SIMULATING FERRORESONANCE IN A SERIES COMPENSATED DISTRIBUTION NETWORK

Owen C. Parks
Student Member, IEEE
Clemson University
Clemson, SC

Adly A. Girgis, Ph.D., P.E.
Fellow, IEEE
Clemson University
Clemson, SC

Marion E. Frick, P.E.
SCE&G
Columbia, SC

Abstract: Electromagnetic transient simulation programs are commonly used in power quality studies of power system networks. This paper describes the analysis of a distribution network that has experienced catastrophic events of a ferroresonant nature. Following a brief overview of ferroresonance, an emphasis is placed on duplicating field measurements in the PSCAD/EMTDC environment. A discussion of possible mitigation routines and their simulated results ensues.

Keywords: Electromagnetic Transient Analysis, Ferroresonance, Power Quality.

I. Overview of Ferroresonance

Many detailed mathematical models of the ferroresonant condition are documented in the literature [1,2,3,4,5]. For the purposes of this paper, however, it is suitable to simply remain cognoscente of some key principles.

The term ferroresonance generally refers to a condition where power system voltages resonate at the natural frequency of certain excited components within that system. These components most commonly include a nonlinear ironclad inductance, typical of transformer windings. For resonance to occur, a capacitance must also be involved. Common sources include capacitor banks used for series feeder compensation, voltage regulation, or power factor correction. Additionally, a transmission line's capacitance may be a key circuit element during a ferroresonant event [1].

A transformer inductance and system capacitance may sometimes be placed together in a series configuration. In some cases this placement is intentional, such as with series feeder compensation. Other times, the series connection is a temporary configuration caused by switching or protection operations. Resonance occurs when components in the series circuit reach critical values. System voltages may far surpass rated values, leading to equipment damage or failure. In some cases, even protection equipment such as lightning arresters will sustain damage due to repeated operation [1].

Studies have shown that certain power system configurations will increase a network's susceptibility to ferroresonance. Protection and switching equipment that operates on a single-phase basis may leave sections of a network open circuited, effectively creating a series LC circuit that is excited by the remaining phase(s) (Figure 1). Equipment grounding may also be of concern. For example, ungrounded wye-connected transformers may excite open circuited phases whereas grounded wye-connected transformers disallow it [2].

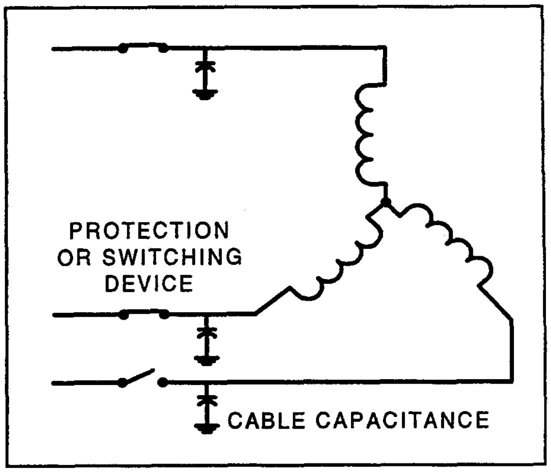

Figure 1. – Three phase wye-connected transformer winding with open circuited phase. Series LC excitation occurs with open transformer phase and cable capacitance.

Transformer loading conditions also have an effect on ferroresonance susceptibility. If a transformer is loaded at or near its' rated value, the load has a damping effect on transients [3]. Conversely, lightly loaded transformers possess fewer damping qualities, and are regarded as one of the main contributing factors to ferroresonant events [2].

There are many possible ferroresonance mitigation techniques that may be employed. Possible solutions include limiting cable lengths between switching equipment and transformers, favoring three-phase over single-phase switching, installing dummy load banks on lightly loaded transformers, temporarily grounding ungrounded transformers, and employing custom switching sequences [2]. Although each of these methods may be advantageous in some areas, they may be impractical in others. Mitigation of ferroresonance in power systems is therefore more effectively addressed on an individual case study basis.

II. Case Study Network

The network shown in figure 2 is a simplified version of a distribution system currently in use. This system feeds several clustered loads in a remote location. These loads are

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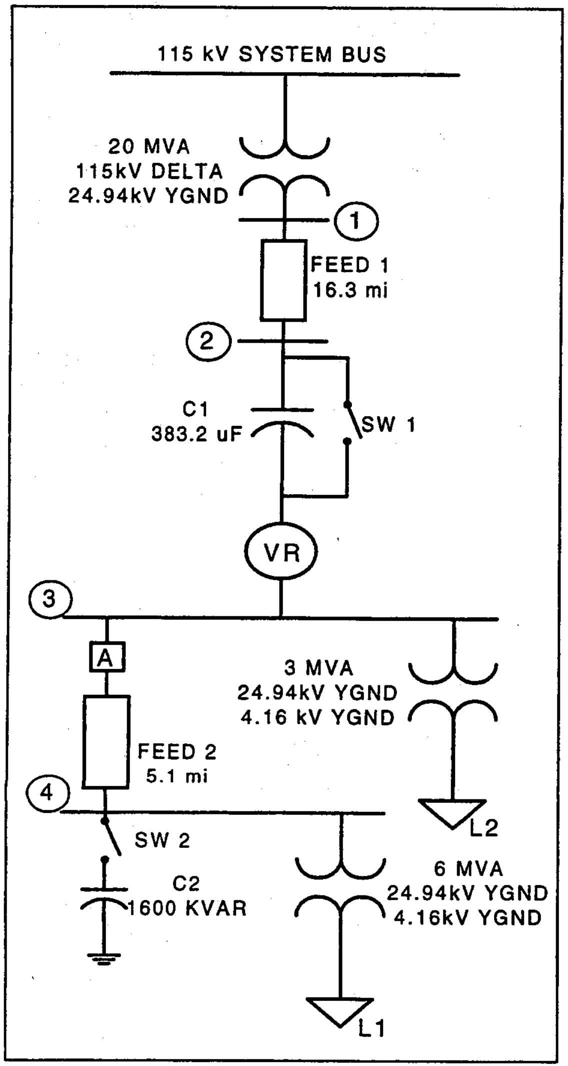

Figure 2. – One-line diagram of distribution network. Field and simulation data taken at breaker 'A'.

used on a highly seasonal basis, and consequently subject the transformers to light loading for prolonged periods of time during the off-seasons. A series capacitor bank is inserted at the end of the primary feeder, 'FEED 1', to reduce the line voltage drop. Additionally, three single-phase voltage regulating transformers are inserted at the end of the primary feeder, boosting voltages at bus 3 to acceptable levels.

Bus 3 feeds two separate branches. The first branch passes through breaker 'A' and is transmitted over a distance of 5.1 miles to bus 4. Attached to bus 4 is a bank of shunt capacitors and a three-phase transformer with maximum load rating of 6MVA. The second branch feeds L2 through a three-phase transformer with a maximum rating of 3MVA.

It should be noted that the system in figure 2 is a simplified version of its' counterpart in the field. The actual network contains monitoring and protection equipment, which for analysis have been omitted. Furthermore, the 6MVA transformer at bus 4 is a simplified model of three single-phase transformers. These simplifications were maintained throughout the study.

During a fault related switching event, the system experienced overvoltages that led to lightning arrester failures and customer equipment damage. Breaker 'A' recorded voltages and currents during these events. The waveforms indicated the occurrence of both single line to ground and grounded three phase faults. The breaker opened and reclosed normally. In the time during and after these events, voltages at bus 3 rose above their nominal values and appeared to be of a ferroresonant nature. The severity of these overvoltages was greatest during operations involving the three phase fault. Figure 3 shows the actual three phase fault related waveforms recorded at breaker 'A'.

IV. Modeling the network in PSCAD/EMTDC

The PSCAD software environment is a graphical interface that allows the user to enter network information and operate the EMTDC simulation engine. For the most part, the need for text programming is eliminated. PSCAD contains multiple libraries of equipment models from which the user may construct their network. If a user desires a custom or advanced model, they are free to generate their own code. The simulations discussed in this study used only the models available in PSCAD, yet required a fair amount of planning to make the transition to the software environment an effective one.

In several cases, parameters in PSCAD models were left at their default values. This practice allows the user to concentrate on values that are suspected to have the most significance in the system. As a result, the complexity of the network model is kept under control because the user limits the number of variables that are considered noteworthy. This in turn makes fine-tuning of critical parameters more manageable.

A. *Transmission Line Models*

The PSCAD software allows the user to generate line model files that correspond to lines in the network. Users work within these files to specify the parameters of the transmission lines. Line files may specify ground return models, geometric cable configuration, conductor sag between towers, and sequence impedance values (non-frequency dependent option). For this case study, a simple linear conductor geometry with two ground return lines was chosen as the model.

B. *Transformer Models:*

Both single and three phase transformer models are permitted in PSCAD. For three-phase transformers,

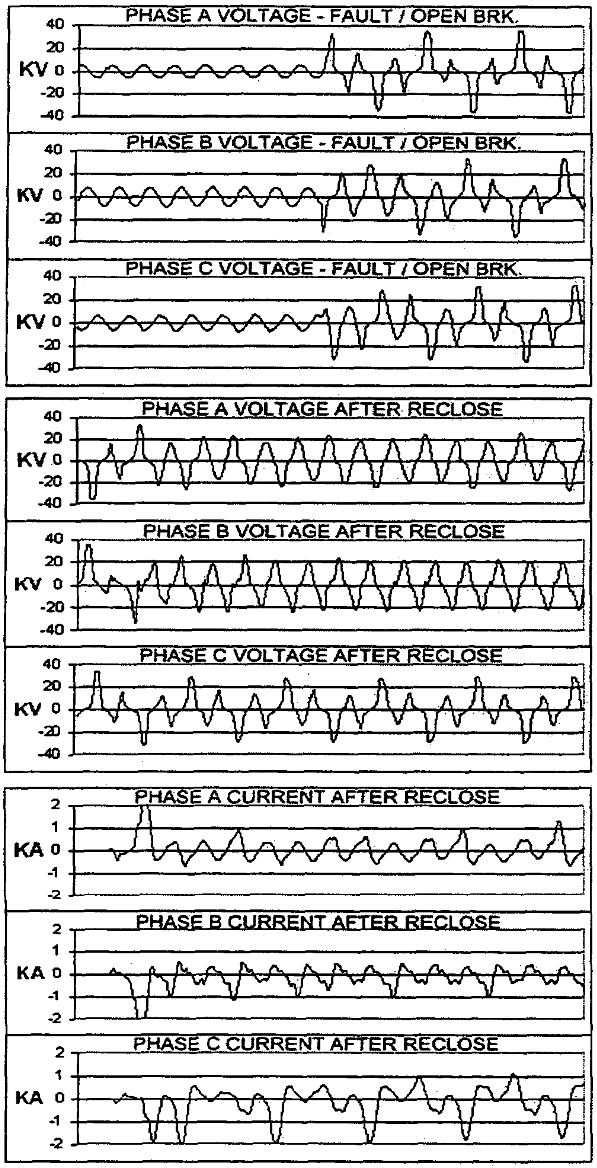

Figure. 3 – Field measurements taken at breaker 'A' during grounded three phase fault.

connection schemes may either be delta or wye. Single phase transformers may be connected in any desired fashion. This freedom allows the user to model specialized devices such as autotransformers and voltage regulating transformers. Saturation modeling may be enabled or disabled. The saturation curve model only requires a knee voltage. This is noticeably different from other electromagnetic transient simulation packages that allow saturation curves to be defined by multiple points along a curve.

In addition to saturation modeling, PSCAD allows the user to simulate tap changers, and account for parameters such as no load losses and air core reactance. Once again, the case study models aimed at keeping things simple. For the three phase transformer models, saturation was enabled with a knee voltage of 1.25pu. No load losses and air core reactances were left at their default values of 0.1pu, and 0.2pu respectively. Connection schemes and voltages matched network values. In the cases of the single-phase voltage regulators, connections used a shunt primary rating of 22.4kV and a series secondary rating of 0.2kV.

C. *Load Modeling*

Load models may vary depending on the amount of information available. For example, if a load is known to be mainly induction machines, then it is appropriate to enter a corresponding induction machine model into the network. In cases where little information exists, the user may either enter resistor, inductor, or capacitor values at the load, or use a single phase load model which specifies MW and MVAR at the load, given a rated load voltage. Our case study makes use of the latter, and keeps the load banks L1 and L2 at 10 percent of their rated value, with a power factor of 0.8 lagging.

D. *Faults, Breakers, and Switches*

Faults in PSCAD are inserted as other normal circuit components. Faults are described by whether or not a certain phase is included in a fault, and if the fault is to ground. A fault impedance may also be specified. Fault timing requires a signal variable to determine the onset and extinction of a fault. This scheme does not permit a breaker opening to cause the extinction of a fault. For faults that occur along transmission lines, a special technique is employed. The transmission line is broken into two separate lines with lengths corresponding to those on either side of the fault. At the junction of the two transmission lines, the fault component is inserted. This scheme was used with the case study, with a three-phase fault applied in the middle of 'FEED 2'.

Breakers and switches, like faults, may be either single or multi-phase. They are also controlled with signal variables that define their initial state and operation times. Users may restrict breaker operations to only zero-current situations.

E. *Data Acquisition*

Data acquisition in PSCAD uses signal variables similar to those used for faults and switches. Signals are output to user defined plots that appear directly in the PSCAD workspace. Users may define signals for voltages, currents, and additional parameters for in depth monitoring of machinery and other equipment. Since the simulations in this study focused on duplicating the data recorded in the field, only voltages and currents at the breaker were logged.

V. Duplicating the field data

The simulation schedule (table 1) contains operations that are necessary for a realistic reproduction of actual recorded events. In the initial simulations, the switch SW1 is left open, and switch SW2 is left closed. Prefault conditions exist up to t=0.6s, at which point a three phase grounded fault in the middle of 'FEED 2' is initiated. The fault lasts until t=0.7s, when the breaker is opened. The breaker is left open until a reclose event at t=0.8s. Following the reclose, voltages and currents are examined until t=1.3s, in an effort to examine any damping that may occur after the reclose. Figure 4 shows the PSCAD output waveforms resulting from this schedule.

EVENT SCHEDULE	
t=0.00s	SIMULATION START
t=0.60s	FAULT INCEPTION
t=0.70s	BREAKER OPENS
t=0.70s	FAULT EXTINCTION
t=0.80s	BREAKER RECLOSE
t=1.30s	SIMULATION END

Table 1. – Simulation schedule used to recreate field data.

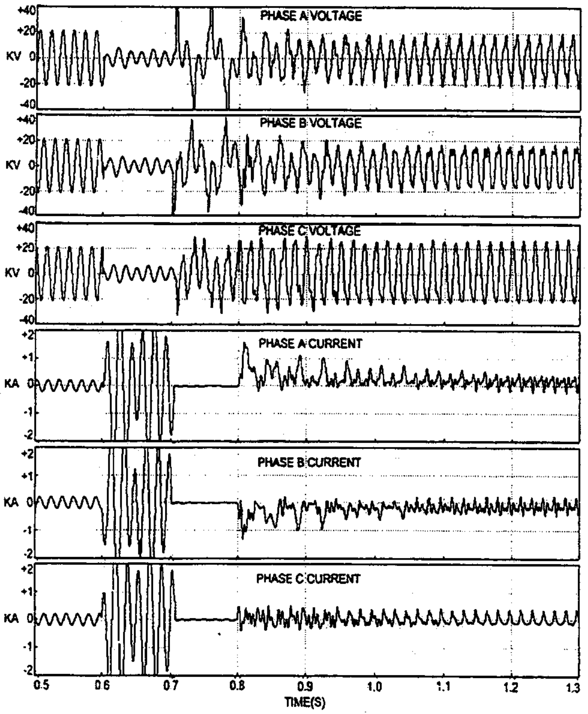

Figure 4. – Initial output. Goal was to recreate events recorded in the field. Event schedule is defined in table 1.

The waveforms in figures 3 and 4 are quite similar. In both figures, the voltages during the fault are significantly lower. When the breaker is opened, ferroresonant voltages far exceeding the nominal values exist. After the breaker reclose, the voltages return to reasonable magnitudes. At this point the shape of the voltage waves are of particular interest. They are slightly distorted, and indicate a flow of nonsinusoidal current, which is confirmed by the current waveforms in both the field and simulated results. At the completion of the simulation, the waveforms maintain their irregularity, and show little signs of damping. Although the exact wave shapes are slightly different, the simulation is a sufficient duplication of field events, and may be used as a basis for exploring further scenarios in this system.

Further simulations focused on determining if the ferroresonant condition exists in this system for different fault types at the same location. A three phase ungrounded fault yielded similar results to that of the three phase grounded fault. A single line to ground fault, however, behaved differently. Ferroresonant voltages appeared on the unfaulted phases of the system during the fault. Following the breaker reclose, nonsinusoidal currents and ferroresonant overvoltages were present in all phases once again. These instances of ferroresonance, however, showed some signs of damping towards the completion of the simulation run at t=1.3s. Double line to ground fault simulations revealed a similar characteristic, with the unfaulted phase again showing signs of ferroresonance during the fault. Post reclose distortion, however, showed little sign of damping by the end of the simulation. An ungrounded line to line fault behaved much like its' grounded counterpart, with the exception of no observed ferroresonance in the unfaulted phase during the fault. It is important to remember that during each of these fault conditions, the fault type may vary, but the switching does not. The breaker always operates on a three phase basis, which will ultimately involve all phases regardless of their presence in a fault.

VI. Exploring mitigation options

Additional simulations were performed to identify key components in the case study network. These simulations were run with the series capacitance removed, the powerfactor capacitor bank removed, and both capacitors removed. The results indicate that not only the series capacitor is to blame for the ferroresonant condition. After the reclose event, the nonsinusoidal currents do not exist when both capacitors are removed, yet are present when the series capacitance is omitted. This suggests that at certain times the powerfactor correction capacitor bank is a contributing factor to the ferroresonant condition. Figure 5 shows the simulation results obtained when both capacitors are omitted from the circuit.

Attempts at mitigating the observed ferroresonance focused on the three phase grounded fault condition because of its' severity and effect on all phases of the system. The approach explored removing the system capacitors during periods of time that were likely to excite the system negatively. In effect, SW1 and SW2 were operated at varying times, which effectively removed and reinserted them from the circuit. This methodology was favored over tuning the circuit because of the wide range of possible fault locations, load

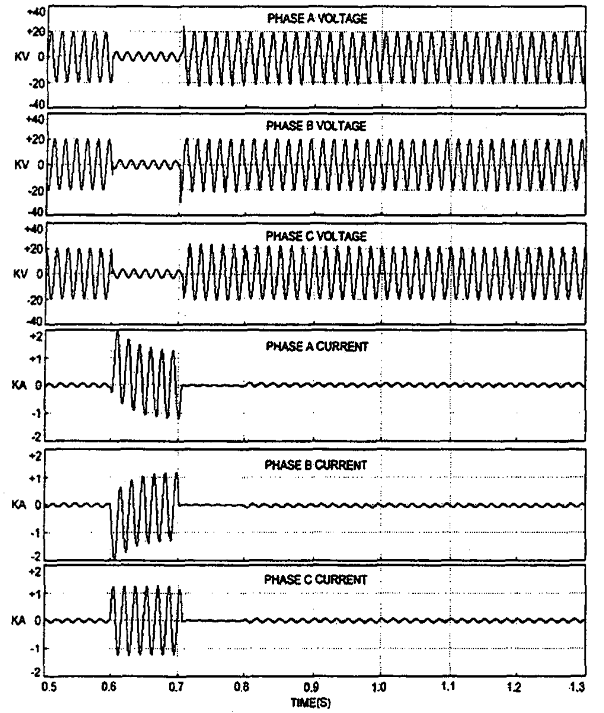

Figure 5. – Breaker readings with system capacitors removed.

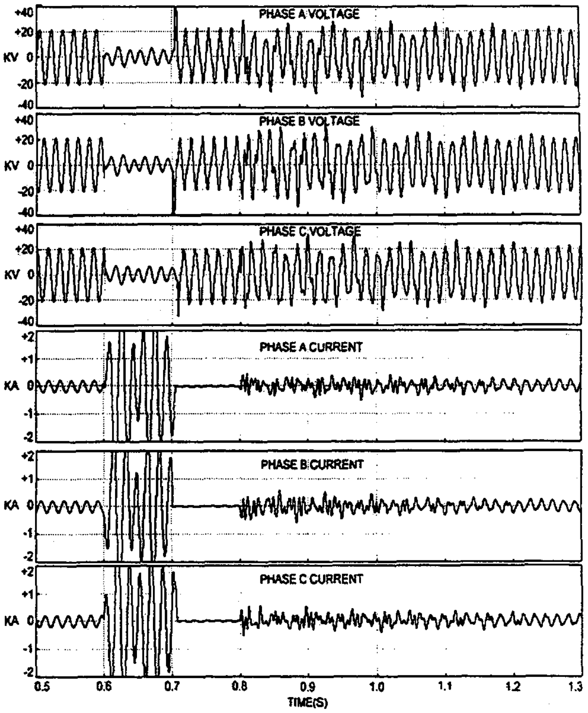

Figure 6. – Breaker readings with series compensating capacitor shorted during open breaker period.

levels, and accompanying mathematical solutions to each configuration. Capacitor switching is also an attractive solution because of the promising results yielded by component removal.

The series capacitor downstream of 'FEED 1' was the first target of the attempted mitigation solutions. The simulation schedule focused on timing the capacitor short appropriately with the breaker events. The first timing option simultaneously shorted the series capacitance and opened the breaker at t=0.7s, and later opened SW1 simultaneously with the reclose of the breaker at t=0.8s. The simultaneous operation did not show any significant mitigation of the ferroresonance. This is most likely because the capacitors are effectively in the circuit at the time that critical switching events occur. For this reason, slight delays between breaker and capacitor switching operations were introduced.

A delay of 10ms was introduced between breaker 'A' opening and SW1 closing. A 10ms delay was also used between the breaker 'A' reclose and SW1 opening. Adding these delays produced a promising result. The ferroresonant voltages present during the open breaker period disappeared. Additionally, the magnitude of breaker currents was drastically reduced after the reclose. Still present, however, were the nonsinusoidal currents after the reclose. These irregularities fade away towards the simulation end at t=1.3s. Also present in these results (figure 6) are transient overvoltages typical of capacitor switching, and slight distortion of waveforms during the open breaker period.

After exploring options with the series compensating capacitor, switching of the powerfactor correction capacitor was addressed. In the previous example, the powerfactor correction capacitor is left inserted in the circuit. After reclosing, nonsinusoidal currents flow through the breaker and eventually stabilize into respectable sinusoids. It is desirable, however, to minimize the duration of these distorted currents. Previous simulations indicated that outright removal of these capacitors reduces the distortion. Therefore, coordinated switching of the powerfactor correction capacitors with breaker operations was explored.

Simulations that involved switching SW2 operated the breaker and SW1 at times that previously produced positive results. The SW2 switching times were therefore the only remaining variables in the system. Closing SW1 and opening SW2 may occur simultaneously because in this case removal from the network is not as critical to operation as insertion. Initial trials reinserted the powerfactor correction capacitors simultaneously with both the breaker and series capacitor, which again proved to be ineffective. Insertion of the powerfactor correction capacitors (closing SW2) was then attempted with a delay of 20ms after the reclose. This delay was also ineffective, and the current waveform continued to show distortion. A much longer delay of 200ms was then used. This delay allowed the current to stabilize without the powerfactor correction capacitors included. After the delay, the capacitors were switched in, with only slight switching transients resulting (figure 7). Table 2 summarizes the switching events that were ultimately used.

EVENT SCHEDULE	
t=0.00s	SIMULATION START
t=0.60s	FAULT INCEPTION
t=0.70s	BREAKER OPENS
t=0.70s	FAULT EXTINCTION
t=0.71s	SW1 CLOSE
t=0.71s	SW2 OPEN
t=0.80s	BREAKER RECLOSE
t=0.81s	SW1 OPEN
t=1.00s	SW2 CLOSE
t=1.30s	SIMULATION END

Table 2. – Simulation schedule used to mitigate ferroresonance during all switching operations. Both the series compensating capacitor and powerfactor correction capacitor were temporarily removed from the network.

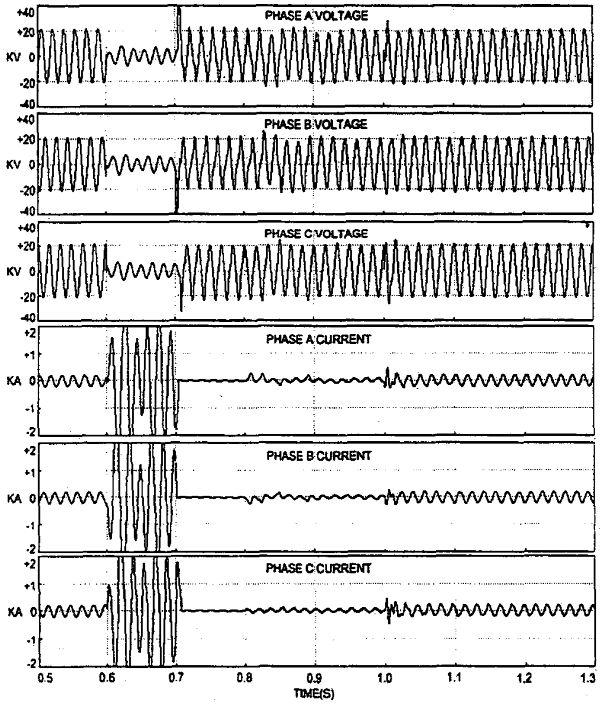

Figure 7. – Output of simulation in which both series compensating and powerfactor correction capacitors are temporarily removed. Table 2 defines the event schedule.

VII. Conclusions

In this case study, the PSCAD/EMTDC environment was used to reasonably duplicate events that resulted in utility and customer level equipment failures. Simulations suggest that mitigation of ferroresonance in series compensated feeders may be accomplished through carefully coordinated removal and insertion of the series compensation device during operations that could potentially excite a network. It was also determined that more than one system capacitance affected the smooth operation of the network during switching conditions. It is therefore worthwhile to examine the contribution of multiple components to a system's overall stability. With the proposed coordinated switching implemented, disastrous events lasting several seconds may be avoided in favor of transient switching events.

Actual implementation of such a solution would require tightly coordinated communications between the affected switching equipment. This may prove impractical for rural systems where devices must communicate over great distances. For clustered switching equipment, however, this option is viable.

VIII. References

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