DIRECTLY CONNECTED STATIC VAr COMPENSATION IN DISTRIBUTION SYSTEM APPLICATIONS

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***Abstract* – Many types of industrial loads on utility distribution systems adversely affect power quality on the distribution line. Large power supplies, motors, welders, and arc furnaces, for example, cause voltage flicker which is experienced not only by the offending industrial power user, but also by any other utility customers receiving power from the same distribution feeder. In addition, the typically poor displacement power factors of these loads result in higher fundamental line currents which must be supplied by the utility.**

One way to alleviate these problems is to provide static VAr (Volt-Amperes Reactive) compensation in shunt with the distribution line. This paper discusses the advantages of applying this compensation directly to the distribution line using high voltage semiconductors versus VAr compensation at industrial voltage levels (such as 480 volts) either via a dedicated step-down transformer or on the customer 480 V plant power. Power system analyses of loads with and without compensation are described and compared to demonstrate the effects of static VAr compensation on flicker, voltage support, power factor, and system harmonics.

Key Words- Static VAr compensation, flicker, power factor correction, harmonics.

I. INTRODUCTION

Electric utilities have always used reactive shunt compensation on ac transmission and distribution power systems. Fixed and switched capacitors and reactors can provide voltage support and increase the capability of the power system to supply real power to the end user.

Fixed reactive shunt compensation is not adequate for dynamically varying loads, while mechanically switched shunt compensation is effective for some dynamic loads. These mechanically switched devices, however, are typically limited to only a few operations a day because of physical stresses on the switches, and the transients that they introduce on the power system, particularly when switching capacitance. The mechanical switches cannot compensate for loads which affect the power system several times per second or more.

A. Solid-state Compensation

For many years, utilities have been using solid-state controllers and valves (solid-state switches) at the transmission level to compensate for loads which may vary as frequently as every few cycles. These static VAr compensator (SVC) systems operate through step-up transformers in order to accommodate the ratings of semiconductors used in the valves.

In recent years, utilities have been interested in applying SVC technology on distribution systems. Customer perceptions of power quality, and a desire to forestall substation and conductor upgrades, have driven the interest in SVCs at the distribution level. SVCs are able to compensate for most dynamic loads since typical response times are 1 to 2 cycles. In addition, they apply compensation in a transient-free manner. The vast majority of SVCs used on distribution systems traditionally have either been applied on the customer side of the transformer or through step-up transformers on the distribution primary. In both cases, the solid-state valves operate at industrial voltage, typically 480 volts ac.

On long, rural feeders, or on any “soft” distribution feeder, SVCs operating at the 480-volt ac level can be impractical. The maintenance and operating requirements for such equipment are prohibitive, particularly at remote installations. In addition, the physical size of a 480-volt SVC is sufficiently large that real estate is a significant factor when planning an installation.

B. Direct Compensation on Distribution Power Systems

Advances in power semiconductor technology have made higher voltage power electronics devices, such as diodes and thyristors, available at a lower cost. The most recent SVC units use these devices to apply the reactive shunt compensation directly at the distribution voltage level. The new technology has been successfully installed on distribution lines with nominal voltages as high as 13.2 kV.

II. ADVANTAGES OF COMPENSATION AT HIGHER VOLTAGE

The most obvious advantage of directly connected distribution voltage level SVCs is their small physical size compared to a lower voltage unit. Conductor sizes are reduced in inverse proportion to the operating voltage, fan cooling is replaced with oil-convection cooling, and size and weight of the capacitors are significantly smaller at the higher voltage. The directly connected SVCs can be mounted on successive utility poles or on a pole-mounted platform, while a 480-volt unit with the same kVAr rating might require its own building. The compact size of the directly connected units allows them to be moved to other locations within a utility's distribution system as required. Similarly, units which are owned by the end user can be relocated to other plant locations as desired.

Because there are no fans or any other moving parts on the directly connected SVC, the maintenance requirements for the unit are minimal. This is a major advantage for remotely located units on rural distribution feeders. On-site monitoring of the units is typically not required. Units are often equipped with remote communication packages to allow diagnostics and system adjustments to be made remotely.

In case of temporary power outages, a well-designed SVC should be self-starting upon application, or re-application, of power.

With a distribution voltage SVC, a step-up transformer is required in order to provide compensation downstream of the end user's service transformer, typically at 480 V. In some cases, this type of compensation may be desirable. The impedance of the service transformer could be high enough to affect the end user's processes even with a "stiff" primary voltage on the distribution system. Even with a step-up transformer, overall reliability, cost, and maintenance considerations for a distribution voltage SVC make it a viable alternative to a 480-volt SVC for this type of application.

III. Simulating And Sizing SVCs

In order to determine the appropriate rating for a proposed SVC installation, calculations are made based on the known load and power system parameters. It is always important to have source impedance or fault current information at the proposed SVC location. Measured load current can then be used to simulate the uncompensated condition of the line. The accuracy of the model can be verified by showing the simulated line voltage to be approximately equal to the measured line voltage. Measured voltage and current harmonic distortion can be helpful in determining if harmonic resonance between the source impedance and the applied capacitive reactance should be expected. Obviously, the SVC should be designed to avoid harmonic resonance problems.

The following four examples will be used to demonstrate SVC sizing and simulation techniques.

A. *Reactive Compensation Applied to Large Power Supply Load*

An SVC was proposed to mitigate a voltage flicker problem caused at the 12.47 kV distribution voltage level by a DC power supply. The front-end electronics for the supply are a 12-pulse type, which is fed from the utility through two parallel extended-delta to wye transformers.

The worst case flicker problem occurs when the DC supply output is cycling at a 1 Hz rate, from 0 to 3800 amps. The utility load under such a condition is highly reactive and varies between approximately 100 kVAr and 500 kVAr as shown in Fig. 1.

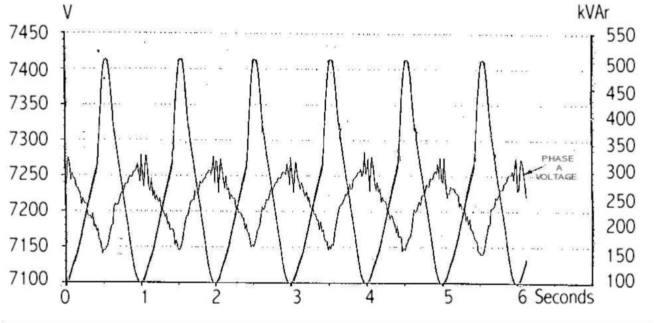

Fig. 1. Measured rms Voltage and Reactive Power

Fig. 2 shows system impedances as well as the proposed location of the SVC.

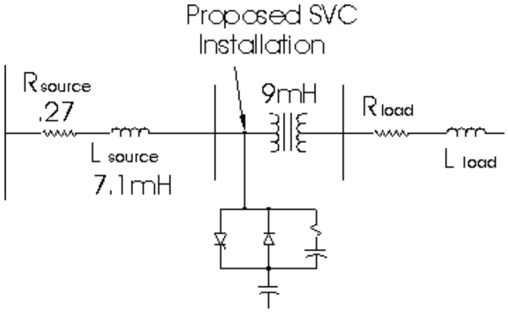

Fig. 2. System Impedance Diagram

In this example, impedances were derived from the following data, which was provided by the end user:

Customer Transformer:	2.8 MVA, 13.8 kV, 5% Z (Assume all reactance)
Short Circuit MVA:	21.7 MVA (single-phase)
X_{source}/R_{source}:	10

Three independently controlled single-phase SVCs were to be applied on the three-phase system. Therefore, all impedances were calculated on a single-phase basis using the following equations:

Customer Transformer:

$$I_{rated} = \frac{(MVA_{rated})10^6}{\sqrt{3}V_{line}} \quad \text{Amps} \qquad (1)$$

$$X_{xfmr} = \frac{V_{line}\left(\%Z/100\right)}{\sqrt{3}I_{rated}} \qquad \text{Ohms} \qquad (2)$$

$$L_{xfmr} = \frac{X_{xfmr}}{2 \times \pi \times 60} \qquad \text{Henrys} \qquad (3)$$

Source Impedance:

$$Z_{source} = \frac{\left(V_{line}/\sqrt{3}\right)^2}{\left(MVA_{sc}\right)10^6} \qquad \text{Ohms} \qquad (4)$$

$$R_{source} = \frac{Z_{source}}{1+\left(X_{source}/R_{source}\right)} \qquad \text{Ohms} \qquad (5)$$

$$X_{source} = \left(X_{source}/R_{source}\right)R_{source} \qquad \text{Ohms} \qquad (6)$$

$$L_{source} = \frac{X_{source}}{2\times\pi\times 60} \qquad \text{Henrys} \qquad (7)$$

Microsoft Excel was used for the simulations. The SVC control algorithm was inserted into the spreadsheet in order to simulate its operation on a cycle by cycle basis. The load was modeled as an inductive reactance in series with a resistance. The equivalent real and reactive load impedances were calculated from the given power factor, reactive power, and load impedance information using (8) through (10).

$$X_{parallel} = \frac{V_{SVC}^{\ 2}}{Q} \qquad \text{Ohms} \qquad (8)$$

$$P = \frac{Q(PF)}{\sin(\cos^{-1}(PF))} \qquad \text{Watts} \qquad (9)$$

where

Q reactive power in VArs;
PF power factor;
P =real power in watts.

Then, $R_{parallel} = \frac{V_{SVC}^{\ 2}}{P}$ (10)

The series equivalent real and reactive load impedances, which are shown in Fig. 2, are then calculated using (11) and (12).

$$R_{load} = \frac{R_{parallel}X^2_{parallel}}{R^2_{parallel} + X^2_{parallel}} - R_{xfmr} \qquad \text{Ohms} \qquad (11)$$

where $R_{xfmr}=0$

$$X_{load} = \frac{R^2_{parallel}X_{parallel}}{R^2_{parallel} + X^2_{parallel}} - X_{xfmr} \qquad \text{Ohms} \qquad (12)$$

After the complex load was modeled, the uncompensated voltage magnitude at the proposed SVC location was calculated using (13):

$$V_{SVC} = V_{source}\frac{\left|R_{load} + R_{xfmr} + j\left(X_{load} + X_{xfmr}\right)\right|}{\left|\left(R_{load} + R_{xfmr} + R_{source}\right) + j\left(X_{load} + X_{xfmr} + X_{source}\right)\right|} \qquad (13)$$

Fig. 3 shows the results of the simulation for Phase A. The analysis gives accurate results, as verified by comparing the results of Fig. 1 and Fig. 3.

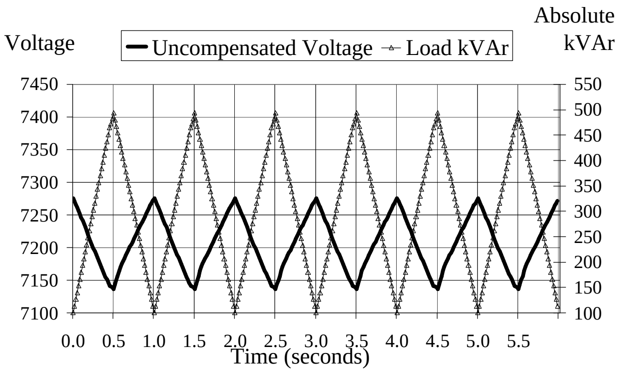

Figure 3. Simulated Voltage and Reactive Load

Next, the SVC was added to the analysis. SVCs compensate by adding capacitance or inductance in shunt with the load. The parallel reactive impedance was calculated with the SVC on line using (14).

$$X'_{parallel} = \frac{X_{parallel}X_{SVC}}{X_{parallel} + X_{SVC}} \qquad \text{Ohms} \qquad (14)$$

Then, by substitution of (14) for $X_{parallel}$ in (11) and (12), the compensated voltage at the SVC was calculated using (13).

Fig. 4 shows the compensated and uncompensated rms voltages for comparison purposes.

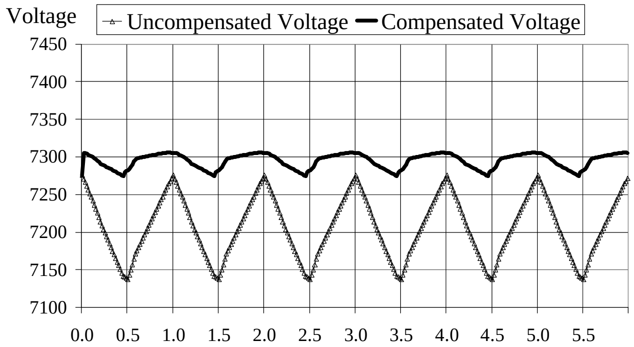

Figure 4. Uncompensated vs. Compensated Voltage

Notice that the magnitude of the voltage variation improves from approximately 1.9% to approximately 0.3% when compensated.

The SVC algorithm used in this example was designed to maintain unity power factor. The SVC is able to provide excellent voltage support and flicker reduction with this algorithm because of the high X/R ratio of the power system. The rating, in kVAr, for the SVC must be at least 500 kVAr per phase in order to compensate for the peak reactive load. (See Fig. 1.) Most of the voltage drop on a power system with a high X/R ratio is due to reactive current. The SVC eliminates the reactive component of current through the source impedance, and therefore significantly reduces fluctuations in the rms voltage. The power factor measured upstream of the SVC is also significantly improved, as shown in Fig. 5.

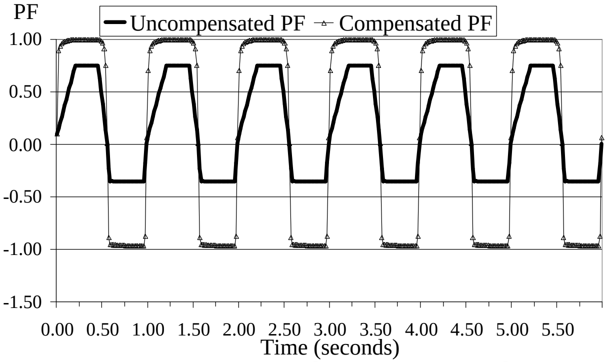

Figure 5. Uncompensated PF vs. Compensated PF

B. Reactive Compensation Applied to Motor Load

SVC sizing was required for a corn drier process which causes voltage flicker on a single-phase 4800-volt distribution feeder. The flicker affects other customers on the same and adjacent distribution circuits. The load consists of 6 induction motors, ranging from 5 to 10 HP, which are line started at various times throughout the process.

The system diagram and proposed SVC location are shown in Fig. 6.

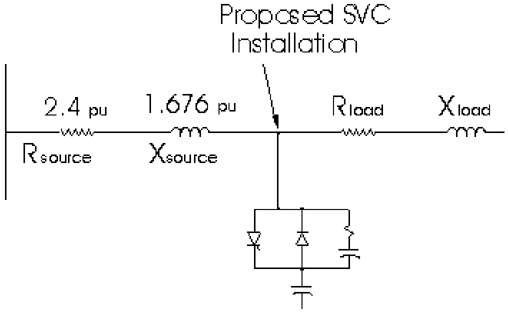

Fig.6 System Impedance Diagram – Motor Load

The utility provided the following per unit information on a 10 MVA basis:

R_{source}:	2.4 per unit
X_{source}:	1.676 per unit
S_{inrush}: VA during motor start (assumed for each motor):	0.02 per unit
PF_{inrush} :Power Factor during motor start (each motor):	0.10
S_{FL}: Full load VA (assumed for each motor):	0.04 per unit
PF_{FL}: Power Factor at full load (each motor):	0.40
$V_{SVC,INRUSH}$ during motor start:	0.94 per unit
$V_{SVC,FL}$ at full load:	≈1 per unit

The equivalent parallel real and reactive per unit impedances during starting were then calculated using (15) and (16).

$$R_{parallel,INRUSH} = \frac{V^2_{SVC,INRUSH}}{S_{INRUSH}(PF_{INRUSH})} \quad \text{pu} \qquad (15)$$

$$X_{parallel,INRUSH} = \frac{V^2_{SVC,INRUSH}}{S_{INRUSH}(\sin(\cos^{-1}(PF_{INRUSH})))} \text{pu} \qquad (16)$$

$$R_{parallel,FL} = \frac{V^2_{FL}}{S_{FL}(PF_{FL})} \quad \text{pu} \qquad (17)$$

$$X_{parallel,FL} = \frac{V^2_{SVC,FL}}{S_{FL}(\sin(\cos^{-1}(PF_{FL})))} \quad \text{pu} \qquad (18)$$

R_{load} and X_{load} were then found by converting the parallel impedances into equivalent series impedances similar to (11) and (12). (Note that $X_{xfmr} = 0$ and $R_{xfmr} = 0$ in this case.) The uncompensated per unit rms voltage magnitude at the proposed SVC location was calculated using (13). This per unit rms voltage was converted to a 120-volt base.

In the simulation, the motors started one at a time, with the starting condition assumed to last 6 cycles. The starting condition was followed by the full load condition for each motor. Every 12 cycles, another motor was started until all 6 motors were at full load. All 6 motors were then assumed to go off line at the same time.

Fig. 7 compares the uncompensated rms voltage to the compensated voltage.

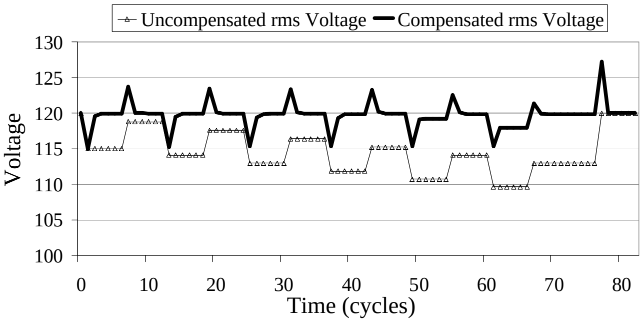

Fig. 7. rms Voltage

Notice that after the one cycle response time of the SVC, the nominal voltage is always corrected to 120 volts in the compensated case. Unlike the power supply case of the previous section, the X/R ratio of 0.7 in this case is relatively small. This results in a significant voltage drop due to the real component of current. The SVC therefore must overcorrect to compensate for this drop. This results in a leading power factor measured upstream of the SVC.

Fig. 8 shows the compensated power factor and applied compensating kVAr for the loading condition of Fig. 7. Notice that a 200 kVAr capacitive rating was required for the SVC.

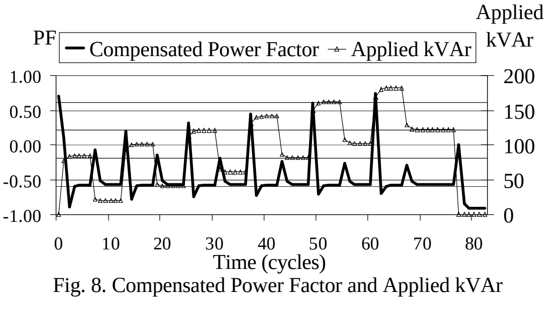

Fig. 8. Compensated Power Factor and Applied kVAr

C. Reactive Compensation Applied to Automated Welding Line

The third example involves an automated welding line used in a manufacturing process. The flicker resulting from the process affects other utility customers on the same and adjacent distribution circuits.

The system diagram and proposed SVC location are shown in Fig. 9.

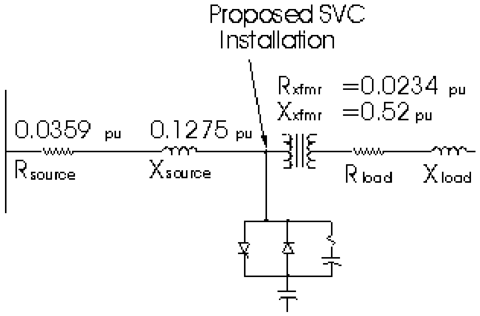

Fig.9 System Impedance Diagram – Welding Line

The utility provided the following per unit information on a 10 MVA basis:

R_{source}:	0.0359 per unit
X_{source}:	0.1275 per unit
R_{xfmr}:	0.0234 per unit
X_{xfmr}:	0.52 per unit

In addition to the above data, the utility provided 209 cycles of data which was measured at the customer service entrance. It included all three phase-to-neutral voltages, currents, and power factors in tabular form. The nominal voltage at the service entrance was 480 volts, or 277 volts line-to-neutral.

The equivalent parallel real and reactive load impedances were calculated using (19) and (20).

$$R_{parallel} = \frac{V}{I(PF)} \quad \text{Ohms} \qquad (19)$$

$$X_{parallel} = \frac{V}{I\sin(\cos^{-1}(PF))} \quad \text{Ohms} \qquad (20)$$

The impedances of (19) and (20) were converted to per unit quantities. In order to verify the accuracy of the model, the theoretical voltage at the welder was obtained for comparison with the given voltage at the welder. The theoretical welder voltage was calculated using (21).

$$V_{welder} = V_{source}\frac{\left|R_{load} + jX_{load}\right|}{\left|R_{load} + R_{xfmr} + R_{source} + j\left(X_{load} + X_{xfmr} + X_{source}\right)\right|} \tag{21}$$

Fig. 10 is used to verify the accuracy of the model by comparing the theoretical and actual welder voltages.

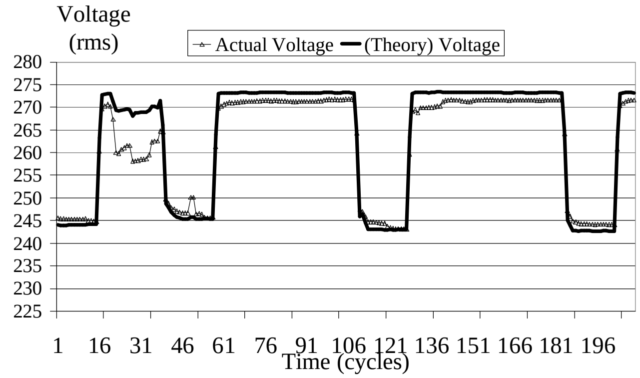

Fig. 10. Uncompensated Actual vs. Theoretical Welder Voltage

The voltage at the proposed SVC installation was obtained using substitution of (19) and (20) into the per unit equivalents of (11), (12), and (13). The results are shown in Fig. 11 for a 120 volt base.

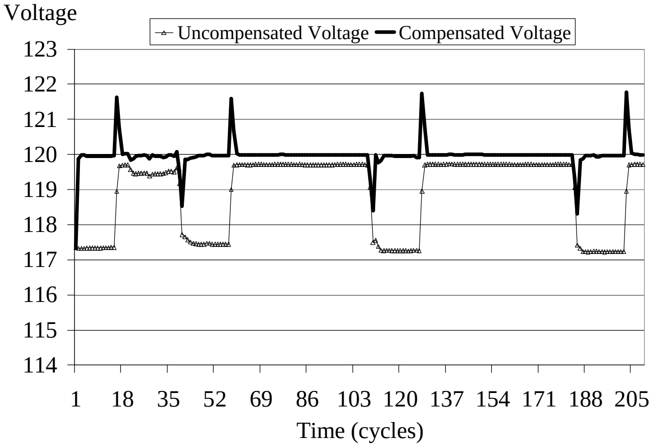

Fig. 11. Compensated vs. Uncompensated Voltage

The X/R ratio for this example was 3.55, resulting in some voltage drop due to the real component of current.

Fig. 12 shows that the compensated power factor is only slightly leading in order to compensate for this voltage drop.

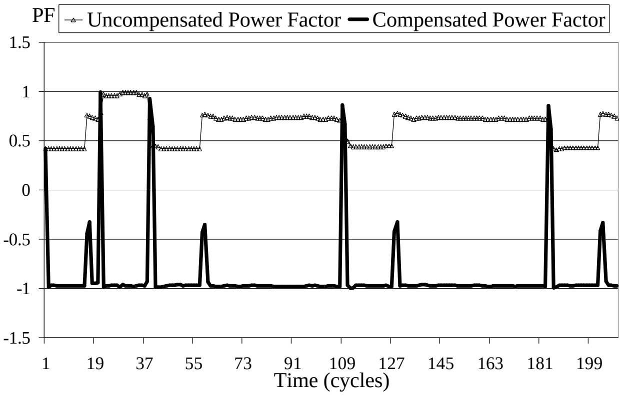

Fig. 12. Uncompensated Power Factor vs. Compensated Power Factor

Fig. 13 shows the applied compensating kVAr. Notice that over 600 kVAr per phase is required from the SVC.

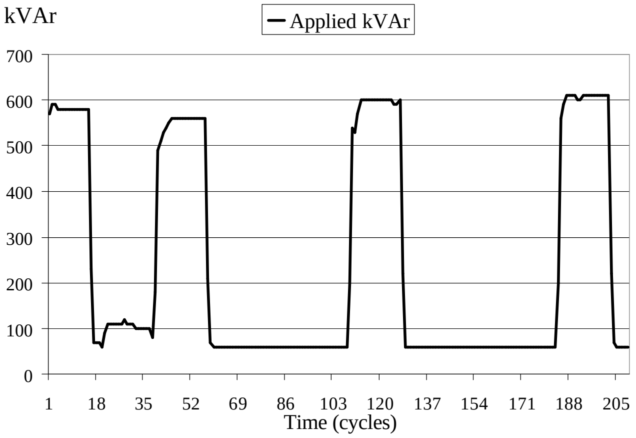

Fig. 13. Applied Compensating kVAr

D. Reactive Compensation Applied to Arc Furnace Load

The final example demonstrates an SVC applied to a multiple arc furnace load fed from a 69 kV/13.09 kV substation. The substation was located adjacent to the plant. Resulting flicker from the arc furnaces was tripping variable speed motor drives within the plant.

The utility provided the following impedance data referred to the 13090-volt side of the substation.

$R_{source,1}$:	0.1431 Ohms
$R_{source,0}$:	0.0543 Ohms
$X_{source,1}$:	1.5135 Ohms
$X_{source,0}$:	1.0856 Ohms

The negative-sequence impedances were assumed to be equal to the positive-sequence impedances [1]. The single-phase values for R_{source} and X_{source} were calculated using (22) and (23).

$$R_{source} = \frac{R_{source,1} + R_{source,2} + R_{source,0}}{3} \quad \text{Ohms} \qquad (22)$$

$$X_{source} = \frac{X_{source,1} + X_{source,2} + X_{source,0}}{3} \quad \text{Ohms} \qquad (23)$$

The utility also provided 16 cycles of real time voltage and current data. The data sampling was triggered from a waveshape disturbance, which resulted from the charging of one or more of the furnaces. The data consisted of 128 samples per cycle in Microsoft Excel format. A discrete Fourier transform was performed on the data to obtain the magnitude and phase angle information for the voltage and current [2].

During charging, the arc furnace terminals randomly change back and forth from an open circuit to a short circuit condition, resulting in flicker on the distribution feeder [3]. The real and imaginary components of current are shown in Figs. 14 and 15.

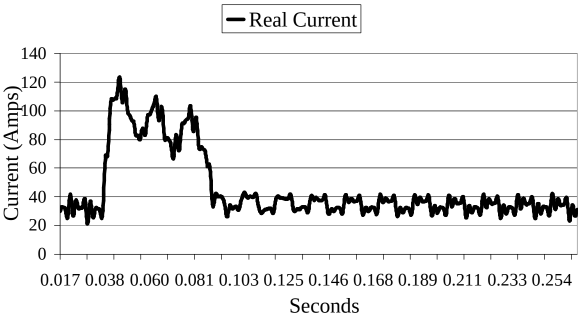

Figure 14. rms Real Current

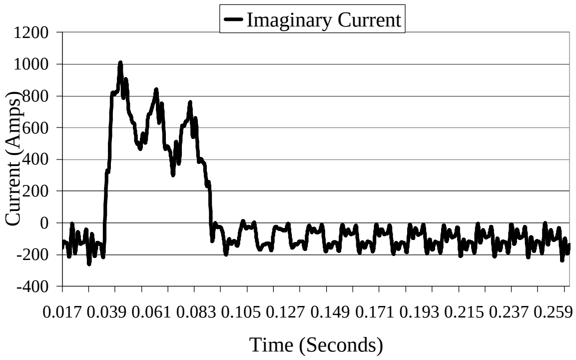

Figure 15. rms Imaginary Current

Since the current, voltage, and phase angle at the SVC were known, the compensated and uncompensated rms voltages were solved easily using the methods of the previous examples.

Fig. 16 shows the rms voltages for the compensated versus the uncompensated case.

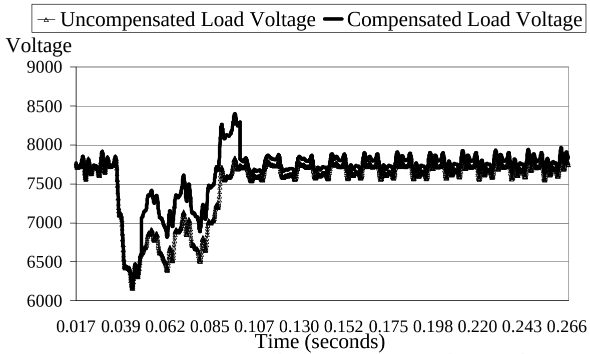

Fig. 16. Compensated vs. Uncompensated rms Voltage

Fig. 17 shows the required kVAr from the SVC to compensate for the load.

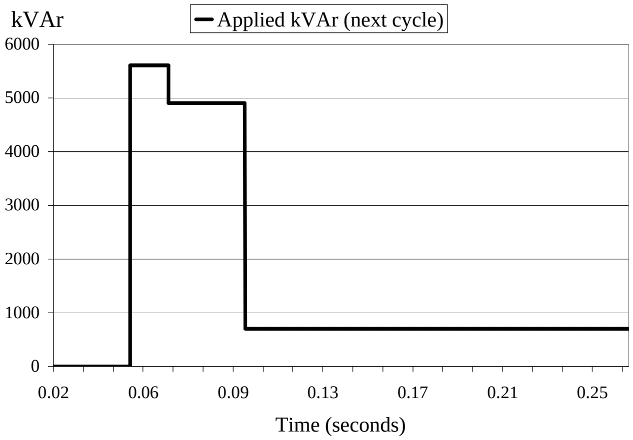

Fig. 17. Applied kVAr

This system would require nearly 6 MVAr per phase for full correction.

IV. HARMONIC CONTROL

The shunt capacitance added by SVCs can resonate with the source impedance of the power system, Fig 18. If this resonance is tuned to a harmonic of the 60 Hz power frequency, existing harmonic problems can be amplified.

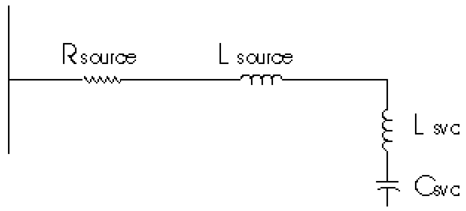

Fig. 18 System Impedance Diagram – Harmonic Case

On a power system the source resistance is small enough that the resonant frequency can be approximated by (24):

$$f_{res} = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{L_{source} C_{svc}}} \quad \text{Hz} \qquad (24)$$

where

L_{source}	Inductive component of source impedance;
R_{source}	Resistive component of source impedance;
C_{scv}	SVC Shunt capacitance.

The harmonic problems can be reduced or eliminated by adding a harmonic filter, an inductor L_{SVC} to the circuit. This inductor is sized to resonate with the SVC capacitance and the source impedance at a frequency of about 2.8 times the 60 Hz power frequency, 168 Hz, given by (25):

$$f_{res} = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{\left(L_{source} + L_{svc}\right) C_{svc}}} \quad \text{Hz} \qquad (25)$$

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