APPLICATION OF RECLOSING SCHEMES IN THE PRESENCE OF CAPACITOR BANK RINGDOWN

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INTRODUCTION

Installation of shunt capacitor banks on transmission lines for local voltage support raises concerns about performance capabilities of existing line breakers. Questions on reclosing philosophies are also raised in cases where a capacitor bank with trapped charge is attached to the line being closed. The traditional approach has been either to trip capacitor banks for line faults before reclosing or to provide fast discharge of capacitor banks through three-phase voltage transformers (VTs). If the disconnected system is ungrounded or partially grounded (via a single-phase VT) following the opening of line breakers, the capacitor may not have a path for discharge and may cause problems if breakers are reclosed.

If three-phase or single-phase voltage transformers (VTs) or some other means of faster bleed down are available in the disconnected part of the system, reclosing can be done faster. How quickly the reclosing can be done is difficult to determine, since bleed down via VTs occurs as a nonlinear "ring down."

The Electromagnetic Transients Program (EMTP) was used to study the discharge phenomenon of capacitor banks in an ungrounded system. In this particular system, all loads are supplied via delta-connected distribution transformers. Single-phase VTs are connected to phase A.

The impetus behind this study was the installation of two 7.2-MVAR capacitor banks at a switching station on a three-terminal 69-kV line for voltage profile support. Another requirement was to have the capacitor banks on line during automatic reclosing for the 69-kV three-terminal line faults. The main objective in performing this simulation was to address concerns about the time taken for capacitor banks on the line to discharge after deenergization. Auto-reclosing time delay could be decided upon only after this discharge time was determined. In addition, there were concerns whether the Transient Recovery Voltage (TRV) ratings of the 1940s vintage circuit breakers were being exceeded.

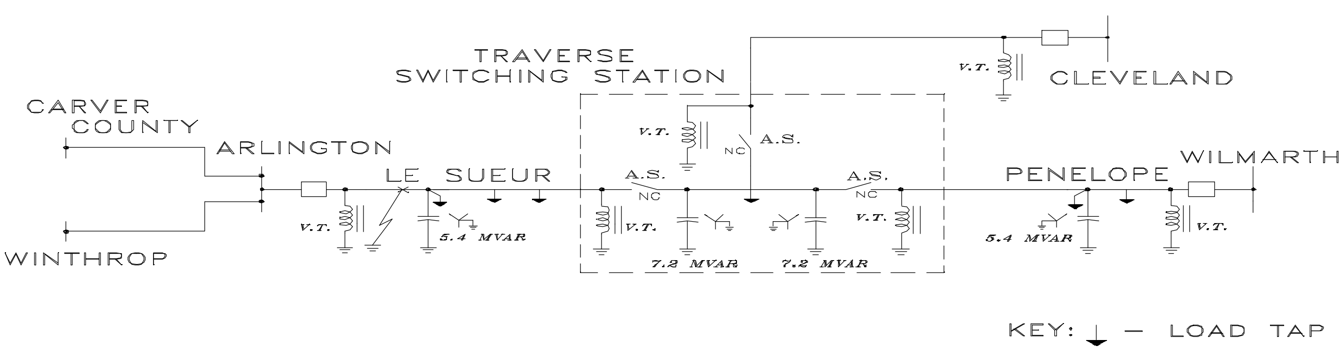


Figure 1. The Traverse Case Study

Table 1. Reclosing scheme

TRIP	OPERATION
1	• Reclose all circuit breakers after 5 seconds
2	• All MODs open after 7 seconds of dead voltage • Reclose all circuit breakers 15 seconds after the first reclose attempt • MODs close a few seconds after the line section potential is restored
3	• Lock out
Note: All reclosers require synch. check: ≥ 75% voltage, ≥3 seconds, ±30° window.	

SYSTEM STUDY

The study area includes a three-terminal 69-kV line. The Traverse Switching Station (Figure 1) is the three-terminal node. If there is a fault on the line, all three circuit breakers will be tripped. Table 1 shows the present practices followed for tripping and restoration. All reclosing occurs three seconds after being enabled, providing synch check conditions are met. The reclosing and the Automatic Sectionalizing (AS) schemes are coordinated to isolate the faulted line section should the first reclose attempt fail. Reclosing after the second trip, should the fault persist, is delayed long enough to allow motor operated switches (MODs) of the AS scheme to open. With the line sections now disconnected from each other at Traverse, a second reclose is attempted after a 15 second time delay. If the fault has still not cleared, the circuit breaker associated with the faulted line section is tripped and locked out. The other two line sections remain energized. The corresponding line MODs at Traverse will reclose after a suitable delay, if the voltages are normal and in synchronism. The MOD of the faulted line section will remain open and a system tie is restored between the two unfaulted line sections.

System loads in this area are tapped at the lines via delta-connected transformers. Therefore, when the circuit breakers are opened to deenergize the faulted line, these delta-connected transformers cannot provide a zero sequence discharge path for trapped charges in the capacitor banks. The synch-check VTs, installed only on phase A, do provide a high-impedance discharge path to ground via their magnetizing inductances. The delta-connected windings of the distribution transformer provide positive and negative sequence discharge paths.

Since EMTP modeling techniques have advanced greatly in recent years, it was decided to investigate these possible problems by performing a detailed time-domain simulation. Existing reclosing time delays had to be

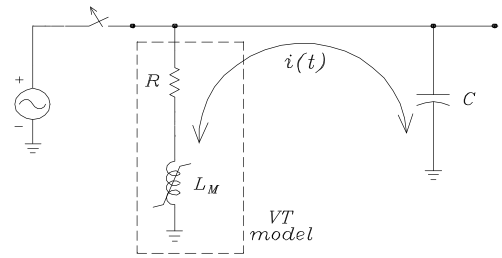


Figure 2. Capacitor discharging through VT

retained for operational advantages, and simulation results would indicate whether existing circuit breakers were adequate and whether additional means of discharging the capacitor banks would be needed.

EXPECTED BEHAVIORS

The system to be modeled is relatively complex, and the behaviors of the complete three-phase circuit are difficult to visualize. Single-phase illustrative examples are presented to help conceptualize the basic behavior. Nonlinear ring down of a de-energized capacitor through a VT is considered, followed by an explanation of TRV.

Capacitor Bleed down

When a line with a connected capacitor bank is deenergized normally or due to the presence of a fault, it is isolated and becomes a floating system. This is because of the lack of a solid ground connection. The only ground connection is provided by the single phase voltage

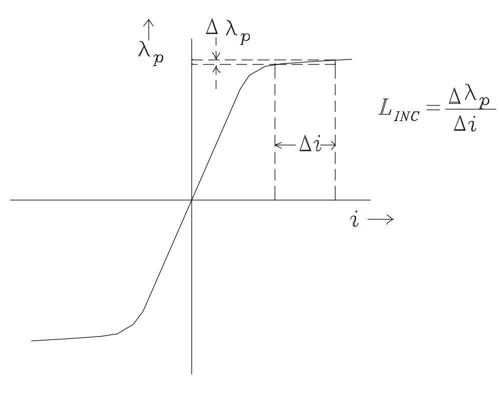


Figure 3. Typical l-I curve for a magnetic core

transformers. Consequently the trapped charge on the capacitor bank bleeds down through the VT's. This discharge occurs not only on the phase that the VT is connected to but also on the other two phases. The discharge transient on the adjacent phases can be attributed to the coupling that exists between the phases and the coupling through delta-connected windings of tapped transformers on the line. Figure 2 shows a simplified per-phase case of a 69-kV capacitor bank discharging through a VT. The discharge path is an RLC circuit, resulting in a damped LC "ringdown". For this VT, R= 3.25 kΩ and the flux linked vs. current (λ-i) characteristic of L_M is given in Figure 3. Due to the nonlinear inductance, ringdown may be nonsinusoidal and its frequency may be hard to predict. Conceptually, the frequency may be approximated as

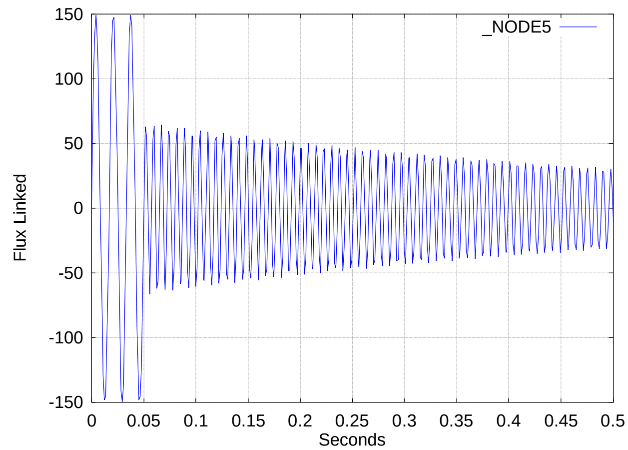
$$f \cong \frac{1}{2\pi\sqrt{L_{sat}C}} \tag{1}$$

where L_{sat} is the effective inductance of the saturable magnetic core of the VT. This effective inductance L_{sat} is actually the value of the incremental inductance L_{INC} at the peak value of flux linked λ_p. According to Lenz's Law, the voltage drop across L_M is defined as the time derivative of λ. If a sinusoidal approximation is applied, the peak voltage e_p across L_M is related to λ_p by

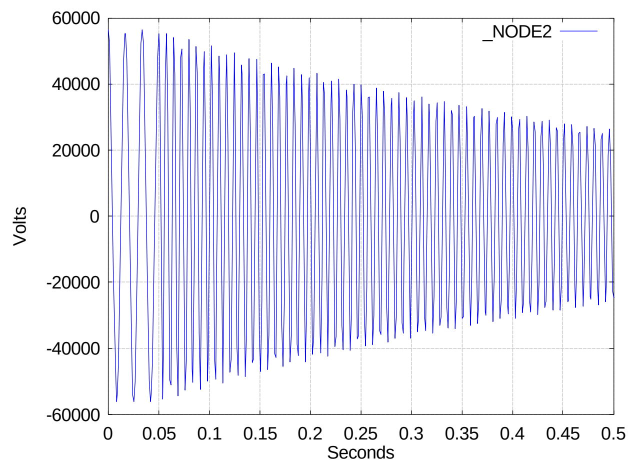
$$e_p = 2\pi f \lambda_p \tag{2}$$

Two cases are presented here to illustrate the possible ringdown transients. In each case, the circuit breaker opens at 50 ms when the capacitor bank voltage is at its peak. In the first (Figure 4), C=30pF (0.05 KVAR). Voltage ringdown is a decaying sinusoid of 140 Hz. Flux linked drops from its 60-Hz level of 150 Wb-turns to only 60 Wb-turns which is in the linear range of L_M (see Figure 3). In the second case (Figure 5), C=1μF (1.8 MVAR). The voltage rings down quickly and nonsinusoidally. Ringdown frequency is less than 60 Hz and decreases markedly with time. Flux linked jumps from its 60-Hz level of 150 Wb-turns to over 600 Wb-turns, which is far into saturation. Excursions this far into saturation are accompanied by very large current surges, providing faster rate of decay.

Since VTs are designed to operate below the knee of the λ-i curve for steady state 60 Hz, it can be said that a ringdown of f > 60 Hz will not cause VT saturation and will be a slowly decaying sinusoid. A ringdown of f < 60 Hz will be nonsinusoidal, will decay more quickly, and will drive the VT into saturation. According to Eqn. 1 it can be shown that the C required for 60 Hz ringdown of this VT is approximately 0.15nF (0.3 KVAR). A larger capacitor bank would ringdown nonsinusoidally, while a smaller one will ringdown sinusoidally.



(a)



(b)

Figure 4. (a)Flux linked in the VT, (b) Voltage across VT during ringdown with capacitance C=30pF.

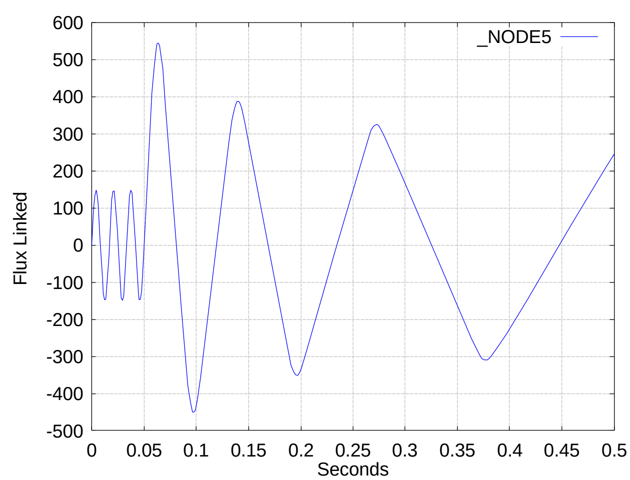


Figure 5. (a) Flux linked in the VT, C=1μF.

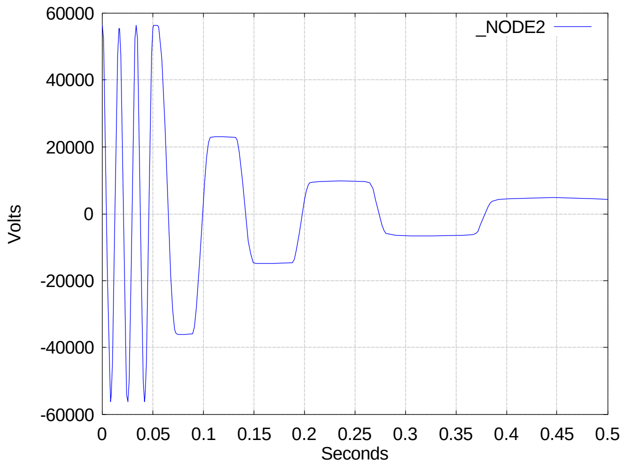


Figure 5. (b) Voltage across VT during ringdown, C=1mF.

Transient Recovery Voltage (TRV)

This is the transient voltage that appears across the poles of a circuit breaker when it interrupts a circuit. Figure 6 shows a conceptual network to explain the phenomenon of TRV across a circuit breaker (4). The inductor and capacitor represent the source impedance and the bushing/stray capacitance of the circuit breaker. The expression for the TRV is given by the following differential equation:

$$\frac{d^2V_c}{dt^2} + \frac{V_c}{LC} = \frac{V_m}{LC}\cos(w\,t) \qquad (3)$$

Solving the above differential equation for the voltage across the capacitor V_c gives:

$$V_c = V_m\left(\cos w\,t - \cos w_0 t\right) \qquad (4)$$

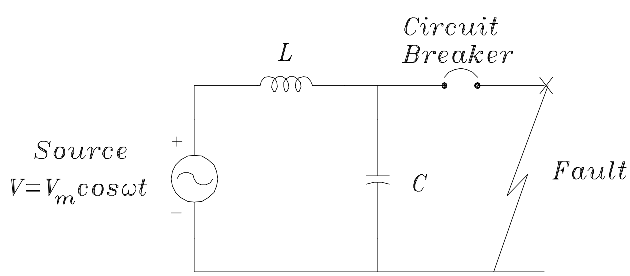


Figure 6. Circuit to explain Transient Recovery Voltage

where, $w_0 = \dfrac{1}{\sqrt{LC}}$.

Since C is very small, w_0 is usually very large. The above expression shows how the voltage across the circuit breaker can at instants be up to twice the rated voltage. This was one of the concerns that was addressed in this study.

DEVELOPMENT OF TRANSIENT MODEL

In order to investigate the system behavior under transient conditions, the Electromagnetic Transient Program (EMTP) was used. EMTP provides the user with the ability to model the power system in the time domain, taking into account nonlinear and frequency dependent behaviors of various components.

Nonlinear Component Modeling

Eqn. 1 represents the expression for evaluating the inductance using a piecewise linear representation of the λ-i curve shown in Fig. 3. Both pseudo-nonlinear and true nonlinear representations are possible (1).

For a nonlinear inductor, the value of L_M is updated at each time step from the piecewise linear curve. As shown in Figure 2, VTs are modeled using a series connection of resistor R and nonlinear inductor L_M to represent the saturable magnetic iron core. The parameters for a VT may vary quite a lot depending on the manufacturer. Table 2 shows a range of parameters for three 50-kV, 50 Hz VTs as taken from a well-documented case (3).

Features of the Model

The model aims at simulating the system shown in Figure 1. Two transmission lines to the Arlington station

Table 2. Linear parameters to model VT's

	R_P	X_P	X_T	N_P:N_T	B_{MAX}
VT#1	3250Ω	2500Ω	0.01Ω	20000:23	1.05T
VT#2	3218Ω	3094Ω	0.01Ω	36320:42	0.77T
VT#3	7588Ω	4833Ω	0.01Ω	25000:29	0.833T

are simulated using distributed parameter models evaluated at 60 Hz. The line section between the Arlington and Penelope stations was modeled using eight pi sections, with delta-connected transformers connected to the nodes between each section. This was done so that the 45-MVA load at 0.9 pf could be distributed over the entire section. The loads on the secondary of each transformer were modeled as series-connected lumped resistors and inductors. The bounds of the system model was set at the stations at Carver Co., Wilmarth, and Winthrop. The external systems connected to these buses were modeled as lumped Thevenin equivalent source and impedance. The Thevenin impedance was modeled as a three-phase coupled R-L network.

The 14.4-MVAR capacitor banks at Traverse and the 5.4-MVAR capacitor banks at Le Sueur and at Penelope were modeled as lumped capacitors with lumped series resistors. These resistors act as damping resistors. EMTP is prone to numerical oscillations due to the method of numerical integration employed. These effects are best mitigated by connecting time-step-dependent damping resistors in series with capacitors or parallel with inductors (1).

RESULTS

Simulations were conducted to observe the transients mentioned in the previous section. Various cases were studied to observe the worst possible transients. The cases discussed here include a) Restrike at the Arlington circuit breaker for a single phase fault on each of the three phases, b) Restrike at the Arlington breaker after a three phase fault close to the breaker, c) Deenergization of line for unfaulted condition by opening the Arlington breaker, d) Deenergization of line for an unfaulted condition by opening the Wilmarth breaker.

Transient Recovery Voltage Transient

The transient voltage across the capacitor was examined for a single phase to ground fault on each of the three phases. The circuit breaker was rated for voltages up to 2.0 p.u. or 112.7-kV peak. Figures 7, 8, 9, and 10 show the TRV across the breaker for a single phase fault on A, B, C phases with restrike and for a three phase fault with restrike on all three phases. The restrike was simulated at the peak voltage of the faulted phase for the single phase fault and at the peak voltage in all three phases for a

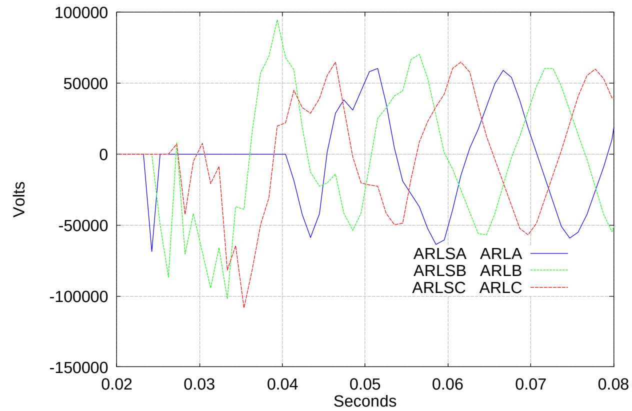


Figure 7. TRV across the Arlington breaker for a single phase fault on Phase A

three phase fault. The peak TRV observed was 104.3 kV, 108.1 kV and 99.2 kV for the single line fault on A, B, & C phases respectively. For a three phase fault the peak TRV was seen to be 115.3 kV. All simulated TRV levels were within breaker limits.

Capacitor Bleed-down Transient

Figs. 11 and 12 show the discharge oscillation for the Traverse capacitor bank after deenergizing the line at the Arlington and Wilmarth ends respectively. The capacitor banks were discharged completely in 0.3 sec, with discharge to half voltage occurring in 10 ms. The time taken for the discharge was seen to be sufficiently small so as to allow the normal 5-second auto-reclosing time interval on this line after a fault. Figs. 10 & 11 also clearly show the frequency variation in the discharge due to the saturable magnetic core of the voltage transformer.

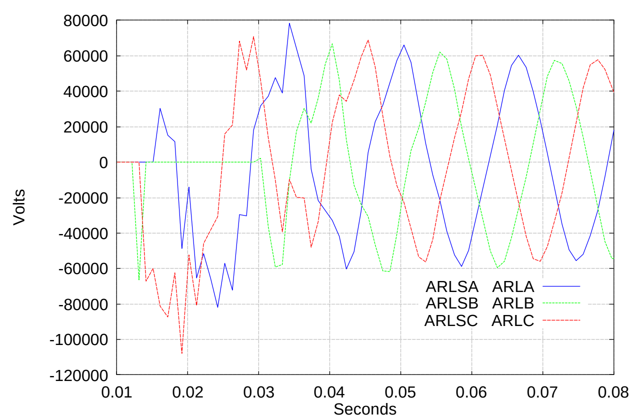


Figure 8. TRV across Arlington breaker for a single phase fault on Phase B.

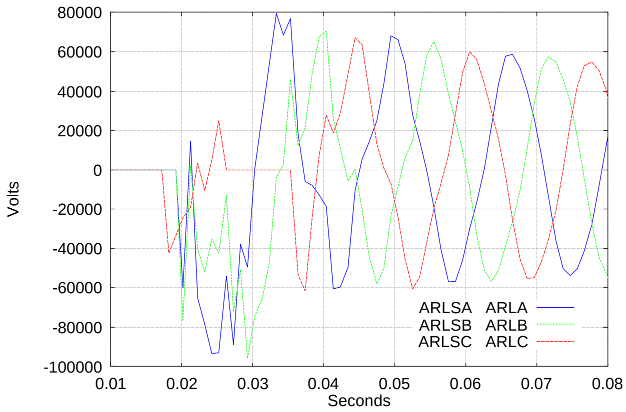


Figure 9. TRV across Arlington breaker for a single phase fault on Phase C.

This figure also illustrates that the trapped charge in all three phases of the capacitor is discharged although the voltage transformer is connected to only one of the phases.

CONCLUSIONS

Transients in power systems have the ability to damage power equipment and reduce power reliability. EMTP modeling ensures that system transients can be predicted so that designs and materials may be modified accordingly. Simulations showed that circuit breakers were within their TRV limits and that no additional measures to speed up capacitor bank discharge had to be implemented. However, care should be taken to ensure that the voltage transformer should be able to withstand the temperature rise due to the discharge of the energy of the capacitor bank into it. This was not taken into account in the study.

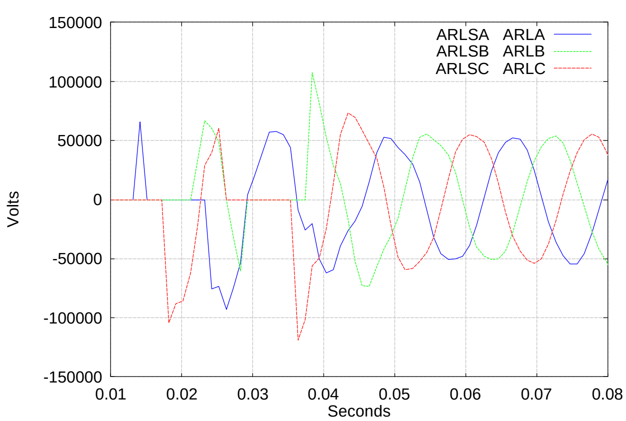


Figure 10. TRV across the Arlington breaker for a three phase fault.

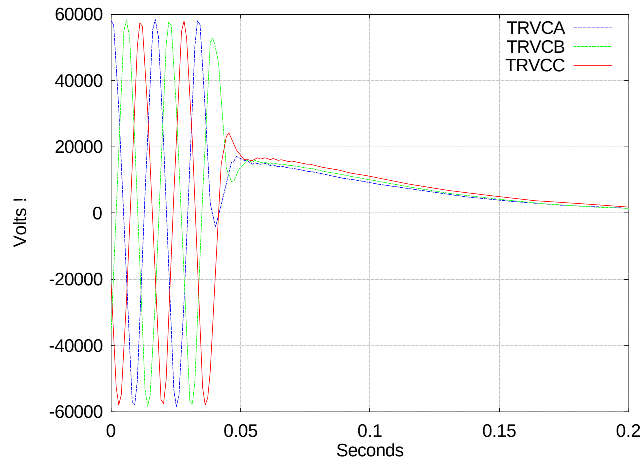


Figure 11. Discharge oscillation in capacitor bank at Traverse with the line deenergized at Arlington.

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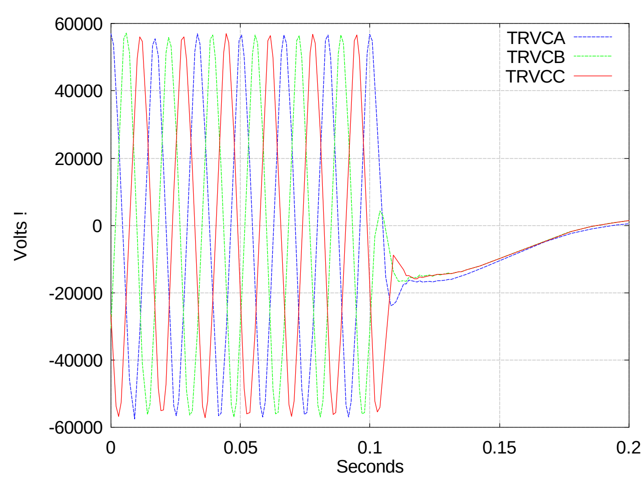

Figure 12. Discharge oscillation in capacitor bank at Traverse with the line deenergized at Wilmarth.