Electrical Systems Design

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315 East Parent Street
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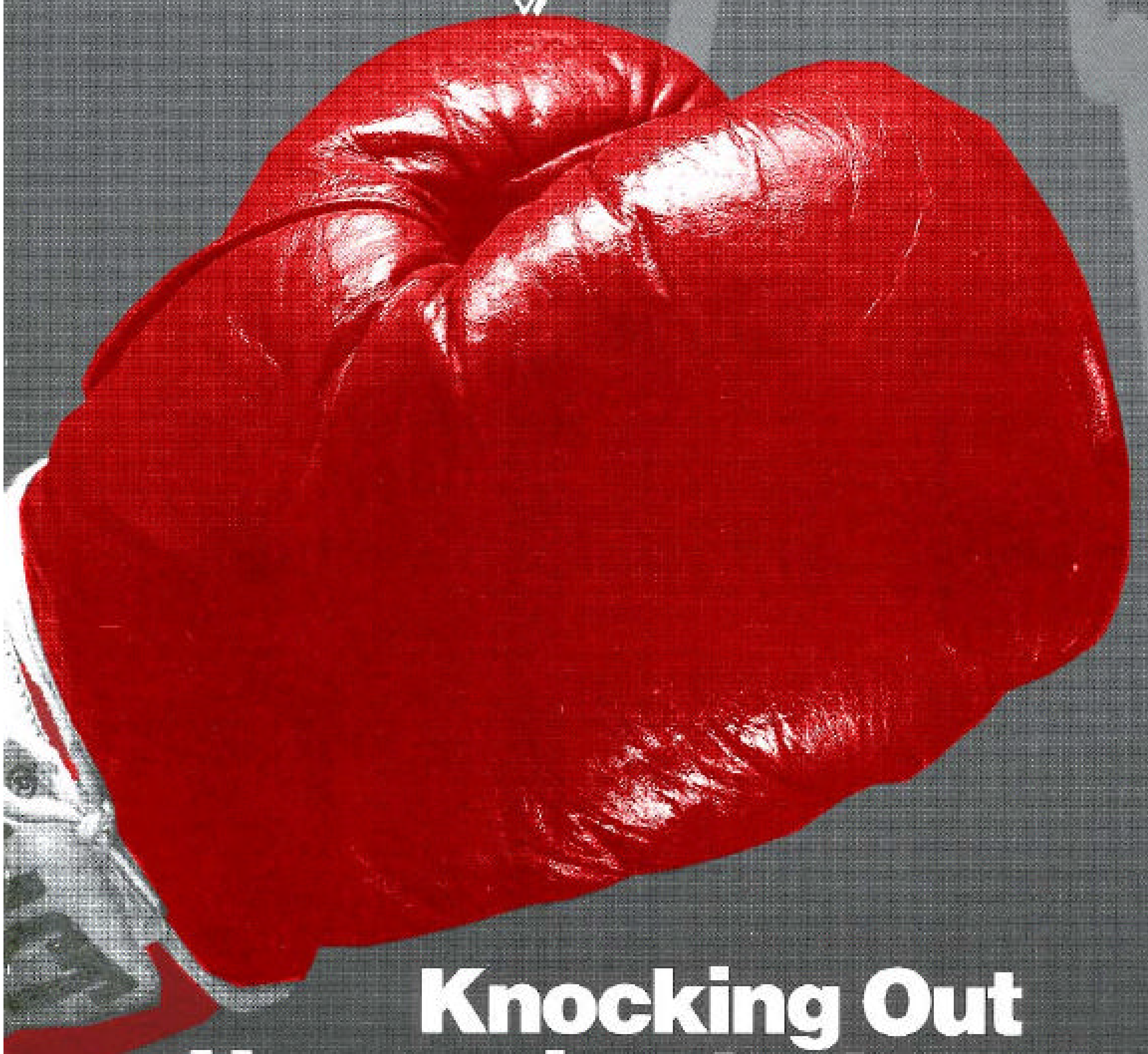

Knocking Out Harmonics And Improving Power Factor

Controlling Harmonics While Improving Power Factor

Interactions between electrical systems, power factor capacitors, and non-linear convertors are examined. By using traps, power factor can be improved, while problems with harmonic distortion are avoided.

By Michael Z. Lowenstein, Manager, Research & Development, Jim Holley, National Sales Manager
and Myron Zucker, P.E., Chairman of the Board, Myron Zucker, Inc.

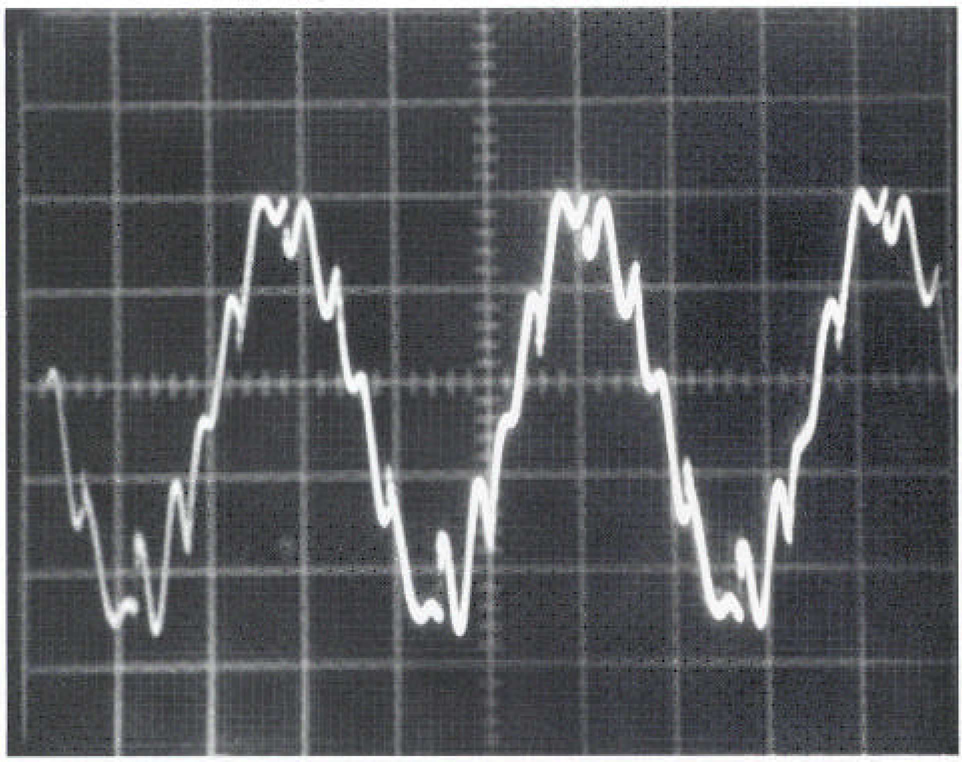

Fig.1. "Dirty Power" as seen on an oscilloscope.

The use of capacitors to improve power factor in electrical systems is well known. A number of different strategies have been well tested in the field. If, for instance, a plant load is reasonably constant, power factor correction capacitors can be connected to medium voltage feeders. If switched to follow the load. Alternatively, correction can be carried out using low-voltage capacitor banks installed at the main switching centers. Automatic controllers can switch capacitance on and off line to compensate for the varying loads. Investigations have shown that a favorable location for power factor capacitors is as close to the load as possible.

Capacitors at the load, by providing reactive power where it is needed, reduce the current which must be carried out by wires all the way back to the substation. Because I^2R losses are reduced, smaller wires can be used, and a circuit capacity formerly used to provide reactive power is released for a more beneficial use. Unfortunately, what has historically been a simple solution to low power factor has been made more complicated by the increase of in-plant harmonic distortion. The symptoms have been visible for a number of years.

Fifteen years ago we investigated a wire drawing plant with an unusual power factor problem. A 200-kVA transformer, operated at 70% pf, was slightly overloaded. The plant engineers had added a substation capacitor bank sized to release about 200kVA of a system capacity. But instead of dropping to 1800 kVA, the transformer load was increased to 2300 kVA. Fortunately, the problem was recognized as a harmonic phenomenon. At the time, harmonic distortion had been studied on transmission systems, but had been considered a major in-plant problem. The incidence of in-plant distortion was quite low since only a few non-linear loads (arc furnaces, thyristor controls, resistance welders, etc.) were in place. Over the last few years the rapid acceptance of adjustable speed drives and static converters, which use silicon controlled rectifiers (SCRs) or other switching devices, has resulted in growing concern for electrical system problems caused by waveform distortion been visible for a number of years.

Dirty Power

Waveform distortion, often referred to as "dirty power", becomes serious when the power deviates significantly from a pure sine wave. Such distortion can take many forms. High voltage spikes, high frequency ringing, voltage "sag", and, as in the case of the wire drawing plant mentioned above, system harmonic resonance, can all be found in situation where dirty power is a problem. The problem, readily visible on an oscilloscope as shown in Fig. 1, manifest itself within the plant in a number of ways.

Premature motor or capacitor failures have been traceable to dirty power. Motor symptoms include overheating, arcing of starting contacts, and in some cases bearing failure brought about by rapid pulsing of the rotor. Capacitors have been observed to overheat, leak, and even burst. Overheating is also the prime symptom of conductors and transformers subjected to harmonic distortion. In the modern computer-controlled plant effect of dirty controls can include out-of-sequence operation, faculty of lost data, can complete failure with destruction of circuit boards.

Often the first noticed symptoms of dirty power is nuisance fuse blowing. A fuse blows because excessive currents produce enough heat to melt the fuse link. Fuses are designed to withstand small over-currents for a long time or large current in-rush for a short time. (I^2t effect). Dirty Power, containing both harmonics and spikes, subjects the fuse to two excessive heating conditions.

	Harmonic						
Location	3rd	5th	7th	9th	11th	13th	TOTAL
13 kV	1.13	2.26	0.50	0.10	0.24	0.13	2.6
480 V sub 1	1.10	7.76	1.10	0.25	0.06	0.01	8.0
sub 2	1.02	6.69	0.56	0.25	0.55	0.06	6.8
sub 3	1.19	7.22	0.51	0.05	0.26	0.04	7.4
sub 4	0.25	5.98	0.40	0.43	0.48	0.06	6.0
sub 5	0.72	7.21	0.80	0.48	0.21	0.23	7.3
sub 6	1.27	5.09	0.27	1.00	1.70	0.99	5.6
sub 7	1.01	5.77	1.37	0.14	0.95	0.27	6.1
sub 8	1.38	6.40	1.57	0.34	1.85	0.71	7.2

Fig.3. Table showing plant-wide distribution of harmonic distortion. Numbers represent harmonic voltage as a percent of the fundamental voltage.

The harmonic current is a continuous overload and causes the fuse to run hotter than normal. The high-current spikes, although of short duration, cause the I^2t rating of the fuse to be exceeded and it blows. Although the fuse is performing exactly as it should, some users view the dirty power problem as a fuse problem. The tendency to replace the blown fuse with a higher rating (never a good practice) without addressing the basic problem. Under standing the basic problem requires a examination of harmonic-system interactions.

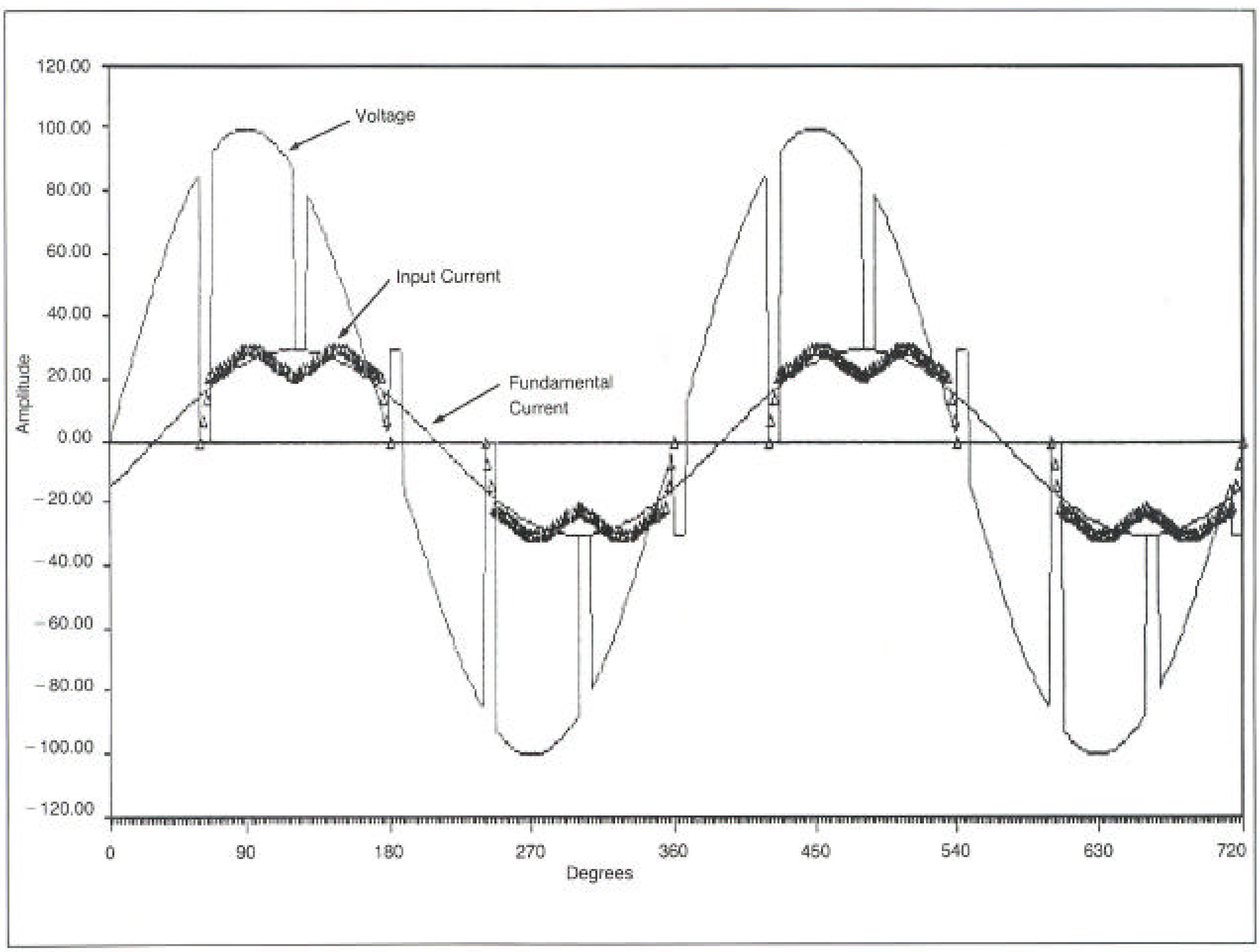

Fig.2. Voltage and current waveforms of a six-pulse convertor.

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The inductance and capacitance in a power distribution system form a resonance circuit. The resonant frequency is usually well above the 60 Hz fundamental frequency. However, the addition of capacitors to the sys tem lowers the resonant point. So long as the system is not excited at the resonant frequency, oscillation will not occur. However, if the power in the system contains distortion at the resonance frequency, the entire system can oscillate, resulting in large harmonic currents.

Electrical harmonic resonance has an acoustic analog, a violin. The sys tem can be tuned to a specific frequency (just as each violin string is tuned to a frequency.) If the system is excited at its resonant frequency (akin to bowing a violin string) a high energy resonance (tone) results. The larger the exciting energy (the heavier the bowing) the larger the harmonic current flowing in the system (the louder the tone.) A large enough current can damage the system (the string breaks). Or, as in the wire drawing plant mentioned previously, power load levels become excessive.

SCRs And Dirty Power

Adjustable frequency and dc motor drives as well as static power converters (such as in UPS systems) contain SCRs or other switching devices. While these drives are valued for their ability to provide precisely con trolled outputs, they have detrimental effects on the sine wave power in the distribution system. A close look at how SCRs function reveals two problems. When an SCR is used to control current flow in a circuit, the current lags the voltage contributing to a low power factor. For a typical SCR circuit, the input current, as shown in Fig. 2., instead of starting at the same time as the voltage, remains zero until the SCR is switched on. Then the current rises almost instantaneously to the value of the fundamental current. Were the device to remain on, the in put current would follow the fundamental current. However, the SCR turns off, and the input current goes rapidly to zero. The input current resembles a "square wave." But this current is supplied by a voltage wave which is nearly sinusoidal The distribution system must produce the square wave current pulse by providing a combination of sine waves of sine-wave of appropriate frequencies.

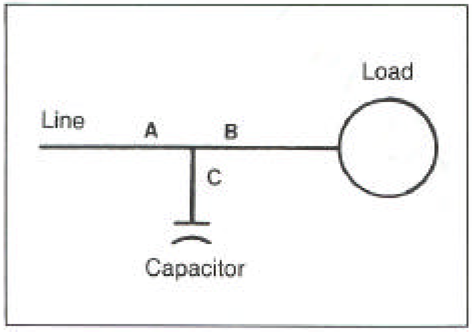

Fig.4. Simplified circuit diagram with power factor capacitor.

	Motor Accelerating To 220 rpm	
Measuring Point	No Capacitor	Capacitor
A	225	110
B	225	225
C	—	225

Fig.5. Reactive power supplied by a capacitor, in amperes.

Measuring Point	A	B	C
Harmonic	(% of 60 Hz current)		
5th	10	0	25
7th	5	0	5

Fig.6. Harmonic concentration in a capacitor.

Parameters	Idle Speed	Full Speed
60 Hz current	18	18
rms current	20	58
Harmonic	(% of 60 Hz Current)	
3rd	0	10
5th	5	10
7th	10	5
9th	5	20
11th	10	100
13th	0	70
15th	0	15
17th	0	15
19th	0	10

Fig.7. Current in a 15 kVar capacitor at a 40=hp motor on the same line as an 850-hp, 6-pulse SCR inverter.

The higher order harmonics (17^{th}, 19^{th}, etc.) do not generally have enough energy content to cause circuit damage, the lower frequencies (picture the bass string of a violin with large vibrations) contain a considerable amount of energy. If the resonance point of the electrical distribution system is turned to one of these harmonic frequencies, large harmonic currents can flow.

The six-pulse converter, which is the type most commonly used, generates significant amounts of 3^{rd}, 5^{th}, 7^{th}, 9^{th}, and 11^{th} harmonics with decreasing amounts of higher harmonics. Although theory predicts that the “Triplen” harmonics (3^{rd}, 9^{th},…) will be absorbed by nearly delta-connected equipment, field measurements show this to be untrue, and the triplen amounts have been found in plant distribution systems.

A second damaging features of SCRs is revealed upon closer examination of Fig. 2. As the 3-phase converter transfers current from phase to phase (commutation) momentary short circuits occur. This results in a series of line notches in the voltage input that “shock” the system six times per cycle. The shock can be manifested as large voltage or current spikes applied to the line. These spikes often contain enough energy to cause a fuse blowing and can damage or even destroy, computers, controls, or circuit components.

The designer of a new power distribution system should be aware of potential problems with SCR equipment to be installed in the plant. Careful distribution of harmonic-generating equipment loads may reduce some problems, interactions between SCR drives and power factor capacitors must still be considered. The designer must be as aware of the special design demands for power factor correction in the presence of SCRs as is the plant engineer faced with problems in an existing plant.

Observing Harmonics

For existing electrical systems it is possible to detect the presence of potentially dangerous dirty power before damage occurs. This is an important first step to eliminating damaging harmonics from the power distribution system. There are two methods of looking at harmonics in distributed power system. One can be observe the voltage wave and the harmonics superimposed on that wave, or one can carry out the same observations on the current wave (deviations from a sine wave will show up in either wave form).

While voltage measurements can be made in-plant, most of the in-plant dirty power is caused by utilization equipment, and it is important to be able to locate specific harmonic sources. This task is best accomplished by measuring current harmonics. The techniques and instrumentation for measuring voltage or current differ somewhat. The voltage wave is most easily observed using an oscilloscope. If harmonic voltages are to be measured there are a number of sophisticated wave analyzers available which can isolate each frequency, calculate its magnitude relative to the fundamental, and determine total harmonic distortion. The point of measurement will usually be a main distribution bus, a1though the voltage can be measured at any point in the system. In observing voltage harmonics it is often noted that similar distortion appears on all substations within the system. The propagation of harmonics through transformers whether isolation, step-up, or step-down is a well-observed phenomenon. Therefore it is a difficult to determine the exact source of distortion. Figure 3 contains data obtained at a typical industrial plant which utilizes a number of adjustable speed drives. Note that the voltage harmonics are widely distributed throughout the plant and that there is no way for the engineer to determine whether the harmonics are generated in a particular substation or are feeding through from another source.

Another difficulty in measuring voltage harmonics involves their relative magnitude. While current harmonics may show large values relative to the fundamental, the low characteristic impedance of the system results in voltage harmonics of smaller amplitude. Analyzing the exact relationship between voltage and current harmonics requires a knowledge of system impedances, which is not often available

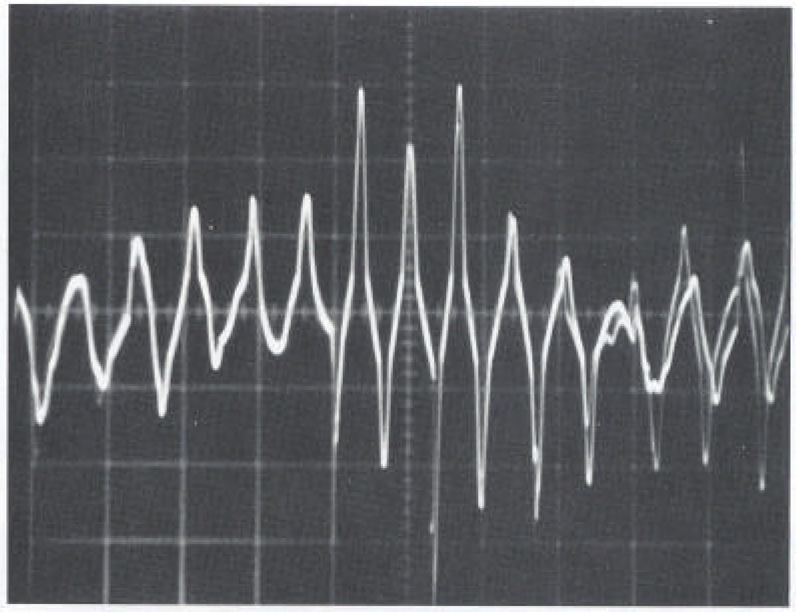

Fig.8. Oscillograph of current in a 15 kVar capacitor at a 40-hp motor on the same line as an 850-hp 6-pulse SCR inverter.

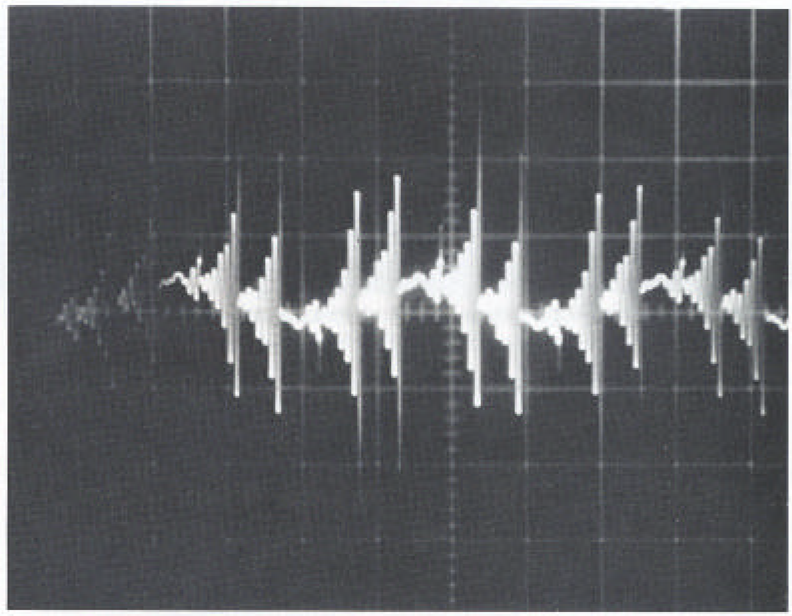

Fig.9. Ringing effect due to interaction between a capacitor and an SCR drive.

However, this relationship may not be needed, since measurement of current harmonics can often identify distortion-causing equipment.

Selection of the measurement location is important. Current harmonic waves have been observed by clipping an oscilloscope across a circuit breaker. The small impedance of the breaker provides a measurable voltage drop. While feasible at high currents, at low loads the voltage to be measured is only slightly above the ambient electrical noise level. A better way to measure current harmonics is to use a clamp-on current transformer shunted by a low-value (10 to 50 ohms) precision resistor. This transformer can be connected for measurements anywhere in the distribution system, or even at low currents the observed voltage drop across the precision resistor is well above the ambient noise. By using a current transformer in this manner, one can observe current waveforms on an oscilloscope. The voltage generated can be used as the input to a harmonic analyzer of the type previously discussed and complete analysis of the harmonic distortion is easily made. Since the current being measured is unique to the measuring point, the harmonic content of a single variable speed motor drive, motor, capacitor, or branch circuit can be isolated.

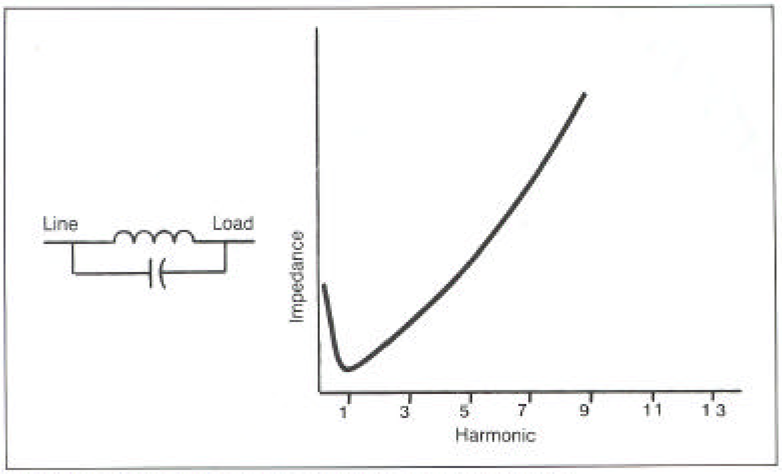

Fig.10. Circuit and band-pass of a tuned series low-pass filter.

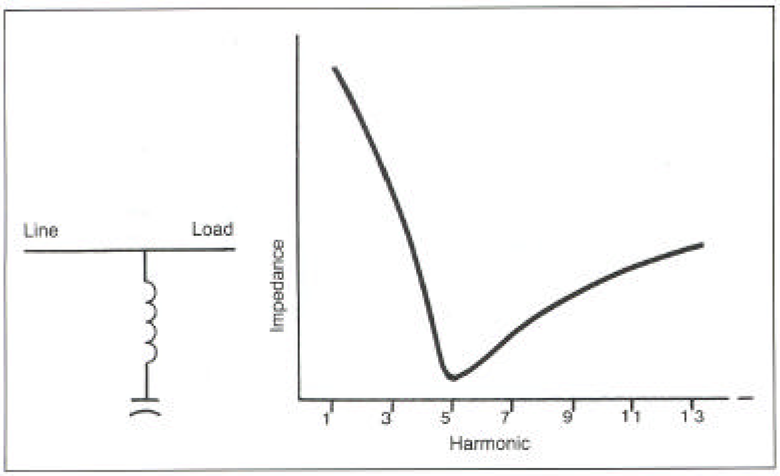

Fig.11. Circuit and band-pass of a tuned shunt high-pass filter.

To realize the benefit of this type of information, one need only examine Fig.4.

Circuit voltage is the same at points A, B, and C, but measured currents differ significantly. At A, the measured current and capacitor current (current measured includes fundamental, reactive, and harmonic components). At B, current drawn by the load is measured. Current measured at C is the capacitor fundamental current plus the reactive and harmonic components flowing between the capacitor and load. In Fig.5, the effect of a capacitor in providing reactive current to a load can be clearly seen as a reduction of current drawn from the line.

If the load is non-linear, such as an SCR adjustable speed drive, the currents will include various harmonics. By measuring harmonic currents, the path of the harmonic distortion can be easily traced. For example, if power factor capacitor fuses are blowing because of suspected excessive harmonic currents, the capacitor current can be monitored at point C as the drive is brought on line and power levels are changed. The exact power level or setting that causes excessive capacitor current can be determined and steps can be taken to correct or avoid the problem.

Capacitor SCR Interactions

The problem of capacitor interaction with SCR drives has been a serious one. Manufacturers of variable speed drives have traditionally recommended against locating power factor correction capacitors in close electrical proximity to the drives.

These recommendations were based on field experience with capacitor fuse blowing, capacitor failure (sometimes explosive) and even destruction of SCRs. Before discussing the solution to this problem, which is now available, it is beneficial to examine in more detail the interactions between SCRs and capacitors.

The impedance of a capacitor is inversely proportional to the frequency of the applied voltage. If the applied voltage contains harmonics, the higher frequencies tend to be "concentrated" in the capacitor. While this serves to remove harmonics from the line, it also increases the current through the capacitor. Figure 6 is an example of this harmonic "concentrating" effect. The load was a 30 hp induction motor with a 7.5 kVAr capacitor mounted nearby. The line feeding the motor contained significant amounts of 5th and 7th harmonics.

Note the high harmonic content of the capacitor current. In this case the source of the harmonics was at a great enough distance from the capacitor that line impedance limited the capacitor harmonic current, and the only effect on the capacitor was an increase in operating temperature. However, when the capacitor is electrically near the SCR drive, the harmonic currents can become quite large.

Experiments were conducted to measure the interaction between an SCR converter and an electrically adjacent capacitor. The converter was a 6-pulse drive powering an 850-hp motor. A 15kVAr capacitor was connected at the disconnect for an auxiliary 40-hp induction motor, only a few bus bar feet from the SCR converter. Capacitor currents were measured as power to the large motor was varied. The results of this experiment, shown in Fig.7, illustrate the ease with which detailed information regarding the generation of harmonics can be obtained using current measurements.

Figure 8 illustrates the capacitor current wave-form at full power. The underlying 60 Hz sine wave is almost buried in the harmonic distortion. Capacitors of 15 kVAr rating are usually fused for 40 A. During this analysis, the rms current in the capacitor was 58 A. It is plain to see why capacitor fuse blowing occurs in this type of installation.

Another interaction between SCR converters and capacitors has been observed. This phenomenon, known as “ringing”, is triggered by the SCR communication notches. The ringing occurs when the notch, appearing to the system as a high amplitude square wave, transmits a pulse of energy. This pulse starts the system ringing at its natural frequency, whether or not that frequency is a characteristic harmonic frequency of the convertor.

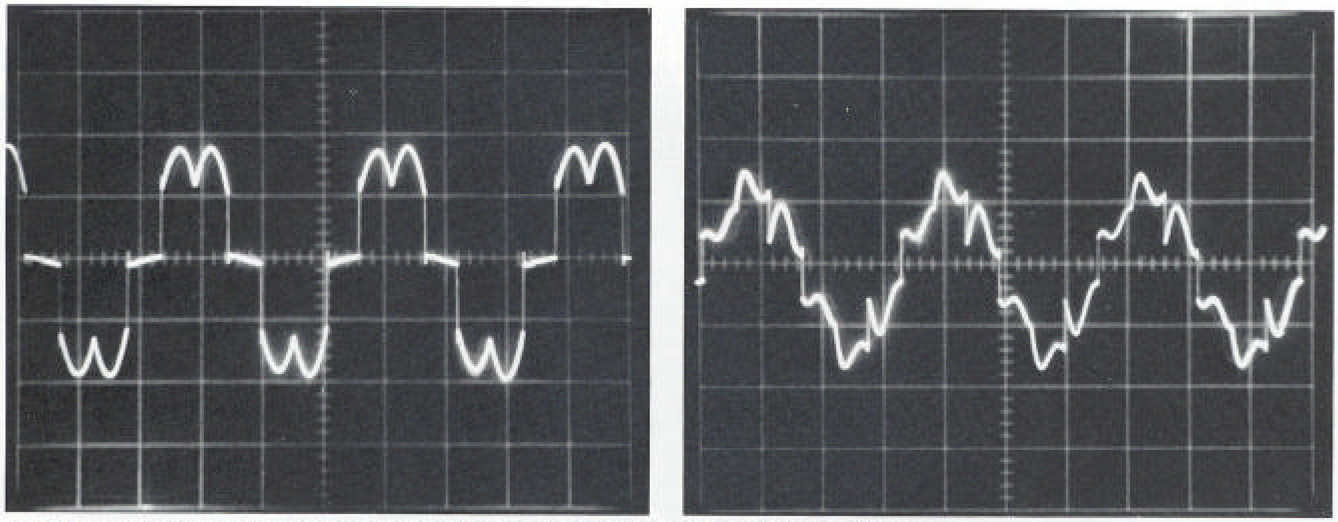

Fig.12. Oscillographs of SCR line current before and after application of 5th harmonic trap.

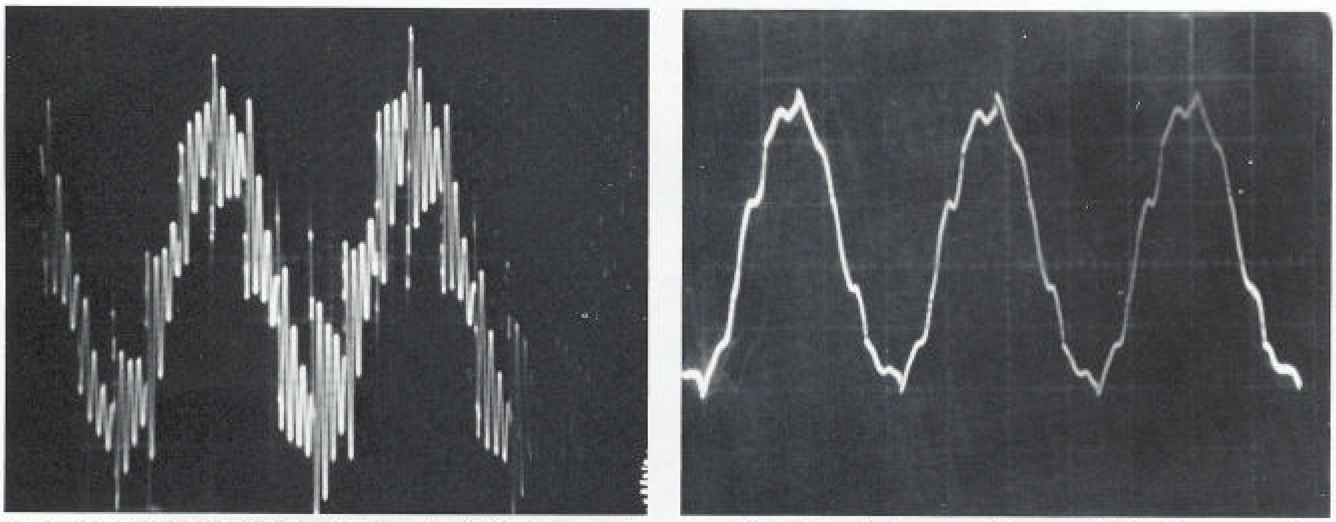

Fig.13. Oscillographs of motor line current with SCR convertor on same line. Power factor correction provided first by a capacitor and then by a 5th harmonic trap.

While such filters work quite well for individual pieces of electronic equipment, they are not cost effective for filtering of an entire distribution line carrying hundreds of amperes, since the entire current of the line must be carried by the filter. For industrial power distribution systems almost all harmonic removal is carried out using tuned shunt filters.

A shunt filter is designed to have a low impedance at high frequencies and to short circuit or "trap" frequencies above those of interest, thus keeping them from circulating throughout the system. "High pass" filters, are installed as shown in Fig.11. Shunt filters need carry only a fraction of the current that a series filter would carry and are thus suitable for use in high current systems. The simplest filter is single tuned and consists of an inductor (or coil) in series with a capacitor. The filter has a low impedance at the frequency to which it is tuned and the impedance rises slowly at higher frequencies.

In practice filters are designed with fairly broad tuning so that they provide effective removal of several frequencies. For example, a filter, or "trap," tuned to remove the fifth harmonic (300 Hz) will have some effect in removing the seventh harmonic (420 Hz) as well.

The harmonic current requirements of the SCR drive are not reduced when a trap is installed. The trap, in the same manner that a power factor capacitor provides reactive power, provides both reactive power and the required harmonic power. The harmonic currents now circulate between the trap and the load, reducing harmonics in the system. Maximum benefit of a trap will be obtained when it is located as close to the harmonic source as possible.

An example of the application of a fifth harmonic trap to the line supplying a typical SCR convertor is shown in Fig.12.

Typical ringing in an electrical system containing an SCR convertor and a capacitor is shown in Fig.9. Note the ringing current decays are retriggered six times per cycle, corresponding to commutation notches of the six-pulse convertor. The ringing frequency in this case is about 2000 Hz. Ringing current adds to the rms current through the capacitor and can contribute to capacitor fuse blowing. In addition to the ringing phenomenon, the commutation notches can result in excessive currents through the SC. At the moment when the SCR appears as a short circuit between two phases, a nearby fully charged capacitor can discharge through the SCR. The resulting current peaks rapidly (large di/dt) and tic instantaneous currents can reach several thousand amperes. Cases have been reported where a large current d spike has destroyed an SCR before a fuse protecting it could blow.

The problems posed by interactions between SCRs and capacitors so far discussed are not going to go away, in fact they will increase as more and more SCR power convertors are brought into use. Nor will the need for correcting low power factor disappear. More and more utilities are recognizing their need to charge for poor power factor, while the increased use of convertors is resulting in overall lowered power factors and higher customer charges. Since the problem cannot be ignored, what can be done?

Harmonics

A tried and true way to reduce harmonic distortion in a power distribution system is through the use of tuned filters. In many low-power installations or in specific sensitive systems such as computers, series filters are used. Passing only frequencies below their tuning point, these are known as "low pass" filters. Such a filter, installed as shown in Fig. 10., can, because of its high impedance at frequencies above a certain point, effectively block the entrance of such frequencies into a load. The desired 60 Hz fundamental is passed through the filter with little attenuation.

Note the reduction of harmonic distortion in the line as evidenced by the improved wave shape. Harmonic currents required by the drive are now being provided locally by the trap. Figure 13 shows the current waveform to an induction motor with power factor correction, following installation of an SCR convertor on the same line. When the power capacitor was replaced with a 5th harmonic trap, the harmonic distortion in the line was dramatically reduced, while power factor correction was maintained.

Conclusion

It is clear that traps can dramatically reduce the harmonic currents circulating in a power distribution system by providing these currents locally. At the same time the capacitors in the filter provide power factor improvement. The engineer who wishes to improve power factor at the load, but who has been kept from doing so because of SCR convertors in the plant, now has a solution to his problem. The inductors in a trap limit instantaneous current through any nearby SCR during commutation, and block the square-wave pulses that trigger ringing.

Traps can be installed anywhere in the electrical system with no danger of damage to SCR convertors. Harmonic traps can be sized to almost any system and they will allow use of both the output control capabilities of SCR convertors and the advantages of power factor improvement provided by capacitors at the load.

The Authors

Michael Z. Lowenstein is manager of research and development and marketing director for Myron Zucker, Inc. He received an AB degree from Oberlin College and MS and PhD degrees in physical chemistry, physics, and instrumentation from Arizona State University.

Jim Holley is national sales manager for the same firm. He received a BSME degree from Massachusetts Institute of Technology.

Myron Zucker is founder and Chairman of the Board of Myron Zucker, Inc. He obtained a BSEE degree from Cornell University and a MSEE degree from Union College. |