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HARMONICS FROM COMPACT FLUORESCENT LAMPS

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Abstract

Measured characteristics of compact fluorescent lamps (CFL) and incandescent lamps with diode type devices show low power factor (47% to 67%) and/or high total harmonic distortion (>100% THD). There is little effect on a building power quality if the CFL comprise less than 10% of the buildings load. Even if the load due to CFL is as high as 26% of the buildings total, the voltage distortion is less than 5%. Circuits along with estimated costs are presented that correct for power factor and suppress the harmonics.

Introduction

This paper presents some data on the performance of compact fluorescent lamps and other types of devices for use in incandescent sockets to improve the efficacy or reduce energy. These systems have low power factor and/or high total harmonic distortion (THD) and their impacts on the power quality is of primary concern. Utilities have also expressed concern since they have been actively recommending their use in their demand side management (DSM) programs through giveaways and rebates. At present no serious power quality problems have been reported with the use of CFLs. One reason may be that these lamp systems presently comprise a very small portion of the lamp market and are usually only a small portion of a building's load. However, if their use continues to escalate such that they are a major portion of a building's load, power quality may suffer. In fact, the poor power factor and/or high harmonics might limit the use of CFLs as an efficacious replacement for the incandescent lamp. Their potential impact on the power quality of the electrical load is simulated for a building where the lighting is initially 50% of the load and resistive (i.e., incandescent lamps with 100% power factor and no harmonics). The change in power quality is calculated after the incandescent lamps are refitted with CFLs.

While CFLs are generally cost effective, their high initial cost compared to the incandescent lamp has limited their acceptance. Thus, manufacturers have introduced the simplest ballast (magnetic and electronic) designs. These low cost designs employ neither power factor corrections nor harmonic filters. Several circuit approaches are described that could be used to reduce the harmonic content of these lamps and are discussed in terms of their cost and applicability for CFLs.

Experimental

New compact fluorescent lamps were obtained and burned in for 100 hours. Lamps were operated either at 60 Hz with magnetic ballasts or at high frequency with electronic ballasts. Light output was measured in an integrating sphere calibrated with a standard NBS lamp. The lamps were positioned base up when burned in and when measured to assure that the lamp's cold spot and mercury reservoir coincided. The lamps operated in this position provided maximum light output and efficacy[1]. The CFL characteristics measured included the light output, input power, voltage, line current and harmonics (fundamental up to the 32nd). In addition to the compact fluorescent lamps, incandescent lamp systems using diodes or triacs in series were also measured.

The building simulated assumed: i) total initial building load was 100 kVA at 0.85 lagging power factor, ii) lighting was initially 50% of the total load at unity power factor with zero harmonics, and iii) the CFL replacements have a THD of 115% (0.60 PF), the CFLs voltage and current are in phase and are four times more efficacious than the incandescent lamps.

Results

Lamp Performance

Tables I and II list the electrical and photometric data collected for the incandescent lamp systems and the compact fluorescent lamps, respectively. The incandescent lamp with the diode has high even harmonics because of asymmetry (dc component) while the lamp with the triac has high uneven harmonics (no dc component). The two incandescent lamps with diodes of opposite polarity are a resistive load. Table II shows that all of the CFLs tested had low power factors (between 47% to 67%). The low power factor of the lamps operated at high frequency is primarily due to high total harmonic content with some leading phase component. The ballast factor determines the lamp's light output and varies from a low of 62% to over 114%. The ballast factors for the electronic CFLs could not be obtained from measurements and were calculated using the manufacturers rated output for the lamps. It is essential for the lighting designer to know a ballast's ballast factor for the CFL in order to obtain a specified illuminance level. The data shows that CFLs operated at high frequency are sometimes twice as efficacious as CFLs operated at 60 Hz.

Building Model

Table III lists the power quality of the building when sockets were refitted with CFLs. When the CFL replacements were about 25%, the building's power factor was reduced by about 5%. When all of the CFL were installed (26.3% of the building load), the voltage distortion at the service entrance is still within the IEEE-519 recommended limits (5%). Figure 1 is a plot showing the impact of a harmonic source of 115% and 55% on voltage distortion as a function of its relative load. For a load with a THD just above 100%, the 5% voltage distortion limit is exceeded when the relative load of the CFLs is above 30%.

Method of Correction

Power Factor

Power factor correction and suppression of harmonic distortion go hand in hand. There are two methods for correcting power factor: passive and active methods. Simple power factor correction can be accomplished using a capacitor to shift phase angle until the line current and voltage are in phase, i.e., power factor = 1.0.

The electronic correction of power factor and/or suppression of harmonic distortion is more complex. The front-end of electronic fluorescent ballasts converts the alternating line current to direct current. This is accomplished using a full wave rectifier bridge followed by a filter capacitor. The bridge conducts during the period of the cycle when the line voltage exceeds the capacitor voltage. The effect is that current is drawn from the power source over a very short time, as shown in Fig. 2. The line current is no longer sinusoidal which results in the generation of harmonics. The amount of harmonic distortion is generally expressed as a percentage of the fundamental 60 Hz current and they are added in quadrature. European Standards (IEC 555-2) express the amount of harmonic distortion in absolute terms as the maximum permissible current allowed at each harmonic frequency.

Conventional Magnetic Ballasts

Most CFLs operated at 60 Hz employ uncorrected magnetic ballasts and suffer from a poor lagging power factor as shown in the Table II. In this case, a capacitor is added to the circuit to correct the power factor. A more elegant circuit[2] developed for the Navy's 20 W F20 T-12 lamp is shown in Fig. 3. This circuit not only corrects the power factor, but reduces the third harmonic to less than 3% for the 20 W F20 T-12 fluorescent lamp. This circuit could also be applied to the CFLs. While the slight extra size might limit applications that require adaptors that fit into the Edison sockets, there are many suitable hard wired CFL applications where the additional size poses no restraints.

Electronic Ballasts

With electronic ballasts, there are more methods available for correcting power factor and suppressing harmonic distortion. The obvious method of solving the harmonic problem is the elimination of the filter capacitor that causes the problem. Unfortunately, without the filter capacitor, the unfiltered dc is 100% modulated at 120 Hz. This modulated wave is undesirable for fluorescent systems since it reduces system efficacy and lamp life while increasing the lamp's flicker. The latter will be the source of stroboscopic and subliminal flicker effects. At present, most CFLs operated at high frequency employ no filtering, as evidenced by their large harmonic content.

Passive Correction Methods

Five methods of passive correction are described. Figure 4 shows a method using a tuned series LC network before the input bridge (L_1, C_1). The value of L_1 and C_1 is calculated to be between 2.5 to 3.0 times the line frequency. C_2 is the filter capacitor and can provide nearly ripple-free output depending upon the size of the capacitor. This circuit corrects the power factor and provides limited harmonic distortion improvements, meeting the current U.S. recommendations but not the current European standards. Placing the inductor before the diode bridge provides the power supply with considerable protection against line spikes and transients.

Figure 5 shows a parallel tuned resonant circuit similar to the circuit shown in Fig. 4. L_1, C_1 are tuned to the third harmonic and this circuit provides good power factor correction and limited harmonic distortion suppression. The main advantage of this circuit is that of cost and size and the attenuation of the third harmonic. The major disadvantages include virtually no attenuation of the higher harmonics, and a slightly more challenging task of building L_1 with acceptable levels of audible noise.

Figure 6 is a circuit similar to the circuit shown in Fig. 4 with L_1, C_1 placed after the bridge, which permits the use of smaller and cheaper magnetically biased inductor. This circuit provides good power factor correction but only limited improvement in harmonic distortion.

Figure 7 is a method of correction sometimes known as the "valley fill" circuit. It has adequate power factor correction and moderate amounts of harmonic distortion suppression. Capacitors C_1, C_2 are charged in series to the peak line voltage such that each will have one half the peak line voltage across it. When the line voltage drops below the 50% point, the capacitors discharge, filling the valley and preventing the voltage from going to zero. The load must be able to tolerate or compensate for a ripple of about 50%. The cost of this circuit is reasonable and the harmonic distortion levels are reduced by about 75%. Further improvements in the harmonic distortion are possible by putting an inductor in series with D_2. Also, a pair of input inductors or a balum should be used for transient protection and RFI suppression.

Figure 8 shows another variation of the previous correction method which allows for a substantial reduction in harmonic energy. This method is also resonant at the third harmonic but here the extra harmonic energy flows into the load and it is possible to use smaller components to accomplish the same end result. This circuit has the potential of meeting most European standards at reasonable cost.

Active Correction Methods

For the higher wattage CFLs, the size and weight of the passive corrective components increase significantly and corrections using active devices become more economically feasible. Figure 9 shows a circuit of correcting power factor with active devices. Although the circuit looks like a conventional switching regulator, the novelty lies in the fact that C_1 is very small and the line frequency ripple is filtered by a large capacitor C_3. The output voltage is controlled by the duty cycle of the switching frequency but, unlike other circuits, the duty cycle is held constant over each half cycle and changes only when the input ripple voltage is held to zero.

Figure 10 shows the same implementation of a fly-back or boost method of correcting power factor that is being used by many power supply companies who sell in the European market. Again, the output capacitor is large and the input capacitor small. For further information on active power factor correction, see U.S. patents 4,737,636, 4,277,728 and U.K. patents 2,024,544 and 2,124,045. Since these active circuits for power factor correction and harmonic distortion suppression can increase cost significantly, they most likely will not be used for the low wattage CFLs unless they are imposed by regulations.

Cost and Other Considerations

Table IV describes the relative cost and merits of implementing each of the above corrective scenarios. While there can be wide variations in cost between different manufacturers, one author's (WRA) experience has been that the simple power factor correction methods can be implemented for a direct labor and material cost of between $0.50 and $0.75 in 1991 dollars. The active schemes can be implemented for between $2.00 and $2,50. The reader should bear in mind that the specific costs are highly dependent on purchasing volumes, degree of factory automation and learning curve experience.

Discussion

Incandescent Lamps

The semiconductor devices in series with incandescent lamps are used in two ways. There are retrofit diode button types, that are placed in sockets or are incorporated in standard incandescent lamps, greatly extending lamp life. As shown in Table I the efficacy is also greatly reduced and becomes cost effective only if the labor cost to change a lamp is high.[3] Some special incandescent lamps are designed to be operated with a diode in series. The diode reduces the 120 volt input voltage to about 85 volts. This allows smaller size and lower resistance filaments that operate at a higher current (increasing filament temperature), permitting better optical control and higher efficacies with little sacrifice of life. Their effects on power quality has been described.[4] However, the results show that if these lamps are made with diodes of opposite polarity in a random manner, the poor power quality aspect will be greatly reduced.

CFL

In most commercial buildings where incandescent lamps are a small portion of the lighting load, power quality problems are unlikely to occur when refitted with CFLs. In the above example, the voltage distortion at the service entrance of the building was below the IEEE-519 voltage distortion limit when all the incandescent lamps were replaced. Another concern is the high harmonic triplens for the CFL since they will increase the neutral currents in three phase electrical distribution systems. Even if both the transformer and neutral wire are properly sized to carry the additional load the I^2R line and transformer losses will be increased. Care must be exercised to assure that these circuits do not become unbalanced by placing all the CFL retrofits on a single three phase branch, further increasing the neutral currents.

Today there are no power factor or harmonic standards for CFL systems. In fact, there are no harmonic standards for any gas discharge lamp system. The IEEE-519 Standard is only concerned with the harmonics for a complete electrical distribution system and not any particular component. There is a consensus by the ANSI Fluorescent Lamp and Ballast Committee for the four- and eight-foot fluorescent ballasts that recommends limiting THD to 32.5% and the third harmonic to 27.5%. Some utilities have offered rebates only for electronic ballasts that limit their THD to 20% or less. The electronic ballast manufacturers have responded to this challenge by introducing a low harmonic version at a slight increase in cost. In the future a similar approach may be taken by the utilities for CFLs or alternatively utilities may provide higher rebates as an incentive to help offset the higher cost of these low harmonic, electronically ballasted CFLs.

Summary

The measured performance of CFL and some rectified incandescent lamps will cause considerable harmonic distortion of the input power. This includes both the electronically and magnetically ballasted CFLs with poor power factors and/or high harmonics. The model of a building's electrical load indicates that there is little cause for concern for power quality problems when the CFLs are less than 25% of the building's total load. Several reasonable low cost passive circuits have been described that can improve the power factor as well as suppress the harmonic distortion. The use of active circuits will be more effective but more costly. The active methods are best considered for the larger wattage CFL (above 30 watts), and for special applications where minimum harmonics are required.

Acknowledgements

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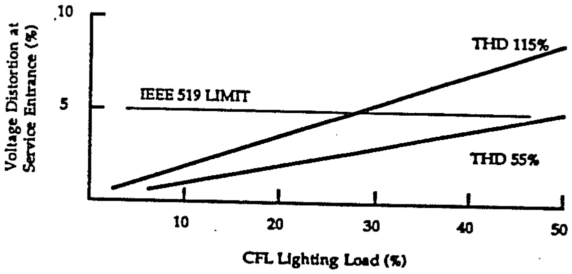

Figure 1. Voltage distortion vs. percent CFL load.

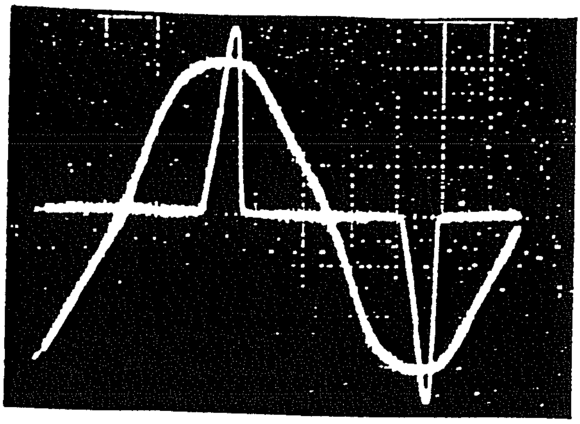

Figure 2. Typical voltage and current wave form for an IBM computer power supply unit. The sine wave is the input line voltage wave form and the spiked wave is the input current. - This produces extremely high harmonic distortion and the measurement will normally measure a power factor of .4-.6. The types of loses associated with this type of distortion can be significantly greater than the losses associated with the .5 power factor.

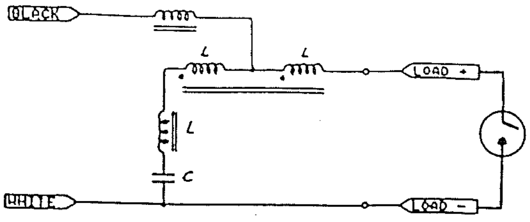

Figure 3. Power factor correction for magnetic ballast.

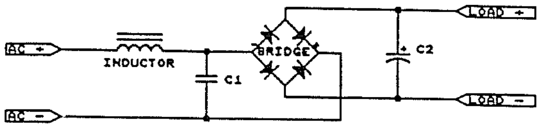

Figure 4. Passive power factor correction I.

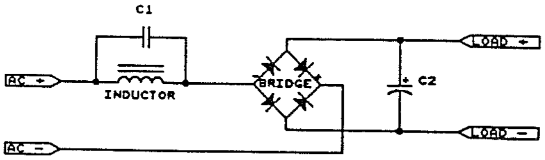

Figure 5. Passive power factor correction II.

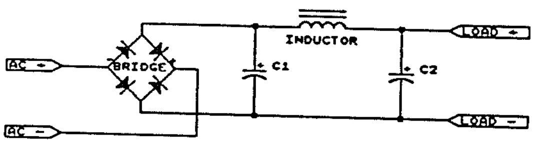

Figure 6. Passive power factor correction III.

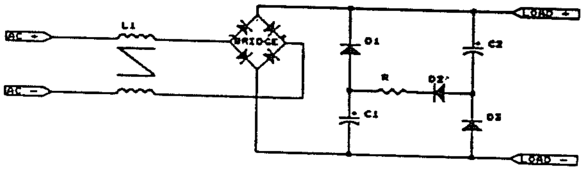

Figure 7. Passive power factor correction IV.

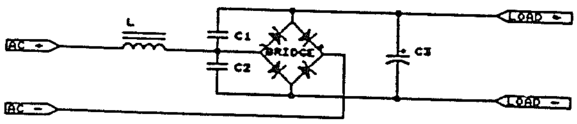

Figure 8. Passive power factor correction V.

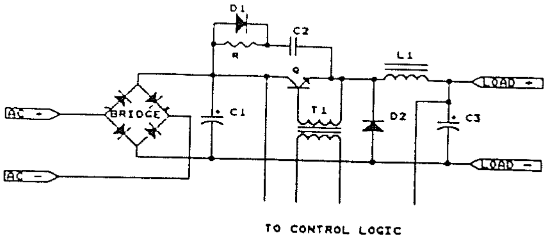

Figure 9. Active power factor correction I.

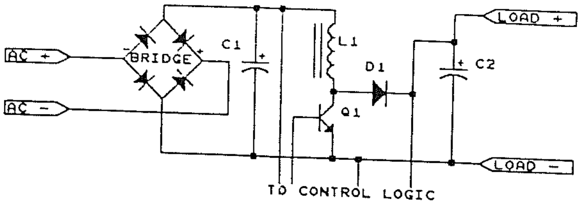

Figure 10. Active power factor correction II.

TABLE I. INCANDESCENT TYPE LAMPS

	100W	100W DIODE	(2) 100W * (2) DIODE	100W TRIAC
POWER (W)	101.3	85.5	175	88.5
CURRENT (A)	0.85	1.03	1.46	0.81
POWER FACTOR	1.00	0.70	1.00	0.92
LIGHT OUT (lm)	1740	780	1584	1290
EFFICACY(lm/W)	17.2	9.2	9.7	14.5
HARMONICS (%)				
2nd	0.1	39.5	0.1	1.8
3rd	2.9	3.9	2.5	22.2
4th	0.1	10.5	0.1	1.8
5th	2.0	1.5	1.8	14.2
7th	1.1	1.2	1.4	9.1
9th	0.4	0.5	0.6	5.6
THD	3.7	41.0	3.4	29.0

* Two 100 watt lamps with diodes in reverse polarity

TABLE II. COMPACT FLUORESCENT LAMPS

	60 HZ				HIGH FREQUENCY				
	7W	7W	15W	20W	20W	11W	15W	20W	20W
POWER (W)	9.5	9.3	19.7	20.3	20.3	10.7	14.3	17.8	23.3
CURRENT(A)	0.17	0.16	0.40	0.33	0.34	0.13	0.18	0.23	0.32
POWER FACTOR	0.47	0.50	0.41	0.51	0.50	0.67	0.65	0.64	0.61
LIGHT OUT (lm)	380	320	560	1040	1030	610	930	1040	1370
RATED LO (lm)	400	400	900	1200	1200	600	900	1200	1200
BALLAST FACTOR	0.95	0.80	0.62	0.87	0.86	1.02	1.03	0.87	1.14
EFF. (LM/W)	40	34	28	51	51	57	65	59	59
HARMONICS (%)									
3rd	8.1	8.6	17.8	12.4	15.3	79.4	81.3	64.5	79.1
5th	2.3	2.6	1.9	2.3	2.6	48.5	50.8	35.1	48.9
7th	1.1	1.3	1.3	2.2	2.2	18.4	20.6	40.8	30.5
9th	0.6	0.8	0.2	1.1	0.9	13.5	16.2	35.1	32.1
THD	8.1	9.1	18.0	12.5	15.7	100	106	98	114

TABLE III. 100 kVA BUILDING SIMULATION LOAD

	Percent Retrofit with Compact Fluorescent			
	10	25	50	100
TOTAL HARMONICS (%)	1.7	4.5	9.8	23.5
TOTAL POWER FACTOR	0.84	0.82	0.78	0.65
% CFL LOAD	1.5	4.1	9.4	26.3
VOLTAGE DISTORTION (%)	0.3	0.7	1.5	4.4

TABLE IV: COSTS, SIZE OF CORRECTIVE CIRCUITS

CIRCUIT	COST	SIZE	COMPLEXITY
Figure 4	Lowest	Largest	Minor
Figure 5	Low	Large	Minor
Figure 6	Low	Large	Minor
Figure 7	Moderate	Large	Medium
Figure 8	Low	Large	Minor
Figure 9	Highest	Small	Major
Figure 10	Highest	Small	Major