Power Factor Correction for Thyristor Equipment in Glass Industry

By
E.O.OGUNDANA
Department of Electrical Engineering
Ahmadu Bello University, Zaria

Abstract
Thyristor power controllers are now widely used in the glass industry for controlling furnace temperature. While offering a number of operational advantages, they operate at lagging power factors which require correction for minimum power cost. Harmonic resonance with the utility feed, however, complicate the use of capacitor banks. The nature of harmonic problems is described and the use of inductors to tune capacitor banks below any possible harmonic frequency is demonstrated.

Introduction

Thyristor controllers have become the preferred method of electric heating control for main melters, boosters, foreherths, and pochet furnaces in the glass industry. Their ability to regulate power enables the establishment and maintenance of precise furnace temperature profiles over a wide range of draws, and their electronic circuitry provides a substantial level of protection for the electrodes. From the standpoint of the utility interface, however, the thyristor controllers introduce problems in power factor and harmonic levels that are coming under increasing scrutiny by some utilities. The abundance of single-phase and unbalanced three-phase resistive loads in the glass industry, coupled with the need for constant power over a wide range of load resistance, means that harmonic and power factor control techniques, may be somewhat different from those in other industries. In particular, third-order harmonics must be carefully considered in the specification of harmonic-limiting reactors for power factor correction capacitors.

Fortunately, it is not necessary to delve into the waveforms of three-phase thyristor controllers to gain considerable insight into harmonics and power factor phenomena, since the single – phase thyristor controller shown in fir. 1 has the important characteristics of all the controller types. All the fundamental relationships can be demonstrated with this simple circuit.

Consider first the case of purely resistive load. Although, practical application always involve load inductance, it may be neglected temporarily to simplify the analysis. Power flow to the load is governed by phase control of the thyristor gates. Fig. 2 shows the load voltage and current waveforms for a phase delay angle, α. With a supply voltage of $E * \sin(wt)$ and a load resistance R, the rms output voltage, rms current.

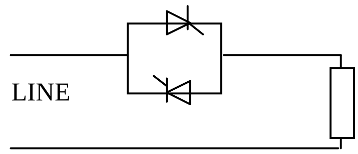


Fig. 1: Single-phase thyristor controller

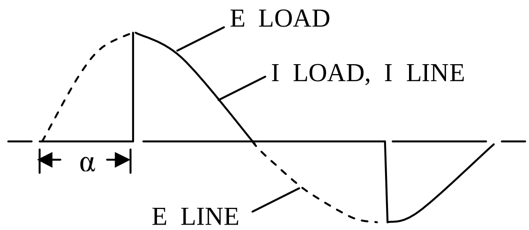


Fig. 2: Power, voltage, and current waveforms.

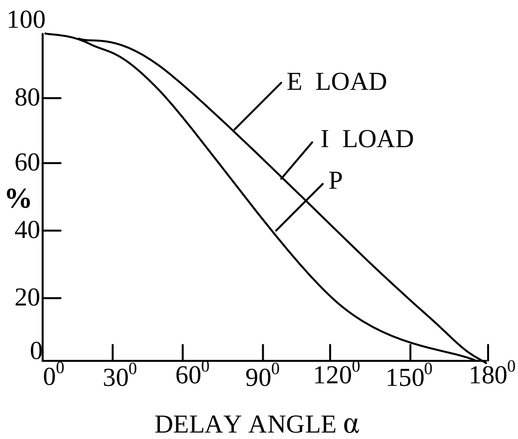


Fig. 3: Power, voltage, and current versus delay angle

power are given by;

$$E_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} (E^{*} \sin(wt))^2 \, d(wt)} \qquad (1)$$

$$I_{rms} = E_{rms}/R \qquad (2)$$

$$I_{rms} = E_{rms} {*}\, I_{rms}. \qquad (3)$$

Fig. 3: Power, voltage, and current versus delay angle.

Fig. 3 shows relationships as a function of delay angle for the full range of available control. Line power and load power are equal since the controller losses have been neglected. In practice, there will be a power loss in the thyristors.

Power Factor

The voltage delivered to the load, as shown by fig. 2, is delayed relative to the start of the supply voltage since wave except for the case of
$\alpha = 0$. This means that the circuit power factor will generally be lagging. If "power factor" is defined as *W/VA*, then (1)-(3) contain the information required to calculate power factor. Here, line voltage should be used since line power factor is the subject of concern; load power factor always being unity with a resistive load. Line power factor, then, may be expressed as

$$Pf = W/VA = E_{rms}\,(\text{load})/E_{rms}(\text{line}) \qquad (4)$$

Note that this power factor is independent of the current and is numerically equal to the per-unit output voltage. A note of caution must be added, however. This relationship is valid only for the case of a purely resistive load. If the load contains inductance, as most do, it will be necessary to use a wattmeter (dynamometer or Hall-effect type) to measure the power in the load.

It is apparent from this discussion that a simple thyristor controller such as this has a poor characteristic for glass furnaces, when the glass is cold (high resistance), the voltage will be high and power factor will be good. When the glass is hot (low resistance) and draw is high, voltage will be low and power factor will be poor; this latter case representing the majority of the working life for the typical glass furnace. Special circuit techniques, such as the auto-tap-changer or series/parallel switch (SPS), can improve this situation dramatically …for power factor correction may still exist.

Harmonics

The nonsinusoidal waveforms of fig. 2 may be resolved into a fundamental frequency component and a series of harmonics by discrete Fourier transforms. In the frequency domain;

$$A_n = \frac{2}{\pi}\int_0^{\pi} f(wt)^{*} \sin(nwt) \qquad (5a)$$

$$B_n = \frac{2}{\pi}\int_0^{\pi} f(wt)^{*} \sin(nwt)\, d(wt) \qquad (5b)$$

Where n takes on all integer values and represents the harmonic order. The original function *f(wt)* is then given by;

$$f(wt) = \sum_{n=1}^{\infty} (A_n {*} \sin(nwt) + B_n {*} \cos(nwt)) \qquad (6)$$

and the rms value of any given harmonic is;

$$Hn = \sqrt{(A^2_n + B^2_n)/2} \qquad (7)$$

Amplitudes of the first few harmonics are plotted in Fig. 4 as a function of delay angle, α. Note that only odd harmonics are present since the waveform is symmetrical about the abscissa. The effect of these harmonics on the power system is considered later.

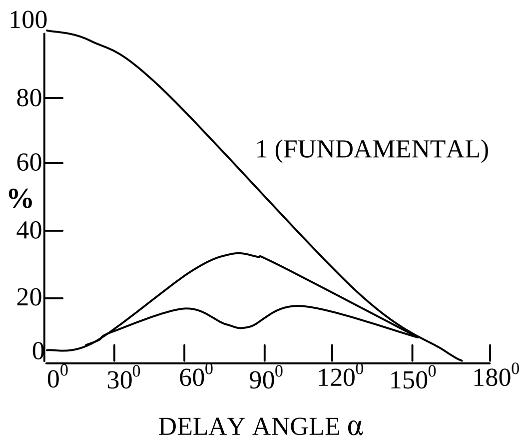
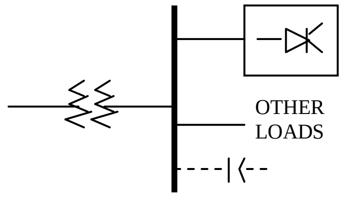
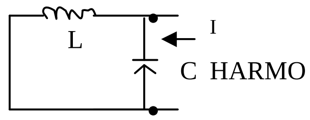


Fig. 4: Harmonic currents versus delay angle



(a)



(b)

Fig. 5: (a) Simplified one-line diagram.
(b) Equivalent circuit for harmonics.

Displacement Power Factor

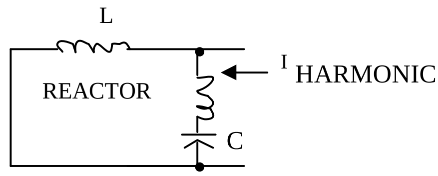
Electric utility metering does not generally measure the power factor as described earlier. Rather, the power factor is computed from kilowatt/hour and kvar/hour meters. These meters are sensitive only to harmonics that are present in both the voltage and the current. If a sinusoidal line voltage at the metering point is assumed (a reasonable assumption in most cases), the wattmeter and varmeter elements respond only to the fundamental component of the line current. The wattmeter yields the product of instantaneous line voltage and instantaneous line current integrated over a half-cycle. This is the value from (3). However, it can be shown that (3) is identical to the product of line voltage and 0.707 times the fundamental current components given by fig. 5(a), that component of load current which is in phase with the line voltage. In the same fashion, the varmeter element responds to the fundamental component of line current, given by fig. 5(b), which is in quadrature with the line voltage. Thus, the utility metering ignores the harmonic content of line current. The "displacement power factor," so called because it measures the phase displacement between fundamental current and fundamental voltage, is given by;

$$Dpf = cos\,(\tan^{-1}(B_1/A_1) = \cos(\tan^{-1}(Q/P)) \quad (8)$$

Where P and Q are the watts and vars or kilowatt/hours and kvar/hours, respectively. The "displacement power factor" is always greater than the "power factor" discussed earlier. Despite the fact that harmonics are apparently being ignored by the wattmeter element, it is reading the actual power in the circuit. The old adage "you can't fool a wattmeter" is generally true, at least for dynamometer and Hall-effect meters.

Power Factor Correction

Most electric utility rate structures contain some form of cost penalty for poor power factor, and correction measures are often cost-effective.



(b)

Fig. 6: Protective reactor.

The presence of thyristor harmonics on the lines, however, precludes the usual practice of simply connecting a capacitor bank, since the potential exists for damage to other connected equipment or to the capacitor bank itself.

Fig. 5(a) shows the simplified one-line diagram for a typical glass plant feed, and an equivalent circuit for harmonic considerations is shown in fig. 5(b). The source inductance of the utility feed is represented by *L* and a proposed capacitor bank capacitance by C. If this parallel LC circuit happens to resonate on a harmonic frequency, problems may arise. The parallel circuit will amplify the harmonic current by (approximately) the *X/R* ratio of the utility feed at the harmonic frequency, so the capacitor harmonic current may be far in excess of the harmonic current by easily be high enough to cause capacitor failure or fuse-blowing. Furthermore, the high impedance of this circuit means high harmonic voltages, which can cause capacitor overheating or failure of connected equipment. Last, but by no means least, amplified harmonic currents will flow into the utility system, where they can cause interface to communication circuits or damage to power factor correction capacitors at other locations.

Tuning Reactors

The simplest way, in principle, to solve this problem is to choose a capacitor bank that does not resonate with the feed inductance at a thyristor harmonic frequency. In the real world, however, one is faced with changes in the utility system configuration due to fault isolation and switching of distribution circuits. The source impedance is really variable, at least over the long-term. A better method is to add a tuning (or perhaps, “detuning”) reactor so that resonance is forced to occur at a lower frequency than the lowest harmonic in the thyristor controller current, regardless of the utility source impedance. Such an arrangement is shown in fig. 6. The reactor adds to the utility source inductance and can lower the resonant frequency of the parallel circuit to any desired value. While this arrangement takes care of harmonic currents, also increase the fundamental current in the capacitor bank. Hence, the reactor reactance subtracts directly from the capacitor reactance, the circuit reactance is lower than that of the capacitor alone; hence the current in the capacitor increases the voltage along with it. By ANSI Standard C55.1, power or correction capacitors are rated for only a 10 percent per voltage, and some allowance must be made for line voltage variations. When these *LC* networks are tuned below fourth harmonic, it is generally necessary to increase the change rating of the capacitor bank. Then the capacitor bank have to be oversized in kvar rating because it maybe taking at a voltage below nameplate value and the effective will be reduced. Because of the finite steps in capacitor range ratings, these considerations cannot be reduced to a simple equation, but must be examined on a cut-and-try basis.

The use of reactors to protect power factor correction means that power factor correction can be applied to individual process lines or furnaces without regard to the overall system. Each installation is self-contained, self-protected, and free from any problems due to other harmonic sources. If the power factor correction reactor/capacitors are connected on the load side of feeder breakers, they can be brought in on an as-needed basis instead of relying on a plant-wide installation. Two advantages accrue from this arrangement: first, the voltage regulation is improved since the system has roughly the proper amount of power factor correction for the load; and second, feeder currents are reduced and losses lowered slightly. Switchgear will also run a little cooler. On the minus side, a number of reactors tend to be somewhat more expensive than a single large unit.

Tuning

The choice of resonance frequency will affect both the capacitor and reactor cost; the lower the frequency, the higher the cost. Most industrial plants with thyristor drives and balanced three-phase loads can be tuned to about 240Hz, since there is little phase unbalance and little third-harmonic production. In glass plants, however, the presence of single-phase and unbalanced three-phase loads means that a resonant frequency of 150Hz is about the highest safe frequency for a do-it yourself installation, absent an investigation of the actual harmonic spectrum under all process conditions. The inductors can be iron-core types and specified simply by their reactance and current rating – the current, of course, being that of the series – tuned *LC* circuit at rated supply voltage. Harmonic currents are not a concern in rating since the increased reactants at harmonic frequencies minimizes them. One caveat should be noted: not all transformer manufacturers are competent at designing iron core reactors. Unless the vendor is experienced in their design, high flux density at the air gaps may increase the losses to an intolerable degree. Generally speaking, the average flux density must be much lower than is appropriate for transformers.

Conclusion

To summarise, thyristor drives, and controllers generate harmonic currents that cause resonance problems with power factor correction capacitors. The use of series reactors with these capacitor banks can eliminate the problems by tuning the *LC* circuit below the lowest harmonic frequency. Loads in the glass industry tend to have phase unbalances, which generate third-harmonic currents and necessitate a lower tuning frequency than is required for balanced systems. a tuning frequency of 150Hz is recommended for general use. Capacitor voltage ratings must be examined carefully to avoid overheating or dielectric breakdown.

Reference

Galloway, J.H, “Harmonic instability in phase controlled rectifier“ IEEE PCIC Conf. record, July 2004 pp.171 – 175

Ainsworth, J.D. “Harmonic insrability between controlled static convertors and AC Networks ” Proc. IEE No. 7, pp.949 – 957. Nov. 2005

Willis, C.A., “Application of harmonic commutation for thyristor rectifiers and inverters ” AIEE Trans. pp.701 – 708 June 2002.

Buseman, F., “The influence of the number of phase used in a converter on harmonic direct current “ Proc. IEE June 2003.

Turnnull, F.G., “Selection of harmonic reduction in static D.C. – AC inverters” IEEE Trans. in Power Electronics pp.44 – 50, Aug. 2004.6.

Kennedy, S.P. “Design and application of Semiconductor Trans. IEEE PCIC conf. Aug. 2001 record, pp.153 - 159