with a solicited opening however; the energy management system (EMS) log indicated that an unsolicited trip of the VBM switch had occurred at the time of the failure. The VBM switch can only have an unsolicited open as a result of an operation of the unbalance relay between the two capacitor racks. This is an over current relay with an instantaneous element which is set to normally operate for an unbalanced condition of two cans. Based on the information provided by Cooper Power Systems it was suspected that the operation of an expulsion fuse on a single can could have lead to an operation of the unbalance relay if the associated fuse leader was improperly retained and failed to clear. Therefore the one capacitor bank failure originally thought to have occurred during a steady state condition had more likely failed in conjunction with an unsolicited operation of the VBM switch.

The investigation then focused more intensely on the switching of these capacitor banks. In addition to this rash of failures, field reports began to trickle back to the Engineering Department indicating there had been numerous difficulties with the new capacitor installations. The crews installing these capacitor banks reported they had experienced difficulty in successfully opening and closing all three phases of the new 400 amp VBM switches prior to placing them in service. It was also discovered that the new capacitor banks presently under construction were also having the same operating problems despite differences in locations or in the length of control cables. Up to this point, it was believed that the primary reason for the problems observed regarding the new 400 amp VBM switches was due to high resistance on long control wire runs between the batteries and VBM switches. Elevated control line resistance by itself no longer seemed like a plausible explanation for the number and frequency of the problems being experienced. It was thus concluded that other aspects of the VBM switch might be involved with this growing list of failures, problems and concerns.

**Switching Device Operation**

The Joslyn VBM Fault Interrupter is a switching device that utilizes vacuum modules to interrupt current. At 34.5 kV, the switches are available with a 300, 400 or 600 amp rating. The VBM switch is available
in either an AC or DC version for all three current ratings at 34.5 kV. In the 34.5 kV, 300 amp unit, a single operating mechanism is used for all three phases with two breaks per phase. It can be equipped with a pair of open and close solenoids or it can be driven by a motor operator. In the 34.5 kV, 400 and 600 amp models, each phase is independently operated by its own mechanism and has two breaks per phase. Each mechanism contains a single open and close solenoid and the same solenoids are used for both opening and closing in either an AC or DC application. There is no option for a motor operator for these voltage and current ratings. The solenoids are not only used to actuate an open or close operation; they are also the only direct source of energy for the 400 and 600 amp mechanisms.

Most all the 34.5 kV VBM switches purchased by JCP&L over the years were configured for DC operation. All of the new 400 amp VBM switches were also specified for DC operation. JCP&L has utilized numerous 300 amp DC powered VBM switches for many years prior to these events with no pattern of notable incidents. These are the most common apparatus used for switching the 5.4 and 10.8 MVAR outdoor capacitor banks in service throughout the JCP&L system. Most of those switches however, utilize a motor operator and not solenoids.

Some 400 and 600 amp VBM switches were also in service prior to the capacitor bank upgrades. It was later discovered that they too had experienced problems related to slow or incomplete operations. The crews considered these incidents to be local in nature and attempted to deal with them on site in various ways. One previously installed capacitor bank using a 600 amp VBM switch was later found, through the course of this investigation, to have been out of service for over six months due to incomplete open/close operations.

A more intensive effort was made to examine the operation of the entire VBM switch in an attempt to identify the root cause of the operational problems. Initially the focus was centered on the requirement that the total series resistance on the DC feed not exceed 0.31 ohms. At some locations with long runs between the capacitor bank and the batteries this proved to be quite a challenge. Once this requirement was finally achieved there were still problems with getting complete and consistent open and close operations on the 400 amp rated switches. Next as per recommendation from Joslyn, flat washer shims were placed under the nylon spacer sleeves of the affected solenoid assemblies. The shims are used to adjust the pin gap (end play) between the solenoid plunger and the actuating pins. This gap must measure between 0.070 and 0.090 inches. Increasing the pin gap increases the operating speed of that phase by allowing the solenoid plunger to strike the control yoke with a greater force. Conversely, decreasing the pin gap will decrease the speed of the associated phase. The shims were added or removed from the individual mechanisms until a single satisfactory timing test of the entire VBM switch was obtained. Even with this guidance from the manufacturer, there was still trouble at many locations, which eventually led FE to request on site assistance from Joslyn.

Switching Device Timing Requirements

The proper timing of capacitor switching devices is critical for their successful operation. During a trip operation, the switch must operate faster then ¼ cycle (4.17 ms.) in order to avoid a nonsynchronous operation. An operation of one of the phases outside of this requirement could cause multiple re-strikes across the vacuum modules and subject the capacitors to subsequent voltage transients on the order of 2.5 to 6.4 per unit for an ungrounded wye configuration. [2] The VBM switch timing test specifications as per the manufacturer are as follows:
TIMING LIMITS FOR CAPACITOR SWITCHING

**TRIP OPERATION**
- Trip Coil Energize to Last Contact Open 100.0 ms.
- First to Last Contact Opening (all phases) 4.0 ms max.
- First to Last Contact Opening (same phase) 1.0 ms max.

**CLOSING OPERATION**
- Close Coil Energize to Last Contact Close 100.0 ms.
- First to Last Contact Close (all phases) 8.0 ms max.
- First to Last Contact Close (same phase) 1.0 ms max.

Joslyn was invited to assist in the timing of a newly installed 400 amp VBM switch at the Windsor substation. Measured series resistance at the site was 0.24 ohms with a strong DC supply of 132 volts. Original timing values for trip operations, from first to last contact opening for the entire device, were recorded at over 1 cycle (16.67 ms). The factory representative installed and removed shims until the best possible timing results were obtained however, they were not repeatable and often not in specification. These test results prompted a detailed examination of the power requirements and operational characteristics of the solenoids themselves. All the evidence seemed to suggest that there was a lack of energy available to the solenoids.

**Switching Device Modifications**

The trip and close control circuits of the VBM switch were closely examined. These circuits are independent of each other but electrically identical. It was observed that the DC application for a 400 or 600 amp VBM calls for the three independent solenoids and associated contactors to be arranged in a series electrical connection. This in turn is also in series with the line resistance thus forming a basic series DC circuit. On a single mechanism 300 amp model there are two solenoids for each trip and close arranged in series with the line resistance. It then becomes obvious that the energy available to the 400 and 600 amp units is only two thirds that of the 300 amp unit assuming each has an equivalent voltage source. In the AC control power version, the three solenoids and associated contactors are arranged in a parallel electrical connection. Therefore in the AC model the parallel group of solenoids and contactors are arranged in series with the line resistance to form a basic series-parallel circuit. The interrupting capability of the contactors does not allow for arranging the solenoids in parallel for DC applications. A simple model of the solenoid trip and close circuits was created to compare the energy availability to the solenoids for the 400/600 amp DC VBM switch and the 400/600 amp AC VBM switch. (See Figure 3)
Where:  
\[ RL = \text{Total Line Resistance} = 0.31 \Omega \text{ (max)} \]
\[ RA = RB = RC = 0.82 \Omega \]
\[ LA = LB = LC = 0.0055 \text{ h} \text{ (initial condition/de-energized)} \]
\[ LA = LB = LC = 0.0600 \text{ h} \text{ (full stroke condition/energized)} \]

**DC and AC Solenoid Circuit Models**

**FIGURE 3**

The actual impedance values for the solenoid are non-linear. During an open or close operation energy is added to the RL circuit with initial condition (de-energized) impedance until minimal threshold energy is achieved which allows the solenoid to begin moving. Once the movement begins the inductive component of the impedance changes with the solenoid movement until full stroke conditions are achieved. The circuit will then continue to operate with those full stroke (energized) impedance characteristics until the energy source is removed.

This operation can be observed when the current is monitored during a timing test. Initially the current has normal exponential characteristics and appears on the timing chart with a positive slope consistent with the initial condition impedance. An inflection and a negative slope can be seen during the movement of the solenoid as the inductive component rapidly decreases. A second inflection back to a positive slope is then seen and the circuit resumes with normal exponential characteristics as defined by the full stroke impedance values. The total energy used to operate the VBM switch is thus calculated at full stroke, which equates to the second current inflection. Total energy into the circuit can then be evaluated by integrating within that time interval.
The results obtained from these simple models were dramatic, as it became obvious why there had been so many operational problems with the 400 and 600 amp DC operated VBM switches. The energy available to each of these solenoids when powered with DC was greatly reduced when compared to the 400 and 600 amp VBM switches operated with AC. Based on the results of these models and actual field experimentation with both AC and DC sources, it was concluded that providing an AC power supply to the solenoids was necessary for insuring the proper timing and operation of all 400 and 600 amp VBM switches on the system. This included all the newly purchased 400 amp switches for the capacitor upgrade project.

In addition to examining the open and close circuits for both AC and DC operation, the manufacturer of the solenoids was contacted for engineering and application guidance. The manufacturer indicated that the solenoid was designed and rated to operate with a 115 volt AC source but it can also be operated with DC. It was pointed out that the AC application of the solenoid was more efficient and inherently faster when equivalent voltages are applied. The solenoid was designed to produce 45 foot pounds of force at a 1 inch stroke at rated voltage. Applying a significantly reduced DC source to the solenoids in this application would then be expected to reduce the output force and produce slower overall switch speeds. [3]

The decision was made in May 2004 to modify the entire group of new 400 amp VBM switches with an AC power supply to the solenoids. The majority of the DC control scheme was not affected. Only the direct power supply portion to the solenoids and the associated contactor configuration was adjusted. A step by step procedure was developed along with new, very rigid timing and testing guidelines. A systematic plan to modify all of the newly installed 400/600 amp DC operated VBM switches was initiated. The result of installing this AC/DC field modification was spectacular with respect to the overall operation and timing requirements of the VBM switches. (See Table 1) At this point, it appeared that the root cause of the capacitor bank failures was directly attributable to the timing of these devices. Correcting this problem through the prescribed AC/DC field modification was thought to be a complete solution to the problem.

TABLE 1
Timing Results of a 400 amp Joslyn VBM switch from original installation through an AC field modification

<table>
<thead>
<tr>
<th>Open Test Number</th>
<th>Fastest Time (ms)</th>
<th>Slowest Time (ms)</th>
<th>Switch Delta (ms)</th>
<th>Solenoid Voltage (volts)</th>
<th>Test Conditions and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.90</td>
<td>67.20</td>
<td>9.30</td>
<td>132 DC</td>
<td>Original first timing test results after assembly with no modifications.</td>
</tr>
<tr>
<td>2</td>
<td>57.10</td>
<td>72.50</td>
<td>15.40</td>
<td>131 DC</td>
<td>Open tests 2 &amp; 3 are the worst and best switch delta values respectively after shims were added to improve original timing results. All testing of DC powered VBM switches displayed similar inconsistent timing results.</td>
</tr>
<tr>
<td>3</td>
<td>59.40</td>
<td>62.20</td>
<td>2.80</td>
<td>132 DC</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>47.30</td>
<td>51.20</td>
<td>3.90</td>
<td>124 AC</td>
<td>Open tests 4 &amp; 5 are the worst and best respectively of ten switch delta values after the solenoids were converted to AC power. These faster more consistent timing results were common after the conversion</td>
</tr>
<tr>
<td>5</td>
<td>41.40</td>
<td>43.80</td>
<td>2.40</td>
<td>124 AC</td>
<td></td>
</tr>
</tbody>
</table>
Continuation of Capacitor Bank Failures

In June of 2004 two more upgraded capacitor banks failed violently during an open operation initiated from the system operator. These failures occurred just days after each of the associated VBM switches was modified and thoroughly tested. Both failures involved two phases with blown power fuses with one phase remaining in tact. Each failure featured ruptured cans, blown expulsion fuses and external flash marks. These failures were a complete surprise because it was believed that the problems associated with the VBM timing was the root cause to the switching failures. It was clear at this point that although the AC/DC field modification was necessary to correct the timing problems it was not a final solution to the problem(s). It was now concluded that the initial engineering and application of this switch required a complete detailed investigation.

Expanded Failure Investigation

The company contacted Joslyn High Voltage again to discuss the continued problems despite the correction of the VBM switch timing issues. It was decided to send the failed Larrabee Cap 5 VBM switch to Joslyn for a complete forensic analysis. In addition to the disassembly of the failed switch, a complete review of the design and application of all the capacitor bank installations was conducted. The company continued to only use the upgraded capacitor banks on a limited basis as required by system conditions. This also required the continuation of the restrictive work rules for operating the upgraded capacitor banks with personnel in the affected substations. The results of the forensic investigation and continued dialog with Joslyn revealed several previously unknown design criteria that were not available during the initial engineering of these capacitor bank upgrades. They included new required clearances and revised inrush ratings for the switches. It was also suggested at this time that other phenomenon might be responsible for some of the timing problems and re-strike issues.

Joslyn also provided FE with a voltage withstand curve for the VBM switch during the investigation. Applying the system conditions associated with the Larrabee Cap 5 failure to this curve revealed that the system voltage comes to within 93% of the stated withstand curves when both modules in a phase open at exactly the same time and voltages are split evenly across both. At the maximum timing tolerance of 1.0 ms between modules on the same phase the system recovery voltage comes to within 97% of the stated withstand voltages assuming an exact even voltage split across the open contacts. There is thus little or no voltage withstand margin available in these switches for any system or device related variation common to operating the 34.5 kV sub transmission system.

Results of Expanded Investigation

Forensic analysis on the failed vacuum modules of Larrabee Cap 5 revealed extensive wear and erosion on both the phase B and C bottles. Both phases were found with blown power fuses. The fuse operation and concurrent contact wear/erosion was caused by a 29.5 kA fault current available at the site. The A phase module, which did not have an associated blown fuse or damaged capacitors, was found to have evidence of contact welding on up to 20% of the contact surface. Joslyn indicated that high inrush current during a closing operation could cause welding of the contact surface and slow an open operation of the affected contact due to the added force needed to break the weld. This condition would likely create recovery voltages exceeding the switch rating and would result in multiple re-strikes. These re-strikes are capable of producing over-voltages well beyond the rating of the capacitors to which they are connected. Beside the extensive contact wear and erosion, there was no evidence of defects and all parameters of the switch met factory standards.

Joslyn later performed an Electro-Magnetic Transients Program (EMTP) analysis on Larrabee Cap 5 and discovered that the back-to-back inrush currents exceeded 12,000 amps. This was a 25% increase over
the original values calculated using the engineering guidance provided by Joslyn. Joslyn also indicated that the guidance was based on formulae from ANSI C37.0731 – 1973, and that it does not account for inrush contributions from the system and from unbalanced capacitor banks. They later found a reference in a Westinghouse T&D publication that used a factor of 1.2 to account for those additional inrush sources for back-to-back capacitor switching. Joslyn considered this factor close enough to account for the increased inrush current obtained from the EMTP analysis. Joslyn then recommended the addition of 250 $\mu$H of inductive reactance between Cap banks 5 & 6 to reduce the inrush current during back-to-back switching.

Joslyn had also informed FE during the course of the investigation that any objects within 32 inches of the VBM vacuum modules could potentially influence the operation of the VBM switch. (See Figure 4)

They indicated that the magnetic field associated with a current carrying conductor in that area of influence could potentially cause the arc across the contacts to be concentrated on one side of the contacts. The concentrated arc could then result in severe overheating of a portion of the contact surface and the potential generation of thermionic emissions capable of causing a re-strike. Additionally, any object in the area of influence, whether energized or not, could result in an unequal distribution of the transient recovery voltage across the two vacuum modules on each phase thus creating a potential re-strike condition. This information was especially troublesome for FE since it did not appear on any prints, was not contained in any company publications and was not verbally communicated to FE prior to the purchase of this group of VBM switches.

FE conducted a survey of the capacitor installations with new 400 amp VBM switches to determine the existing minimum clearances around the vacuum modules. It was discovered that 13 of the 23 installations had objects less then 32 inches from the vacuum modules however, only four of the nine that failed were in this group thus eliminating the 32 inch clearance issue as a sole source for the capacitor failures.

**CONCLUSIONS**

It was concluded that the most probable cause of the capacitor failures experienced in the JCP&L system were due to re-strikes of the VBM switches during open operations. All the evidence indicates that there was significant potential for these VBM’s to re-strike due to any of the following conditions, which were discovered during this investigation:

1. Timing problems associated with contact welding due to higher then expected inrush current magnitudes.
2. Timing problems associated with VBM switches operated with DC.

3. Voltage withstand problems caused by objects within a 32 inch clearance of the vacuum modules.

4. Generation of thermionic emissions due to energized objects such as CT’s within the 32 inch clearance zone.

5. Voltage withstand problems due to normal variations in system voltages.

**ANALYSIS**

One of the most important lessons learned from this experience is realization that upgrading system components requires an engineering approach similar to that of a new installation. Consideration needs to be given to the ever-changing dynamics of the system itself. Time must be invested in studying the impact of the upgraded device to the system and the impact of the system on the upgraded device. It was also realized that insufficient and/or inaccurate engineering information provided from any outside source, such as a vendor or contractor, can greatly impact the outcome of the project despite all the efforts to perform system studies and evaluations.

The maintenance and testing procedures for the VBM switch were reviewed and revised to insure proper operation of the device as well as prescribe methods for addressing all the deficiencies identified. It is critical to test every VBM switch on the system to insure that the timing is correct and that it meets all other recommended test criteria. The operation of the VBM switch with a DC source does not provide the necessary energy for the repeatable synchronous operation of these units. VBM switches that cannot be timed within specification using the DC source at the site must be modified, as per procedure, to utilize the AC/DC field modification.

Following the investigation an effort was made to insure that high system voltages were minimized although they were not directly attributed to the capacitor failures. The system operators were educated about the over voltage restrictions on capacitor banks and that they were not designed to operate for long periods at system voltage levels above 110% of nominal. The company is considering the future installation of an automated capacitor switching scheme.

Due to the general overall characteristics of capacitor switching and especially the switching of ungrounded wye banks, it was decided to increase the margins on every device associated with new capacitor banks in the entire FE system. All of the upgraded capacitor banks will be converted to the new standards. This new criteria is discussed in the following section.

**Design of Future Capacitor Bank Installations**

FirstEnergy has adopted a new design standard for 34.5 kV capacitor banks, throughout its seven company territory. The design changes are as follows: (See Figure 5)
Future design of capacitor bank installations

FIGURE 5

1. A switching device designed specifically for capacitor switching and or an appropriately rated circuit breaker will be used for all capacitor bank switching. Vacuum technology will not be used in any of these switches. Pre-insertion resistors will be used on the new capacitor switchers to limit inrush currents during capacitor energization.

2. The inrush and outrush currents will be calculated allowing at least a 25% margin for the system contribution. Current limiting reactors will be sized considering the inrush and outrush currents and will take into account the reduction gained in energization inrush values gained by pre-insertion resistors.

3. Lightning arrestors rated at 29 MCOV will be installed on each capacitor bank between each phase and neutral and between neutral and ground.

4. Capacitors will be sized at 20,800 volts (or greater) phase to ground to give an minimum 4.43% operating margin over the nominal voltage.

5. Capacitors will utilize external current limiting fuses instead of the external expulsion fuses currently being used. This is expected to minimize outrush currents from parallel capacitor units into a failed can.

REFERENCES


BIOGRAPHY

Lawrence P. Hayes is a Senior Engineer in the Substation Maintenance department at FirstEnergy Corporation. Larry has over 22 years of experience in the construction, maintenance and operation of substation electrical equipment and has held numerous positions in both engineering and management in the FirstEnergy family of companies. Larry has a BSEE from Drexel University in Philadelphia, PA and he is a registered Professional Engineer in New Jersey and Pennsylvania.