Protection Challenges of a Second Harmonic Capacitor Filter Bank

Presented at: Western Protective Relay Conference
Spokane, Washington, USA
October 16, 2014

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1. Introduction

American Electric Power’s (AEP) project to replace the 2nd harmonic filter bank at their Roanoke substation was driven by a need to increase the size of the bank for both harmonic filtering capacity and 60 Hz VAR support. Like many capacitor bank replacement projects in North America, the scope included the replacement of externally fused capacitors with fuseless capacitors. Changes were also made to the capacity of the static VAR compensator (SVC) located at the Roanoke sub.

Filter banks and the SVC are required at the Roanoke substation due to the presence of a customer owned electric arc furnace. The protection of the 2nd harmonic filter bank is based on bank neutral over-voltage. This approach is complicated by the non-linear nature of the neutral voltage signal at Roanoke which is rich in both harmonic and inter-harmonic components. In addition, the neutral voltage is very dynamic, undergoing rapid changes as the arc furnace burn progresses and the SVC output changes. This paper investigate the impacts of arc furnace and SVC switching operations at Roanoke substation on neutral voltage unbalance (59NU) protection function of a 2nd harmonic capacitor filter bank. The qualitative investigation is presented using simulations of various switching modes of the arc furnace and SVC. The lessons learned and recommendations are presented in detail.

2. Roanoke Substation Capacitor Filter Bank Installation

Figure 1 shows a simplified one-line of the Roanoke substation. The substation contains three (3) 138 – 34.5 kV Delta/Grounded-Wye transformers which provide service to the customer’s complex. Transformers 2 and 3 are paralleled through 34.5 kV buses 2 and 3 to feed the ladle furnace and associated loads. The 2nd harmonic filter bank is connected to the SVC bus which is connected to 34.5 kV bus 3. There are also 3rd, 5th and 7th harmonic filter banks connected to the 34.5 kV system.
The original filter bank design is shown in Figure 2. It was an Ungrounded-Wye configuration and contained 80.8 MVAR of 60 Hz VAR compensation (60 externally fused 449 kVAR cans per phase). The 120 Hz tuned LCR filter section had a current carrying capacity of about 1000 amps. The new filter bank design is shown in Figure 3. It is an Ungrounded-Wye configuration and contains 80.9 MVAR of 60 Hz VAR compensation (48 fuseless 562 kVAR cans per phase). The 120 Hz tuned LCR filter section has a current carrying capacity of about 1200 amps. The original resistance potential device (RPD) is retained to measure the neutral voltage. Initially, the new bank was to be protected by one modern micro-processor based neutral over-voltage relay (59N-1). However, as a result of difficulties caused by the dynamic non-linear nature of the neutral voltage, the settings had to be desensitized and a second relay (59N-2) had to be added to handle the alarm and stage 1 tripping. The original relay is retained for second-stage tripping and oscillography capture. A separate modern micro-processor based over-current relay (50/51DF) is used to protect the resistor from over-load.
3. **Considerations from IEEE Guide C37.99-2012** [1]

IEEE C37.99-2012 “Guide for the Protection of Shunt Capacitor Banks” recommendations for Capacitor filter bank (clause-9.1) are summarized below and illustrated in Figure 4. Capacitor units used in filter banks may be required to have more stringent ratings than typical capacitor units due to the harmonics normally present in the filter bank environment. In these applications, higher capacitor voltage ratings and fuse current ratings may be required. Generally, the additional overloading specifications on the various filter bank components should accommodate the higher peak voltages and the increased losses imposed on the reactors and resistor assemblies.

a. **Unbalance capacitor bank protection element to compensate system unbalances (59N)**

Unbalance protection methods detect problems with capacitor units. IEEE C37.99-2012, Clause-8.2 specifies various methods for unbalance protection. One of the effective methods for ungrounded wye bank is “Neutral Voltage Unbalance” (clause-8.2.2). Neutral voltage unbalance element with operating quantity derived from different of 3V0-3VN can cancel-out system unbalances. Bus zero-sequence voltage can be derived from measured three phase voltages at bus VT or measured from a broken delta bus VT winding. Inherent, capacitor bank unbalance (due to difference in capacitance of each phase) can be compensated as well.

b. **Alternate Unbalance Protection scheme for H-configuration differential currents (60)**

In this case, an unconventional capacitor unbalance scheme is provided by means of current measurements between legs of the high-voltage and low-voltage capacitor banks as a result of capacitor failures. Note that the 60 relay in bank C1 (Figure 41) is only sensitive to imbalances in the C1 bank and that the 60 in bank C2 likewise is only sensitive to imbalances in the C2 bank. Also, this protection may require that dual bushing capacitor units be provided so that the current through the two legs can be measured independently. This unbalance protection scheme should carefully evaluate the effect on the protection of off nominal system frequency as well as deviations in capacitor values as a function of temperature (dC/dT). In this regard, the availability of the filter bank is considerably improved if compensation means are provided.
Figure 4: A typical protection scheme for ungrounded-wye filter bank
c. **Overcurrent & Thermal element (50/51, 87, 49)**

The overcurrent function (50/51) provides fast tripping for high-level short circuits near the circuit breaker terminal. Overcurrent relays should be properly coordinated, and the response of the relay to the presence of harmonics should be evaluated to avoid undesired operation. This protection is redundant to the differential (87).

Thermal overcurrent protection (49) may be implemented using root-mean-square (RMS) current compensated with ambient temperature and can be set to trip at RMS current values or temperature.

d. **Resistor Overload protection (51R)**

The damping resistor R in each phase of the filter bank should also be protected against overloads (including both fundamental and harmonic). The 51R relay operates on the true RMS current flowing through the resistor. The time overcurrent curves should provide coordination with the \(I^2t\) overload capability of the resistor.

e. **Bank Over-voltage protection (59)**

Sever over-voltage results in excessive stress on the capacitor units. Peak measuring over-voltage relays may be used for this application, and should be coordinated with the capacitor manufacturer’s specified capability withstand curve.

4. **Application Challenges & Event Investigation**

The initial setting recommendations from the capacitor manufacturer for the neutral over-voltage relay (59N) are shown in Table 1(b) and were based on the percentage of nominal affected capacitor voltage. These settings proved problematic for the relay which would operate fine during normal system conditions and then alarm and or trip when the customer’s arc furnace started a melt. Table 1(a) shows the settings that were applied to the neutral over-voltage relay for the original, fused can, bank.

Fuseless bank designs often have provide much smaller protective relay operating quantities than are provided by comparably sized fused banks. An inspection of the old and new settings in Table 1 yields a good example of this challenge.

<table>
<thead>
<tr>
<th>Function</th>
<th>Pick-up (Primary Volts)</th>
<th>Pick-up (Secondary Volts)</th>
<th>Delay (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alarm</td>
<td>110</td>
<td>0.991</td>
<td>10.00</td>
</tr>
<tr>
<td>Trip</td>
<td>276</td>
<td>2.486</td>
<td>10.00</td>
</tr>
</tbody>
</table>

**Table 2(b): Initial setting recommendations for the new fuseless can bank neutral over-voltage relay**

<table>
<thead>
<tr>
<th>Function</th>
<th>Pick-up (Primary Volts)</th>
<th>Pick-up (Secondary Volts)</th>
<th>Delay (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alarm</td>
<td>40</td>
<td>0.360</td>
<td>5.00</td>
</tr>
<tr>
<td>Trip</td>
<td>75</td>
<td>0.676</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The 60 HZ neutral voltage calculations for various numbers of shorted series groups are shown in Table 3(a) (C1 - Main Section) and 2(b) (C2 - Tuning Section). A close examination of the calculated neutral voltage reveals the fundamental difficulty with this bank’s protection. The voltages are a small percentage of the 22 kV RPD primary rating and the secondary voltages are very small, especially when compared to the RMS voltage normally seen as a result of the harmonic and inter-harmonic components that result from the SVC and arc furnace operation.
In an attempt to improve the neutral over-voltage relay’s performance, the settings were recalculated based on the percentage of rated affected capacitor voltage (see table 3) which resulted in a slightly increased secondary voltage. Unfortunately, the relay still experienced false alarms.

Detailed harmonic analysis was carried-out on the voltages measured in the field during alarm element false operation. Figure 5 shows the difference in inter-harmonic content in Vn with the arc furnace (AF) off (a) and on (b). Similarly, Figure 6 shows the difference in inter-harmonic content in the bus V0 (VA+VB+VC/3) with the arc furnace off (a) and on (b). The y-axis shows the measured voltage (secondary volts). It can be observed that with the arc furnace on (burn condition), there is significant inter-harmonic components (30 Hz, 90Hz, 150Hz, 210Hz, 270Hz, 330Hz, and 390Hz), which have notable variations over time. Note also that the inter-harmonic amplitudes (during AF on) in V0 are 2 to 3 times higher than those in Vn.
Figure 5: Inter-harmonic content in Vn with SVC online: a) AF off; b) AF on

Figure 6: Inter-harmonic content in V0 with SVC online: a) AF off; b) AF on

Figure 7 illustrates this phenomenon by showing the frequency response of the cosine (real part of the phasor) and sine (imaginary part) filters that constitute the full-cycle Fourier phasor estimator [3]. In addition to this filter, advanced IEDs may also apply a special filter for removing high-frequency components.

As illustrated in Figure 7, a typical phasor estimation algorithm completely removes the harmonics (i.e. gain=0pu) but not the inter-harmonics where the gain is around 0.2-0.3 pu. Also as explained earlier, the inter-harmonic magnitudes present in V0 and Vn are significantly different (2 to 3 times). Under these conditions, if the capacitor filter bank is inherently unbalanced, it will cause some difference in filtered Vn & V0, which will result in some small value of Vop.
5. Simulation Analysis to Understand Impact of Arc Furnace & SVC Switching on 59N

Figure 8 illustrates the simulated system used to study the impact of arc furnace & SVC operation on the 59N element of the second harmonic capacitor bank. While an attempt has been made to simulate the actual system as close as possible, the accuracy of the study is limited by the unavailability of detailed SVC control and arc-furnace design parameters. However, the accuracy is adequate to gain a qualitatively understanding of the behavior of the operating quantity (of 59N) in various cases of arc furnace and SVC switching.
a. Static VAR Compensator (SVC) and Arc Furnace (AF) Modes of Operation

Proper working of the simulation model can be illustrated by Figure 9 which shows the voltage measurements at the bus that is feeding the arc furnace. As shown in the figure, the arc furnace and SVC are initially off and the voltages are nominal (34kV L-L RMS). The AF and the SVC are switched on at 0.4sec and 0.8sec respectively as seen on the waveform. Switching the AF on while keeping the SVC off introduces significant harmonics in the bus voltages. Significant harmonic content is measured as the total harmonic distortion (THD), as shown in Figure 9(B). The AF generates significant odd harmonic content in the voltage signal while second harmonic content is very low (Figure 9(C)). However, switching of the AF (at 0.4sec) or SVC (at 0.8 sec), while the second harmonic filter bank is on, generates significant second harmonic contents in the voltages, as shown in Figure 9(C). By switching the SVC on the THD is reduced from 20% to less than 1.5%.

In order to test and analyze the behavior of neutral voltage unbalance protection, the following modes of SVC and AF operations are considered.

- Mode 1: AF is switched on at 0.4 sec while SVC off
- Mode 2: SVC is switched on at 1 sec while AF is on
- Mode 3: AF is switched off at 1.7 sec while SVC is on
- Mode 4: AF is switched on at 2.5 sec while SVC is on
- Mode 5: SVC is switched off at 3.3 sec while AF is on
Each above mode is further tested for inherently balanced and unbalanced second harmonic filter banks.

b. Case 1: Inherently Balanced Filter Bank

This case demonstrates the behavior of neutral voltage unbalanced protection when applied to an inherently balanced 2nd harmonic filter bank for all five modes of operation (Mode 1 to Mode 5). The purpose of creating such system conditions is to understand the neutral voltage unbalances in an inherently balanced filter bank due to switching or running of AF and/or SVC. As shown in Figure 10, the operating signal $V_{op}$ (Figure 10(B)), which represents the unbalance between the neutral voltage $V_X$ (Figure 10(A)) and the bus zero-sequence voltage $V_0$ (Figure 10(A)), is approximately equal to zero. Hence, neutral voltage unbalance protection remains secure if the 2nd harmonic filter bank is inherently balanced.

\[
V_{op} = |V_0 - V_X| = 0
\]

![Figure 10: V0, VX and Vop signal for inherently balanced filter bank](image)

Figure 10: V0, VX and Vop signal for inherently balanced filter bank

c. Case 2: Inherently Unbalanced Filter Bank

This case demonstrates the behavior of neutral voltage unbalance protection when applied to an inherently unbalanced 2nd harmonic filter bank. There are two cases presented in Figure 11: Unbalance compensating factor ($K$) is not applied, and $K$ is applied. In the case when $K$ is not applied, switching the AF off at 1.7sec (Mode 4) results in significant operating voltage, which is greater than the threshold of 0.012 pu. Consequently, it results in the false alarm of the relay.

The following k-factors represent the inherent bank unbalances that are chosen based on the following definition [2]:

\[
V_{op} = |V_0 - V_X| = 0
\]
KAB = CB/CA = 134 μF/134μF = 1
KAC = CC/CA = 134.6 μF/134μF = 1.00447

Where CA, CB, CC are the total capacitance of each phase of the second harmonic filter bank.

Figure 11: Vop for inherently unbalanced filter bank

With properly set K-factors the neutral voltage unbalance due to the switching of the SVC on/off can be mitigated [2]. Nonetheless, the operating quantity (Vop) still goes high during the transient condition at 1.7 sec.

Therefore, it is recommended to carry out system studies with proper modeling of the arc furnace and SVC and their switching modes, in order to derive appropriate settings for the 59N element.

6. Possible Solutions & Recommendations

a. Apply Capacitor Bank Unbalance Compensation – A partial but mandatory solution

This solution is was most desirable because it involves the least amount of redesign. As previously stated, the neutral voltage unbalance (59N-1) is a modern micro-processor based relay intended for operation on Ungrounded-Wye shunt capacitor banks [2]. It operates on the neutral voltage and includes compensation factors designed to account for the normal imbalances of the capacitor bank. The general equation for the operating voltage is:

\[ V_{OP} = \frac{1}{3} |V_x (1 + K_{AB} + K_{AC}) - 3V_0 + V_B(1 - K_{AB}) + V_C(1 - K_{AC})| \]

Where \( K_{AB} \) and \( K_{AC} \) are unbalance ratio settings based on the differences in capacitance (\( C_A, C_B \) and \( C_C \)) between the phases as follows:

\[ K_{AB} = \frac{C_B}{C_A}, \quad K_{AC} = \frac{C_C}{C_A} \]

The relay also compensates dynamically for bus voltage zero-sequence imbalances (\( V_0 \)) by applying a restraint signal as follows:

\[ V_{REST} = |V_x + V_0| \]
It is important to note that the neutral voltage ($V_N$) and the bus zero-sequence voltage ($V_0$) are fundamentally filtered quantities. Also, the $K$-factors are static settings designed to account for static differences in the phase capacitances which are not expected to change dynamically. While the restraint is a dynamic quantity, its dynamics are based on the changes in the fundamentally filtered bus zero-sequence voltage.

Initially, the $K$-factors in the relay were set to account for the operating voltage during a period when the SVC was on and operating stably and the customer’s arc furnace was off. Figure 12 shows the relay operating quantities before (a) and after (b) setting the “$K$” factors. Note the change in $V_{op}$ from 0.0224 pu to 0 pu:

![Figure 12: Relay values before (a) and after (b) adjusting the “K” compensation factors](image)

When the customer’s arc furnace started, the relay went into alarm. Figure 13 shows the relay values. Note the non-linear nature of the neutral voltage ($V_N$) and the erratic levels of operate, restraint and bus zero-sequence voltages.
Figure 13: Relay values during furnace operation

It is recommended that unbalance compensation K-factors should be developed based on the worst unbalance scenarios, i.e. arc furnace turned on with SVC on. Unfortunately, this will reduce the sensitivity of the unbalance protection, hence, may not be acceptable in all situations.

After trying a variety of K-factor combinations with limited success, the field team decided to apply an additional relay with different technology for filtering harmonics (59N-2). This second relay provided improved stability with an increased alarm pick-up and delay. The original relay was retained for stage 2 high-speed tripping and for records capture. Table 4 shows the final settings.

Table 5: Final settings for the neutral over-voltage relays

<table>
<thead>
<tr>
<th>Function</th>
<th>Pick-up (Primary Volts)</th>
<th>Pick-up (Secondary Volts)</th>
<th>Delay (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alarm</td>
<td>60</td>
<td>0.541</td>
<td>30.00</td>
</tr>
<tr>
<td>Trip Stage 1</td>
<td>75</td>
<td>0.676</td>
<td>1.00</td>
</tr>
<tr>
<td>Trip Stage 2</td>
<td>200</td>
<td>1.802</td>
<td>0.10</td>
</tr>
</tbody>
</table>
b. Reconfigure Capacitor Filter Bank

The team considered several alternative bank designs to see if they would result in a more protectable package. Unfortunately, the economics of any of these choices were not expected to be good since the bank had already been installed in the field. The team generally thought that a split-wye design might have been easier to protect using current balance between the two neutrals. This method has the advantage of being able to adjust the core-balance CT’s ratio to achieve statistically significant operating signals. There should also be fewer harmonics present in this unbalance current during normal operation, reducing the filtering challenge.

The team also considered replacing the cans with larger units (more series groups with over-all higher voltage ratings). This was a more realistically achievable option considering that the existing structure could be reused and the basic design would not be affected as long as the net capacitance remained the same. A notable limitation of fuseless capacitors is that you should never allow more shorted series groups than are present in each can or the cans might fail on over-current [2]. This imposes a limitation on the tripping voltage for the existing cans. Larger cans would have allowed more shorted series groups, resulting in more robust protection signals. Even though this was more economical than the split-wye option, the team still felt it was prohibitively expensive.

Finally, the team considered adding current balance relays as recommended in IEEE C37.99 [2]. Figure 14 shows the addition of current balance relays to the Roanoke 2nd harmonic filter bank. The series/parallel “H” configurations for the C1 and C2 sections result in equivalent capacitances of C1 and C2 respectively. As in the case of the split-wye design, the current balance relays may have fewer harmonics to deal with during normal operation and the CT ratios can be adjusted to provide more robust protection signals. Similar to the split-wye arrangement, the addition of the C1 and C2 section current balance relays would have been cost prohibitive as a retrofit since the “H” configuration requires 2-bushing cans [1] and an entirely different physical structure from the existing bank’s structure.

![Figure 14: IEEE C37.99 current balance relays](image-url)
c. Owner to investigate system configuration changes and its impact on existing P&C at planning stage, and clarify the impact in specifications

During capacitor bank design the vendor makes various choices to arrive at a design that meets the owner’s specifications for the most economically attractive package. Protection of fuseless capacitor banks is often problematic due to the relatively small changes in operating condition (i.e. bank unbalance) that occur with series group failures. As a result, owner specifications should include some comments on the protection of the bank including minimum operating signal levels for alarm and tripping functions or other criteria (over-all bank voltage rating margin, etc.) that result in adequate protection signal levels. In the case of the Roanoke bank, the real problem is that the protection signals are too small to be reliable. Different bank designs could have been supplied that would have provided significant change operating quantity to detect the bank unbalance.

Since the protection challenges were not discovered until start-up, the duration of start-up increased significantly and the in-service date was delayed. Perhaps the most reliable way to assure that capacitor bank designs are protectable is to assure that a knowledgeable protection engineer reviews the specifications before they go out for bid and is a member of the bid evaluation team.

7. Conclusion

This paper investigates the impacts of arc furnace and SVC switching operations at Roanoke substation on the neutral voltage unbalance (59N) protection function of a 2\textsuperscript{nd} harmonic capacitor filter bank. The upgrade of the 2\textsuperscript{nd} harmonic capacitor filter bank from externally fused to fuseless has created start-up issues and false alarm of 59N element. The capacitor manufacturer recommendations for neutral over-voltage pickup setting were too small/sensitive for this system with high harmonic/inter-harmonic presence from arc furnace and SVC switching operations. The false alarm events were investigated based on harmonic and inter-harmonic content in the measured voltages. 59N measures the difference between system zero-sequence voltage (V0), and ungrounded-wye neutral voltage (Vn). Significant amounts of harmonics and inter-harmonics were observed in both V0 and Vn during operation of AF and SVC. Moreover, it was found that inter-harmonics amplitudes (during AF on) in V0 are 2 to 3 times higher than that of Vn. With help of a system simulation, a qualitative analysis was carried out. The simulation showed that if the 2\textsuperscript{nd} harmonic capacitor bank is inherently unbalanced the impact of inter-harmonics may be sufficient to cause false alarms.

Several recommends are presented based on this investigation. After applying unbalance compensation K-factors, the operating quantity (Vop) was negligible for normal system operation. However, during the switching of the AF with the SVC on, the transient operating quantity may rise to generate a false alarm. One possible solution is to calculate unbalance compensation K-factors considering a worst case scenario (during arc furnace and SVC switching). However, this may desensitize the 59N element. Another solution is to increase the pickup and delay to avoid false alarms, again sensitivity would be compromised. Other more expensive solutions explored included increasing capacitor unit size (KVAR and Voltage), and applying current differential protection (60) at split-wye or H-configuration, based on the assumption that the impact of inter-harmonics on current differential would be less. However, these options were not applied or studied due to financial and schedule limitations. Finally, based on this experience, it is suggested that the system owner should involve their P&C team for any changes in the system such as changing from externally fused to fuseless capacitors, at the planning, specification and bid review stages.
8. References