OVERCOMING PROBLEMS WITH HARMONICS AND LOW POWER FACTORS

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Abstract

The use energy-efficient discharge lamps (fluorescent, sodium, etc.) can lead to substantial energy and capacity savings. However, it must be ensured that the lighting loads present a high power factor and do not inject large amounts of harmonics in the network. Otherwise there will be negative impacts, both for the utility and customer, which will decrease those savings.

Discharge lamps have non-linear current-voltage characteristics which give rise to harmonics. Traditionally discharge lamps have been used in conjunction with iron core ballasts which can also produce a poor power factor. The paper describes how these problems appear and suitable mitigation measures.

Electronic ballasts are increasingly being used both in conjunction with long tubes and with compact fluorescent lamps due to their higher efficiency and overall superior performance. The power electronic devices in the electronic ballasts generate harmonics and sometimes a poor power factor. This applies especially to compact fluorescent lamps due to space/weight/cost limitations. The paper presents an assessement of the performance of electronic ballasts, with relation to power factor and harmonics. The impact of recent developments in microelectronics in electronic ballast performance is also analyzed. Recently low-harmonic modular type compact fluorescent lamps have been introduced into the market, which deserve to be promoted due to their lower overall life-cycle cost and better performance.

In order to ensure the penetration of low harmonic distortion lighting equipment into the marketplace, standards are being introduced in Europe and the USA. Additionally, the need for incentives to promote equipment whose characteristics surpass the standards is discussed.

Acknowledgements

The author wishes to thank Ing.V.Vajao from Philips-Portugal, Dr.N.Kramer from Philips-Netherlands, Ing.J.Cruz from Osram-Portugal, H.Fahnrich from Osram-Germany, Dr.R.Verderber from Lawrence Berkeley Laboratory, T.Jednacz from Electronic Ballast Technology-USA, W.Anderson from Sylvania Lighting-USA, J.Vuola from Helvar-Finland, B.Christiansen from Samsung Semiconductor--USA, J.Spangler from Illinois Institute of Technology-USA, S.Kalinovsky from Consolidated Edison of New York-USA, and N.Grimshaw from Advance Transformer, for information supplied for the preparation of this paper.

INTRODUCTION

Energy-efficient lighting can save substantial amounts of electricity, decreasing at the same time the need for expensive investments in generation, transmission, and distribution equipment. However, discharge lamps, especially when used with electronic ballasts, may give rise to problems such as poor power factor, harmonics, and electromagnetic interference.

These potential problems have increasing importance due to the growing penetration of other loads with similar behaviour. Loads such as computers, peripherals, office equipment, and other electronic equipment having switching power supplies, electronic variable speed drives, together with electronic lighting, may present around 50% of the total load by the year 2000 in industrialized countries. Thus utilities and regulatory bodies are paying more attention to the needs of ensuring an optimal use of the power system networks, which implies that the loads must present high power factor and low harmonic distortion.

POWER FACTOR

An ideal load, when fed by a sinusoidal voltage waveform, would absorb a sinusoidal current in phase with the voltage waveform. This situation is characterized by a power factor of one, and no harmonic distortion. An electric resistance heater or an incandescent lamp show this behaviour. When the current is not in phase with the voltage waveform or the current shape is distorted (different from a sinusoid) the power factor is less than one and is given by the expression:

$$\text{Power factor} = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{1/T \int_0^T v(t)\, i(t)\, dt}{V_{rms}\, I_{rms}}$$

The real power,measured in watts, is the rate of change of energy, , which is converted and consumed by the load. Reactive power is power stored in inductances and capacitances of the load, which does not perform any real work but which travels forward and backward in the conductors feeding the load. The vector sum of the real and reactive power is the apparent power (Figure 1). The power factor can range from zero to one and is a measure of the effectiveness of how the current is being used to transmit power.

A poor power factor implies that for a load consuming a certain amount of power, a larger current is necessary. If we compare two loads with the same power, but one with a power factor of one and the other with 0.5, then the second load needs twice as much current. A low power factor has negative impacts both for the consumer and for the utility [1,2,3], namely:

- Increase in the losses of cables, transformers and lines. The losses grow with the square of the total current. A power factor of 0.5 means conductor losses four times larger than with a power factor of one.
- The cables, transformers and switchgear in the consumer premises become underutilized, as the current they carry is only partially utilized to deliver power. The same happens on the utility side with the equipment (cables, transformers, lines, and generators) which have to supply a larger current, than necessary.

To reflect the costs associated with the under-utilization of its equipment due to low power factor, most utilities charge medium and large consumers a penalty if their overall power factor falls below a certain limit, typically between 0.85 and 0.90.

When a poor power factor is caused by an inductive load, it can be improved up to 1 by adding a capacitance to the load which supplies the reactive power required by the inductance, and vice-versa with capacitive loads. This is due to the fact that the current in a pure inductance lags the voltage by ninety degrees whereas in a capacitor it leads by ninety degrees. If the capacitance is sized to absorb a current whose magnitude is similar to the one in the inductance, they will add to zero and thus the power factor will be close to one.

HARMONIC DISTORTION

A periodic waveform which deviates from a pure sinusoid can be decomposed into a sum of sinusoids whose frequencies are multiples of the frequency of the waveform. Figure 2 shows the decomposition of a square wave in a series of sinusoids. The lowest frequency component is called the fundamental and the other sinusoids of higher frequencies are called harmonics. For a 50Hz waveform the 150Hz component is called the 3rd harmonic, the 250Hz the 5th harmonic and so on. The parameter which measures the amount of distortion is the total harmonic distortion (THD) defined in Europe as:

$$\text{THD} = \sqrt{\frac{2nd^2 + 3rd^2 + 4th^2 + 5th^2 + \ldots}{I_{rms}}}$$

THD is thus the relative value of all the harmonics combined, as a percentage of the total current Irms. In the USA the definition of THD is slightly different as:

$$\mathrm{THD} = \sqrt{\frac{2nd^2 + 3rd^2 + 4th^2 + 5th^2 + \dots}{I_{\mathrm{fundamental}}}}$$

Although for low values of distortion the two THD values are similar, the same does not happen for larger values and there is a need for a common definition [4].

When a load is fed with a pure sinusoidal waveform and the current absorbed is non-sinusoidal, such as in discharge lamps, the harmonics do not perform any useful work in the load. However there are negative impacts both for the consumer and utility [3,5,6], such as:

- The total current is increased, leading to a decrease in the power factor with all the associated problems already mentioned in the previous section. If a poor power factor is caused by harmonics it cannot be compensated with a capacitance.
- Possible interference in nearby communication circuits parallel to power lines.
- Possible ressonance between inductive and capacitive elements, which may cause damaging overvoltages.
- Possible interference with distribution line carrier systems.
- Substantial increase of the losses in the neutral of 3-phase systems, possibly to the point of overloading.

In most industries and commercial buildings the distribution of electricity is normally made with a 3-phase and neutral system. Figure 3 [1] shows a 3-phase voltage system, whose waveforms are displaced by 120 degrees. The connection of fluorescent lamps to a 3-phase system allows a substantial reduction in flickering and stroboscopic effects. In a 3-phase system with loads balanced, the sum of the fundamental currents of three phases is zero and there is no current at that frequency in the neutral. Figure 3 also shows the third harmonic component. The odd triplet harmonics (3rd, 9th, 15th,...) are in phase in the 3-phase conductors and they sum in the neutral as shown in Figure 3. Thus if the third harmonic is 33%, this means that the neutral is carrying the same current as the 3 phase conductors.

This means that if the neutral is sized equal to the phase conductors, the odd triplet harmonics should not exceed 33%, in order to avoid overheating. Building codes normally specify the neutral with the same cross-section as other conductors.

FLUORESCENT LAMPS WITH MAGNETIC BALLASTS

Figure 4 shows the voltage/current characteristics of fluorescent tubes (1). The voltage waveform is almost square in shape (such as in Figure 2) and is thus rich in harmonics. Traditionally iron core inductances, i.e. magnetic ballasts, have been used in series with discharge lamps. The ballasts provide the starting voltage, limit the current in the lamp, and help to stabilize the supply voltage variations [1,2]. The inductance of the ballast limits the harmonic currents. The ballast is also responsible for some harmonic generation due to the non-linear magnetization characteristic of the iron. Poor quality ballasts presenting high magnetic flux densities present a larger harmonic distortion.

The inductance of the magnetic ballasts presents a poor power factor, typically around 0.5, which needs to be compensated. Figure 5 shows two possible ways of performing power factor compensation. A capacitor, which generates a similar amount of reactive power as absorbed by the magnetic ballast, is placed in parallel, producing a power factor close to 1. (Figure 5-a). Another possibility shown in Figure 5-b features a capacitor in series with one lamp and ballast. The capacitor is chosen in a way to compensate the reactive power absorbed by both lamps. The power factor of the series connection capacitor-ballast- lamp is around 0.5 leading (overcompensated). By contrast, the other lamp in series with the inductance features a power factor of 0.5 lagging. Thus excess reactive power of the first circuit is absorbed by the second circuit, producing a power factor close to 1. Due to the phase shift in the currents of the two lamps there is a decrease in flicker and stroboscopic effects, when compared with single lamp operation.

High-quality magnetic ballasts, with increased cross section of copper conductors and of the iron core featuring high performance magnetic steel, present not only lower losses, but also less harmonics. This is due to operation in the quasi-linear portion of the magnetization characteristic.

Low quality magnetic ballasts present a compensated power factor of around 90% and total harmonic distortion (THD) in the region of 20-30% [5,7,8]. The power factor cannot be compensated closer to 1 due to the harmonic distortion. Low quality ballasts barely meet the building codes specifying a minimum of 0.9 power factor. High-quality magnetic ballasts can achieve a compensated power factors up to 98% and present a THD in the range of 12-15% [7].

Compact fluorescent lamps with magnetic ballasts are not individually compensated due to space/weight/cost reasons presenting a poor power factor in the range of 0.4-0.55 [3,7] and a THD in the range of 7-15%. If a large number of compact fluorescent lamps with magnetic ballasts are used in a given location, the power factor can be centrally compensated with a single capacitor to raise the power factor to around 0.9. Since compensation will decrease to about half the fundamental current, THD will approximately double in the compensated scheme, but it will be for most lamps under the limits imposed by standards (See Section on Standards).

FLUORESCENT LAMPS WITH ELECTRONIC BALLASTS

Electronic ballasts are being increasingly used to drive fluorescent lamps due to the improvement in energy efficiency, longer lamp life, dimming capabilities, lighter weight, and less flickering and stroboscopic effects although they are more expensive than magnetic ballasts. Figure 6 shows the diagram of a high frequency electronic ballast [10]. The alternating supply input, 50 Hz in Europe and 60 Hz in USA, is rectified and filtered with a capacitor producing a (DC) direct current voltage, which is then converted by an inverter into a high frequency (20-50 kHz) voltage waveform which is applied to the lamp.

If no precautions are taken, the current waveform absorbed in the input stage by the rectifier and filter is highly distorted (Figure 7), with a large harmonic contents [11]. Although the fundamental of the current is in phase with the voltage, the power factor can be as low as 0.5-0.6 due to the harmonics. There are two ways to mitigate this problem -- passive or active power factor correction [5].

In the passive scheme an inductance-capacitor low-pass filter is used before the rectifier (Figure 6). This low-pass filter not only reduces the harmonics to acceptable levels but also acts as an electromagnetic interference (EMI) filter to prevent conducted EMI from being propagated in the network. Additionally the input filter can also protect the electronic ballast from high voltage transients coming from the network. Electronic ballasts with passive power factor correction feature a high power factor of around 0.90-0.96 and a distortion (THD) in the range 22-32% [5,7,10].

Figure 8 shows the principle of active power correction [11,12,16]. Active correction is normally implemented through the insertion of a high-power factor preregulator between the rectifier and the capacitor filter. The control circuit switches the power transistor in such a way that the current drawn from the AC input is almost sinusoidal. With this type of circuit a power factor close to 1 can be achieved, such as 99.8 %, and a THD of less than 5% [5,12]. The ballast still requires an input filter, although smaller, to suppress interference. Several manufacturers make special-purpose integrated circuits for power factor correction of electronic ballasts and of switching power supplies [13-16].

Whereas the extra cost of the input filter for passive correction represents around 15% of the ballast cost, active correction adds an extra 10-15% on the cost [5], although the price premium is likely to fall with mass production of the integrated circuits which perform power factor correction.

Most compact fluorescent lamps with electronic ballasts do not have power factor correction. The large manufacturers claim that although they have the technology, they are not implementing power factor correction due to space/weight/cost reasons. This causes a low power factor of around 0.6 and THD distortion which reaches 100% (USA THD definition) [3,7].

Recently some manufacturers in the Far East have introduced competitively priced modular compact fluorescent lamps, with active power factor correction, presenting a power factor of 0.9 and a THD distortion of around 30%. These type of lamps provide a number of advantages compared with the common integral compact fluorescent lamps (either magnetic or electronic ballasts), namely:

- Substantially lower life-cycle cost, as the base of the lamp containing the ballast lasts typically 50,000 hours. When a lamp fails, only the lamp needs to be replaced. This leads to lower costs and better use of resources. When an integral lamp fails the whole unit has to be discarded, although the most expensive of its parts (the electronic ballast) may still be good.

- Better performance when there are voltage variations, as the active power correction circuit can accomodate large voltage fluctuactions, keeping the light level fairly constant.

- Improved power factor and lower harmonic distortion

The first two factors are particularly important for the penetration of compact flurescent lamps in developing countries

HARMONIC STANDARDS AND INCENTIVES

The growing impact of loads which generate harmonics into the network provides a strong push for creating and updating harmonic standards [9]. Table 1 presents the International Electrotechnical Commission Standard IEC-555-2 on harmonic limits for lighting equipment. Lamps with a power rated below 25W such as compact fluorescent lamps do not have to comply with the limits, due to their small power rating. However large scale introduction of compact fluorescent lamps may change the situation and may make compulsory the production of low-harmonic compact fluorescent lamps.

In the USA, the American National Standards Institute (ANSI) standard for high frequency fluorescent ballasts is still in the committee stage. The proposed limits, (Table 2) similar to IEC-555-2, basically address neutral overloading in 3-phase with neutral systems by limiting THD to 32% and the odd triplets (n=3,9,15,) to 30% of the fundamental. The proposed limits are met by most of the magnetic ballasts. The Institute of Electrical and Electronics Engineers (IEEE) is also updating the Recommended Practice which deals with harmonics. Table 3 shows the draft of IEEE-Standard 519 which limits the current harmonics which customers may inject in the low and medium voltage network. The limits are for all the consumer premises and not for single pieces of equipment. The proposed limits are much stricter than IEC-555-2, especially for large consumers. Whereas large consumers may not inject harmonics above 5%, small consumer are limited to a maximum of 20%.

Utilities already charge customers with poor power factor. The penetration of low harmonic equipment, namely lighting, can be increased with incentives (rates or rebates) or through regulatory action such as standards [5,9]. It is technically possible to produce high-efficiency, high-power-factor, very-low- distortion lighting equipment. But it costs more to produce a ballast with 5% than with 20% THD distortion, with similar efficiency. A few utilities in USA (e.g Boston Edison), are only giving rebates with electronic ballasts if these have a harmonic distortion below a certain level (typically 20%). These incentives need to applied widely and extended to modular/high power factor/ low harmonic compact fluorescent lamps. At the moment there are few incentives for the production and marketing of the extra-high-quality equipment. The development of power integrated circuits to perform most of the functions in an electronic ballast, leading to substantial cost reductions, could be accelerated by large scale use of utility incentives.

CONCLUSIONS

Energy-efficient lighting may give rise to power factor and harmonic problems. Existing technology can solve those problems and is being used for that purpose. The already good performance of most electronic ballasts for long fluorescent tubes can be significantly improved.

Compact fluorescent lamps, due to their low power, are being exempted from harmonic limits, presenting poor power factor and high harmonic distortion. There have also been volume/weight/cost constraints to achieve high power factor and low harmonic compact fluorescent lamps. Recently, modular/ high power factor/ low harmonic compact fluorescent lamps were introduced which offers better performance and substantilly lower life-cycle costs. The large scale penetration of this type of lamps, which will bring substantial benefits to consumers and utilities, needs to be accelerated by information, marketing and incentives.

Increasingly stricter standards are also creating the market for low-harmonic distortion lighting equipment. Attractive utility rates and rebates are also required to increase the penetration of such equipment.

REFERENCES

[1] C.Meyer and H.Nienhuis. 1989. "Discharge Lamps", Philips Technical Library, Kluwer Technical Books, Deventer-Antwerpen.

[2] H.Hewitt and A.Vause. 1985. "Lamps and Lighting", Edward Arnold Publishers LTD, London.

[3] S. Kalinowsky and J.Martello. 1989. "Electrical and Illumination Characteristics of a Energy-Saving Fluorescent Lighting as Function of Potential", IEEE Transactions, Vol.25, No2, March/April 1989, pp.208-215.

[4] N.Grimshaw. 1991. "Line Current Harmonics of the Electronic Ballast for Fluorescent Lamps", IEEE IAS 26th Annual Conference, Detroit, October 1991.

[5] T.C. Jednacz. 1990. "Power Quality Design Implications of High Frequency Lighting Ballasts and Controls", Power Quality For End-Use Applications Conference, USA, March.

[6] B.Christiansen. 1990. "EMI and Electronic Ballasts", Powertechnics Magazine, September 1990, pp.25-30.[7] R.Verderber and O.Morse. 1988. "Performance of Electronic Ballasts and Other New Lighting Equipment". Electric Power Research Institute, Research Project 2285-4, Palo Alto, California, USA.

[8] B.Christansen. 1990. "A Comparison of Magnetic and Electronic Ballasts", Electrical Manufacturing, May 1990, pp.45-47.

[9] J.W. Anderson. 1991. "Status of ANSI and IEC Standards for the Harmonic Limits of Electronic Fluorescent Lamp Ballasts", IEEE IAS 26th Annual Conference, Detroit, October 1991.

[10] Philips Lighting. 1990. "General Technical Manual for HF Ballasts", June 1990, Netherlands.

[11] B.Christiansen. 1990. "Correcting Fluorescent Lamp Ballast Power", Powertechnics Magazine, May 1990, pp.33-36.

[12] B.Christiansen. 1990. "Basic Design Calculations for an Electronic Ballast PFC Circuit, Powertechnics Magazine, August 1990, pp.32-35.

[13] A.Swager. 1990. "Power-Supply IC controls both PWM and Power-Factor Correction", EDN, December 6,1990, pp. 57.

[14] D.Strassberg. 1991. "Power-Factor-Corrected Switching Power Supplies", EDN, April 11, pp. 90-100.

[15] F.Goodenough. 1991. "Dual. PWM-Controller IC Fixes AC Power Factor", Electronic Design, February 14, 1991, pp.125.

[16] J.J.Spangler, B. Hussain and A.Behera. 1991. "Electronic Fluorescent Ballast Using Power Factor Correction Techniques", IEEE Applied Power Electronics Conference and Exposition, Chicago, USA.

Table 1: IEC-555-2 Standard. Harmonic current limits for Class C equipment (Lighting)

Harmonic order n	Maximum value expressed as a percentage of the fundamental input current of the luminaires	
	C_1	C_2
2	5	2
3	30% x pf*	30 x pf*
5	7	10
7	4	7
9	3	5
$11 < n < 39$	-	3

C_1: Lighting equipment excepted those having an electronic ballast.
C_2: Lighting equipment having an electronic ballast.
* pf is the circuit power factor

The harmonic current limits of self-ballasted lamps, semi-luminaires and luminaires with an input power greater or equal than 25W shall not exceed the relative limits on Table 1

Table 2: ANSI Proposed Standard for high frequency electronic ballasts

	Current harmonic limits Maximum values*
Fundamental	100%
2nd Harmonic	5%
3rd Harmonic	30%
>11th Harmonic	7%
Odd Triplets	30%
Total Harmonic Distortion (THD)	32%

* Measured under nominal line voltage

Notes: 1. Band width is limited to 2Khz
2. All values are percentages of the fundamental.

Table 3: IEEE - 519 RECOMMENDED PRACTICES AND REQUIREMENTS FOR HARMONIC CONTROL IN ELECTRIC POWER SYSTEMS (Draft proposal).
Current Distortion Limits for General Distribution Systems (120 volts to 69,000 volts)

Maximum harmonic current distortion in % of fundamental						
Harmonic order (odd harmonics)						
Isc/IL	<11	11<h<17	17<h<23	23<h35	35<h	THD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above
*All power generation equipment is limited to these values of current distortion, regardless of actual Isc/IL
Where Isc = Maximum short circuit current at PCC.
And IL = Maximum demand load current(fundamental frequency)lat PCC.

This table lists the harmonic current limits based on the size of the load with respect to the size of the power system to which the load is connected. The ratio Isc/IL is the ratio of the short circuit current available at the point of common coupling (PCC) to the maximum fundamental load current. It is recommended the load current, IL, be calculated as the average current of the maximum demand for the preceding twelve months. Thus as the size of the user load decreases with respect to the size of the system, the larger is the percentage of harmonic current the user is allowed to inject into the utility system. This protects other users on the same feeder as well as the utility which is required to furnish a certain quality of power to its customers.

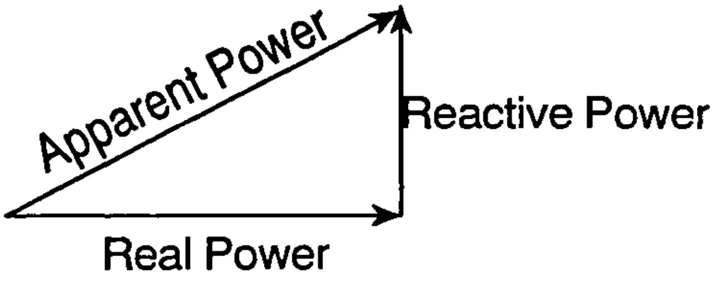
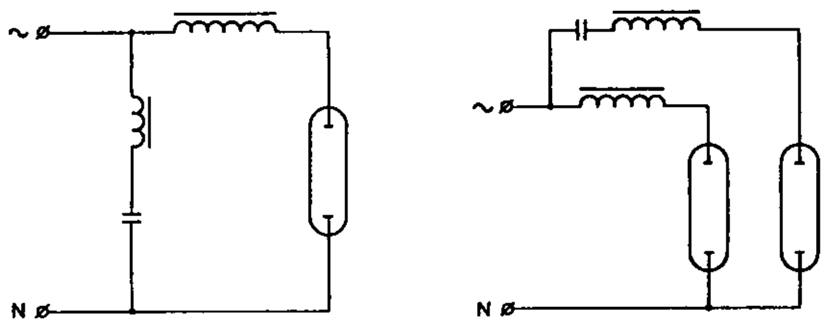


Figure 1: Relation between real power and apparent power



a) b)

Figure 5: a) Circuit diagram for parallel compensation. There is a filter coil in series with the compensation capacitor to prevent signals transmitted over the mains being short-circuited.b) In the duo-compensation circuit the combination of an inductive and capacitive circuit provides a power factor close to one.

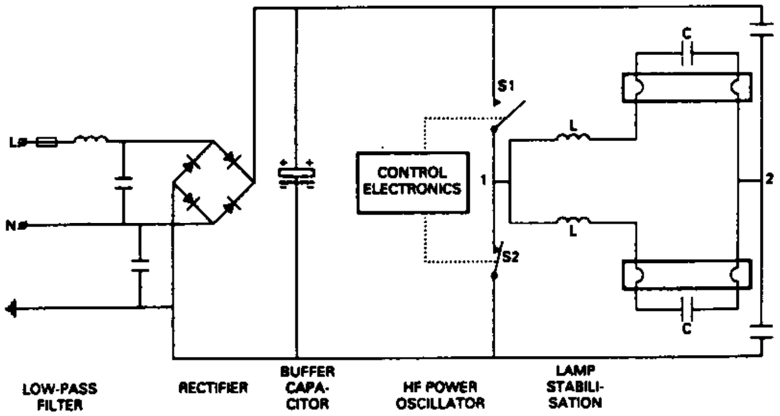
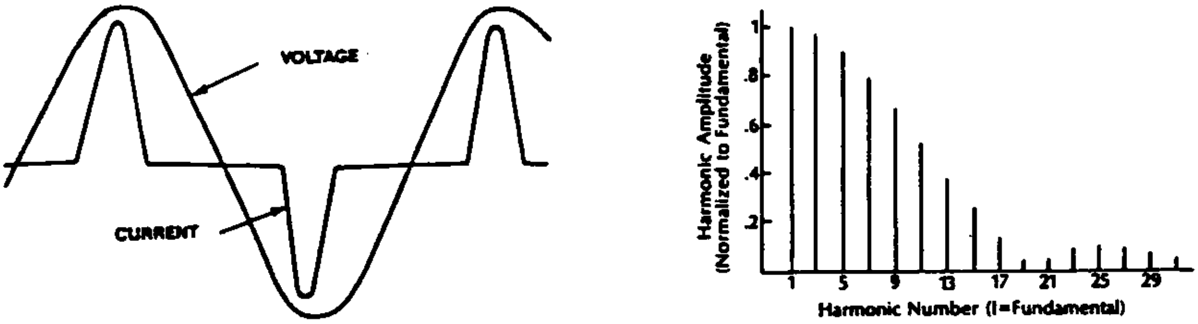


Figure 6: Circuit diagram of an electronic ballast with passive power factor compensation.



a) b)

Figure 7: a) Input current waveform of a rectifier followed by a capacitor filter, b) Harmonic contents of waveform in a)

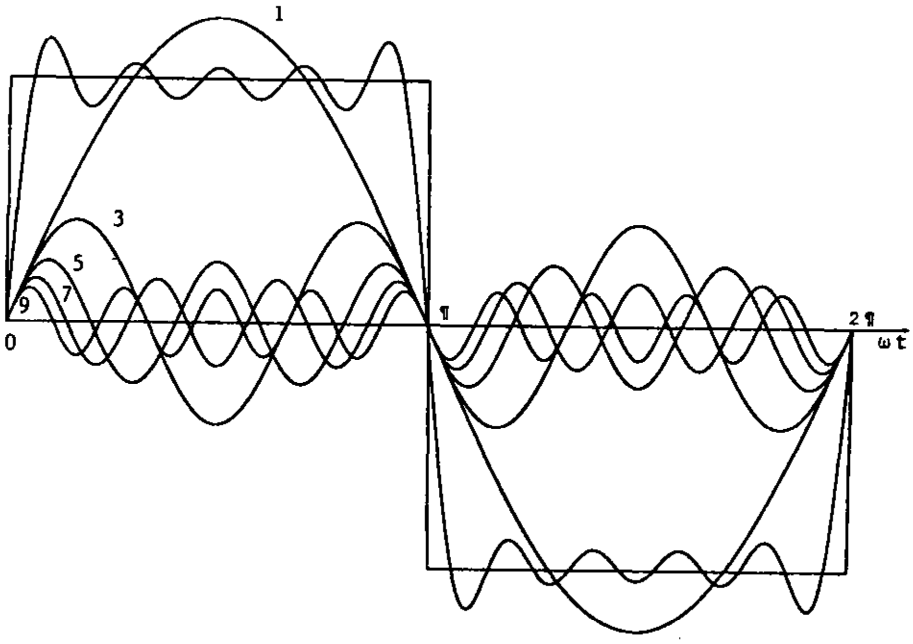


Figure 2: Square wave decomposed inodd harmonics from 1 to 9. Their sumapproaches fairly the square wave.

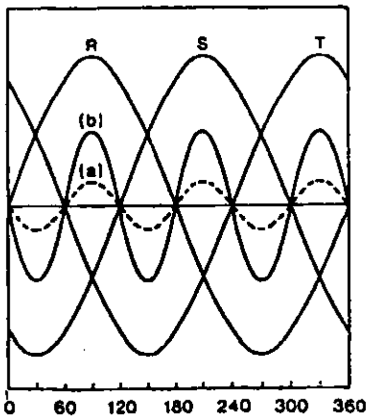


Figure 3: Fundamental and thirdharmonic in a three-phase system. R, S and T are the fundamentals inthe three conductors.
a) third harmonic of a phase
b) third harmonic of all three phases in the neutral lead

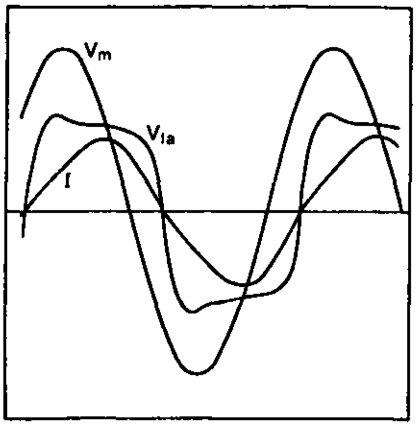
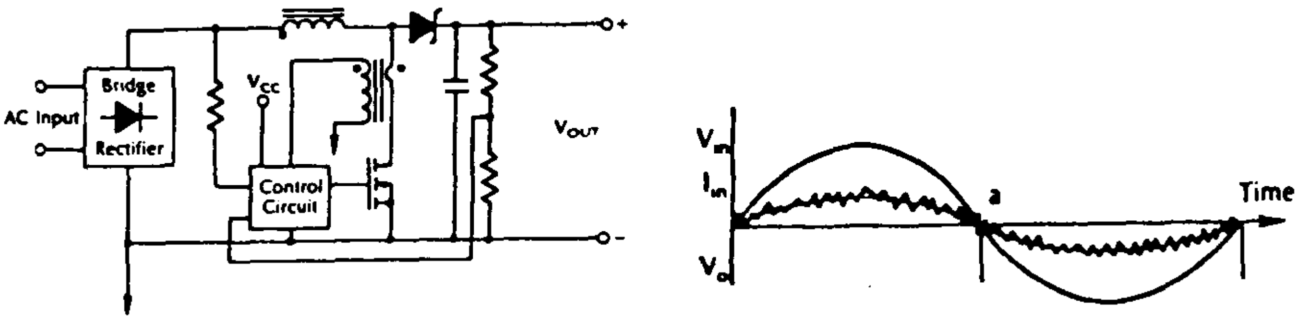


Figure 4: Phase shift between supplyvoltage Vm, lamp current
I and lampvoltage Vla in a discharge lamp withan inductive ballast.



a) b)

Figure 8: a) Simplified diagram of the active power factor correction circuit.b)Input current and voltage waveforms of circuit in a)