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Power Quality Implications Of Compact Fluorescent Lamps In Residences

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Overview

There continues to be a growing proliferation of high reliability, low cost electronic products that can represent non-linear loads from a power systems point of view. These products include entertainment devices such as TV's, VCR's, and audio equipment; information technology devices such as PC's, printers, and fax machines; variable speed motor drives for HVAC, and white goods appliances; food preparation and cooking products such as microwaves and cooktops; and lighting products, which include electronic ballasts, compact screw-in fluorescent lamps (CFLs), and other power conversion devices that operate a variety of lamps.

The drivers that have resulted in this proliferation are a direct result of the availability of low cost switch mode devices and control circuitry as well as the benefits that such technology can bring to end users:

- Lower operating costs
- Energy cost savings
- Short economic paybacks, often under two years
- More features, improved performance
- Size and weight reduction
- Improved form factors
- Pollution reduction from fossil fuel generation of electricity

The proliferation of such products results in an increased growth of so-called non-linear loads from a utility point of view. Products with non-linear loads are not new- but it can be argued that we have entered a period where the growth will be unprecedented in all major end-use segments: residential, commercial, and industrial. This growth has led to an increasing concern by some utilities on the effects from such loads on power quality. While some utilities are more concerned than others, it is fair to say that even utilities that are centrist on such issues are spending more effort to instrument their service areas so that they can monitor THD(V) in an attempt to correlate end user and system disturbances with the increase of such loads within their service areas.

While at the highest levels, utilities are concerned with distortion to the voltage waveform that they supply to their customers, they are also concerned with the effects of non-linear loads on their distribution infrastructure, which can include capital equipment and added heating losses within the systems. Some are concerned with disturbances that may occur within the premises of their customers since such customers may attempt to fix the blame for local interaction problems on the power quality as supplied by the utility.

This paper will not go into detail on the fundamentals of the above issues, There are dozens of relatively recent papers that can be referred to for various treatments of this subject from a utility perspective. This paper seeks to put into perspective the subject of CFLs and power quality in a manner that has not been discussed previously, and that will explain why the implications presented by CFLs from a power quality perspective are not as severe as some have postulated.

Scope

This paper will concentrate primarily on the implications of non power factor corrected "screw in" CFLs in residences and on residential power quality. Utilities are often internally conflicted on this issue. The engineering departments tend to be conservative, since they are entrusted with the reliability of the system. Accordingly, they also tend to be risk averse on power quality issues, even when the loads are small and experience indicates that problems have yet to occur with such products as non-power factor corrected CFLs (also called normal power factor by some; but in this paper the terms low power factor or non-power factor corrected will be used interchangeably). This paper presents some recent work that has been done using CFLs in aggregate and with other loads to try to better understand why non- power factor corrected CFL usage has not posed a problem in the last two decades, and particulalry in the last decade when costs have become reasonable and products have made inroads into the residential market place. It is also hoped that this paper will help to justify why utilities should not hesitate to endorse all CFLs, even non-power factor corrected versions over the next several years, as work continues to evaluate and understand aggregate effects..

Benefits of CFLs

A brief review of CFL benefits is helpful to set the stage. CFL's use approximately 25% of the power that would be consumed by an equivalent light out put traditional incandescent lamp. End users and energy advocacy groups realize the savings this can represent in both energy costs and the preservation of natural resources. Such performance provides benefits for utilities who are often looking for ways to reduce connected load or for strategies that can help slow the rise in overall demand. Hence the sometimes conflicted utility dilemma. One department may want to promote low cost, non-PF corrected CFLs at the same time another department cautions against the possible detrimental effects to system power quality.

Since the technology used is fluorescent, which has a much longer innate life than incandescent technology, the CFLs easily achieve rated lifetimes that are 13 times longer in use. This feature alone often convinces the end user to try CFLs in "high usage" applications despite their high initial cost.

As opposed to earlier models, today's CFLs product light outputs equivalent to the most popular incandescent types. Improved color has removed some of the aesthetic objections for residential use, although the size, appearance, and color are still barriers for many residential decision makers, as is initial cost.

Since non- PF corrected CFLs draw about half the RMS current as their full wattage incandescent counterparts, CFL loads reduce current loses that occur throughout the distribution infrastructure, both on the utility side and within the users premesis.

Power Quality Aspects of CFLs

Let us then review *all* the power quality aspects of non-PF corrected CFLs. (This paper concentrates on this category since it is these CFLs that are the lowest in cost and represent the best opportunity for consumer acceptance.)

Efficiency/Energy Savings	Power use reduced to 25% of the equivalent incandescent bulb Reduced "I squared R" distribution losses throughout the electrical infrastructure
Power Factor	Lower than for an incandescent bulb; typically 0.5 for low or non-power factor correced types. Some power factor corrected models range from 0.8 through PF greater than 0.9
Harmonic Currents, THD	Greater than an incandescent lamp; THD(f) for current is typically 150% with some as high as 175%. Harmonic currents are on the order of 15ma per watt. "Low distortion" CFLs have THDs less than 32%, but costs for such system drive up price, increase size, and reduce product performance to some degree.

A Perspective

Given the above, what is the problem? Today's CFLs are more reliable, lower cost, smaller, more attractive, have higher performance than ever before. They have an overall excellent 20 year history in both residences and commercial installations. Manufacturers are aware of no power quality problems either within installations or at the distribution level from such products. Virtually the entire installed base of screw-in CFLs is of the low power factor version (PF approximately 0.5) and with input current THDs in the 150% range.

Yet, these CFLs are still often swept into the general debate on power quality that rages today and are sometimes not endorsed by utilties for incentive programs.

Is this concern justified? The answer is certainly "no" today. There are simply *no* problems that can be attributed to this distributed load throughout residences, even in regions of the country where energy rates are high and where there is reasonable product demand.

Let us review why this is so today, put this in context for the next several years, and then discuss what the implication may be for the future. First we must review how CFLs are actually applied in residences.

Residential CFL Application and Use

Power system engineers are generally familiar with loads that replace equivalent loads even when the technology is upgraded. A more efficient 1/2 HP motor drive still drives a 1/2 HP motor. CFL usage is very different. CFL manufacturers did not design CFLs to use the same energy as the incandescent lamps that they replace. The vast majority of CFLs are designed and used to replace an incandescent lamp at approximately the same *light* level since it is the light level a consumer seeks. Unlike most other non-linear loads, both end users (local environment) and utilities (PCC and back into the distribution system):

- See much lower power consumption per lamp replaced (25% of incandescent wattage).
- See much lower RMS current draw oer lamp replaced, even for low or non-PF corrected CFL products.
- Benefit from reduced I squared R losses
- See only a small increase in harmonic currents (mA/watt)

Power Factor

Let's break down the two most popularly discussed elements of "power quality", namely, PF and harmonic currents/THD for CFLs. It can be shown that even a low PF CFL draws much less total RMS current than the incandescent lamp it replaced. This means that if we only consider PF, a low PF CFL actually has better "power quality" from an RMS current demand perspective than the original incandescent lamp with its 1.0 PF! This is shown dramatically in **Figure 1**. Note that the CFL PF could degrade all the way to 0.3 and still draw less RMS current than the original 100 watt incandescent lamp it replaced.

The only way PF would be an issue would be if CFL manufacturers produced lamps with the same equivalent wattage level as the incandescent lamp it replaced.....however this would provide no user benefit and would not be accepted.

Low PF is not an issue for residential screw-in CFLs.

Harmonic Currents and THD

Screw-in residential CFLs pose no threat to either the utility system or to the local premises environment.

CFLs represent a very, very small portion of the residential lighting load, even in concentrated urban areas. Fewer than 20 million screw-in CFLs are sold annually in the United States, and this includes the commercial sector. The market is not growing at a rapid rate. The largest portion of the CFL market today is represented by the plug in CFL and that is predominately used in dedicated commercial luminaires. True, screw-in CFLs will grow in residences, but relatively slowly, and certainly not in any respect close to the penetration levels that would compete with the literally ***billions*** of incandescent lamps sold into residential households every year.

The average power level of such CFLs sold into residences is approximately 20 -25 watts. This is four time lower than a modern TV or PC. The worst case third harmonic current associated with such a CFL is approximately *200 milliamps*. There is no direct evidence that such harmonic currents circulating within a local residential branch circuit are problematical. Other consumer products have circulated such currents for decades. There is no direct evidence that even aggregate CFLs produce aggregate harmonic currents that have caused problems with local low voltage utility transformers that serve multiple residences, or that such harmonic currents result in unacceptable voltage distortion on either the primary or secondary side of the residential service transformer, or that such CFL harmonic currents from residences cause unacceptable THD(V) levels at locations upstream from the residence.

Supporting Data

Furthermore, the data taken on both a typical commercial branch circuit and at the load center in a typical residence show that the addition of other types of loads commonly found in residences dramatically swamps out or dilutes any possible component of harmonic current provided by the lower power CFLs. See Figures 2, 3, and 4 for typical results. While the specific results will vary with local line impedances and internal residential circuit impedances, the overall effects are indicative of what typically happens today, and helps to explain why such products have not caused problems. (Note, too, that this behavior will be typical of any non-linear load with the same input characteristics of non-PF corrected CFLs. Many non-linear power supplies have this characteristic, such as power supplies for TVs and PCs.)

Figure 2 compares a single CFL and its singular current THD(f), and the effect that can occur when multiple CFLs are applied down stream on a branch circuit. As additional loads were added, of various types, the THD was reduced still further. While the addition of such loads is not predictable, the overall effect is nonetheless real and helps to explain why real world systems have not typically encountered any problems. Since most residential loads are still linear or quasi-linear, and can be relatively large in comparison to CFLs, it is logical that a CFL or even several per household would should not casue any immediate issue in the local environment. The test set up for Figure 2 was a laboratory simulation of a relatively high source impedance presented to a relatively long branch circuit. It can be seen that as even one 250W incandescent load is added to multiple CFLs that the incandescent or linear load predominates. Although one could argue that the harmonic currents are merely being “masked” by the linear load currents, one must consider that any resultant voltage distortion is still in some manner related by a transfer function to the total current THD.

Figure 3 depicts the reduction in THD as other relatively small loads are added in the simulated laboratory environment. A desk fan and incandescent loads are shown by themselves to provide some indication of their their individual linearities.

Figure 4 shows the measured power factor for the same exact combinations of loads presented in Figure 3, and demonstrates the improvement in system PF that occures simultaneously as system THD(i) improves. It should be noted that moderately high aggregate power factors are achieved at moderate THD levels.

Figure 5 depicts the current waveform from one type of screw-in compact fluorescent. It is a relatively classical shaped current waveform for this type of load. Note that as additional identical product loads are added (**Figure 6**), that one cumulative effect is a “filling in” of the current drawn from the branch circuit. This reduces the overall THD and increases the aggregate PF even before additional non-CFL loads are considered. It is very likely that this effect is even more pronounced in the field when multiple non-linear loads from different product designs interact in an aggregate basis.

Figure 7 shows the combined current waveform when ten 23 watt Genura reflector EFLs (a non-electroded version of a CFL) are operated along with a single 250 watt incandescent lamp. Additive aggregate effects for various harmonic currents can be seen in **Figure 8.** Most interesting is the aggregate effect as harmonic order increases. The additive effect is not uniformly linear as harmonic order increases and actually shows an apparent reversal as harmonic order exceeds the ninth harmonic. This data also shows why setting harmonic limits above the 9th or 11th harmonic may turn out to be overly burdensome for many products.

In another set of experiments, aggregate and interactive effects were observed in an actual residence. In this case the measurement point was chosen to present the most pessimistic situation within the residence, directly at the bus bars of the residential load center. It is here that the impedance presented by the power supply is lowest, and is closest to that which would be found at the residential LV side of the local distribution (pole) transformer.

Figure 9 demonstrates that when the THD of the aggregate current is measured directly at the load center, the THD remains constant as additional CFL loads are added. This would be expected since at this point the distribution source impedance is very low. However, even a single typical refrigerator reduces the overall system THD and increases its power factor significantly. Even more interesting is the effect of moving the location of the aggregated CFLs to a more distributed configuration on the first floor. In this configuration, the aggregate THD at the load center is reduced compared to locating the aggregated CFLs directly at the load center. This indicates that distributed effects may represent still another beneficial field mitigation.

Clearly the major conclusion that can be drawn from even this limited series of experiments is that there is significant mitigation that occurs for low powered non-linear distributed loads in residences. Although this testing was concentrated on CFLs, it is exepected that similar effects would be found for TV sets, PCs, audio systems, and other laods that are relatively prolific in total, yet have not directly been the cause of problems up to this point in time.

There is every reason to suspect that effects of the type measured in this paper would also be measured directly at the residence side of the local utility pole transformer as devices cycled on throughout the adjoining residences, although such measurements were not made due to the inherent difficulty and liabilities that could be incurred from such testing.

Models versus Data Monitoring in the Field

Models are useful tools that can sometimes assist in an attempt to understand complex phenomena, but models are not able to, in themselves, adequartely predict the disturbances attributed to small non-linear loads such as CFLs. For such models to be reasonably accurate, the models would need to incorprate the transfer functions that would accurately describe how CFLs act in aggregate fashion, how CFLs interact with other linear and non-linear loads, how CFLs interact under a variety of local impedance situations, and how aggregate local system effects translate to the PCC on both sides of the local LV transformer. While such a model could probably be constructed, it would take a great deal of validation testing with field devices to in fact properly qualify such a model. The use of incomplete models can and probably lead to overly conservative predictions regarding the cumulative effects of low power non linear loads such as CFLs.
Such models should not be relied on as the sole basis for utility policy decisions that deal with approving or endorsing low wattage, low power factor CFLs.

Rather, utilities would do better to spend resources instrumenting residential (and commercial) areas to monitor current and voltage THD in an attempt to correlate any increase in THD levels with either real or perceived customer or utility problems attributed to THD and harmonic current content. Granted, models may be less expensive to operate than a monitoring program, but only field data over time will conclusively demonstrate if there is a problem with harmonic currents.

As a follow on to the kind of initial work performed for this paper, it is suggested that a joint industry/utility series of field tests should be devised that would better quantify the levels and types of mitigation that such aggregate and diverse load factors provide.

Conclusions

Currently available CFLs do not pose a power quality problem for users or utilities. Experience indicates that utilities should not hesitate to fully recommend both low and high power factor screw-in CFLs for residential customers and incentive programs, realizing that most user/consumers will continue to prefer the lower priced non-PF corrected models. Taken together, the benefits of such CFLs strongly outweigh any perceived near term risks from power quality issues. Data presented in this paper underscores why there is very little risk for utilities to endorse such products in the near term.

Both utilities and manufacturers need to stay close to the power quality subject and to work cooperatively to develop future national and international standards that set harmonic and/or PF requirements for products and systems. As the use of non-linear load products continues to grow, and as higher power devices are developed, future potential problems can best be avoided by developing and adopting fair, reasoned, practical requirements for key product sectors, including lighting. There is no compelling argument that can be made for the implementation of immediate, severe harmonic limits from low power distributed non-linear loads. Any requirements applied to products should be based on actual field data, not strictly from models, and implemented in a time phased, trial use and review fashion.

Neither manufacurers, policy makers, utilities, nor mutual customers benefit if real future power quality problems develop in the residential sector.

While such work continues, utilities are advised to accept an interim requirement for low wattage CFLs ($P < 75W$) that would require PF to be equal or greater than 0.5. This sets a minimum PF that has proven historically acceptable and ensures that any new products must at least meet this minimum requirement. Until the national and international work is completed on harmonic limits for North America no THD requirement should be imposed.

Postscript

CFLs in Light Commercial Applications

This white paper specifically deals with the implications of CFLs in residential use. However, many of the conclusions could be applied as well to commercial applications where there is a reasonable mix of linear and non-linear loads or where low PF CFLs would not be expected to be the predominant load. For example, using screw in low power factor CFLs in hotels, motels, and retail stores have not proven to create any power quality issues for users or utilities since the CFL loading tends to relatively small compared to other loads—HVAC (motor loads), additional incandescent and halogen lighting (particularly in commercial establishments), ovens (food preparation), and so forth.

For applications where higher quantities of CFLs would be specified, and where the load would be a higher proportion of the total connected load, it would be expected and recommended that luminaires designed for pin-based (plug-in) CFL lamps and separate ballasts be used rather than screw-in CFLs. Ballasts for such applications, which are designed for heavy commercial use and which are typically supplied with the luminaires (fixtures), are readily available in high PF (PF equal to or greater than 0.9) low THD (less than 32%) versions. In addition, such commercial grade CFL systems generally will provide improved performance and aesthetics since the luminaires are optimized specifically for such systems.

CFL Power Factor Implications - an Example

$$PF = \frac{\text{Power Consumed in Watts}}{\text{Voltage x Current}} \qquad \left[P = VI\ ,\ \ I = \frac{W}{PF \times V} \right]$$

Compare: P.F. Implication of a 25W CFL, 100W Incandescent Bulb

Voltage (RMS)	Power (Watts)	P.F.	25W CFL Current Draw A (RMS)	100W Inc. Current Draw A (RMS)
120	25	1.0	0.208	0.833
120	25	.9	0.231	
120	25	.8	0.260	
120	25	.7	0.298	
120	25	.6	0.347	
120	25	.5	0.417	
120	25	.4	0.521	
120	25	.3	0.694	
120	25	.2	1.042	
120	25	.1	2.083	

- **25W CFL Draws 0.5A Less Than 1.0 PF 100W Incandescent**
- **25W CFL @ 0.6 PF Has Greater "Power Quality" Than 100W A Line**

Figure 1

THD From Mixed Loads

Load Combination	THD (I)
1 23W EFL *	170%
11 23W EFLS	143%
11 23W EFLS + 1 250W INC	73%
1 23W EFL & 1 25W HPF CFL	67%
1 23W EFL + 1 25W HPF CFL + 1 95W INC	23%
1 23W EFL + 1 250W INC	13%
1 250W INC	1.5% (Ambient)

Note: * Low P.F., 120V, 23W, 1190 Lumen GENURA EFL

Figure 2

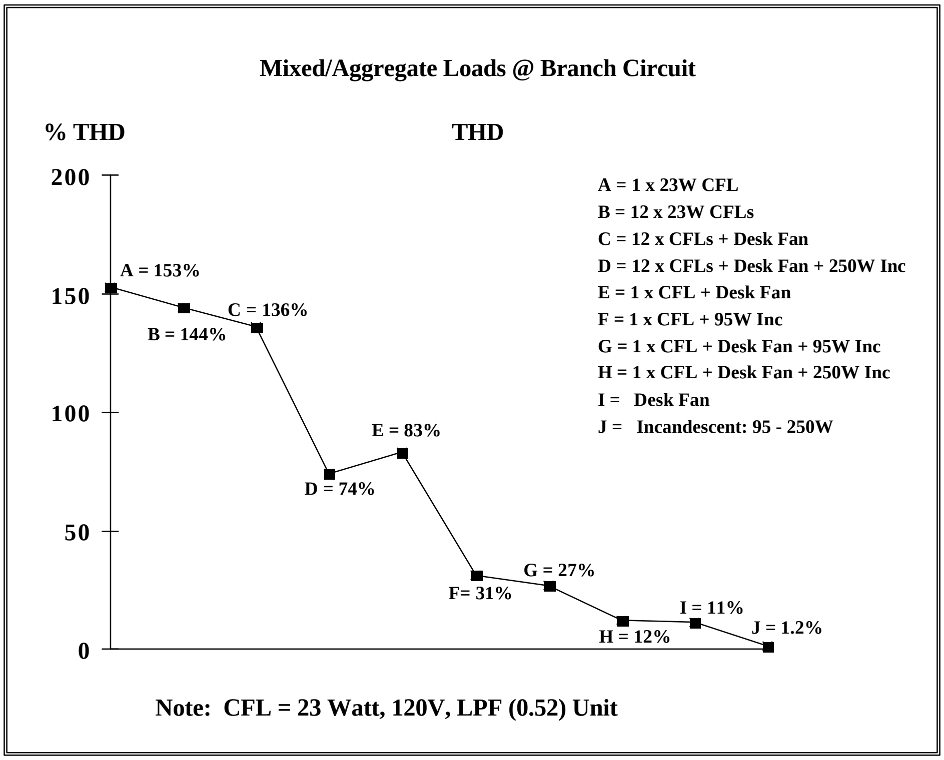

Figure 3

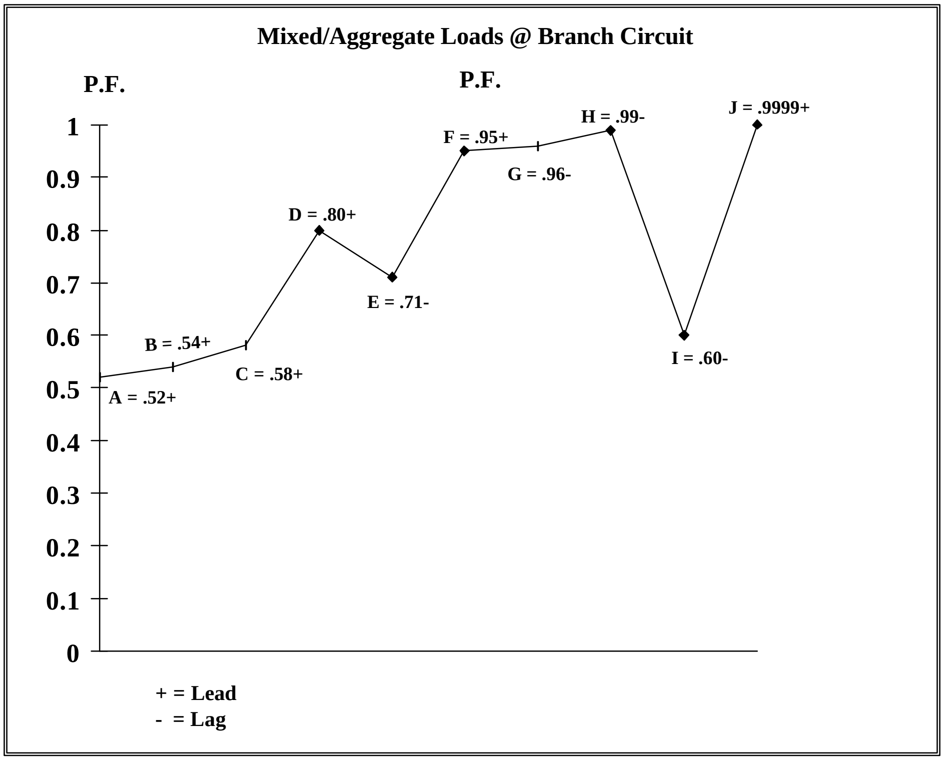

Figure 4

Single 23W LPF GEL GENURA EFL 120V/60HZ

FIGURE 5

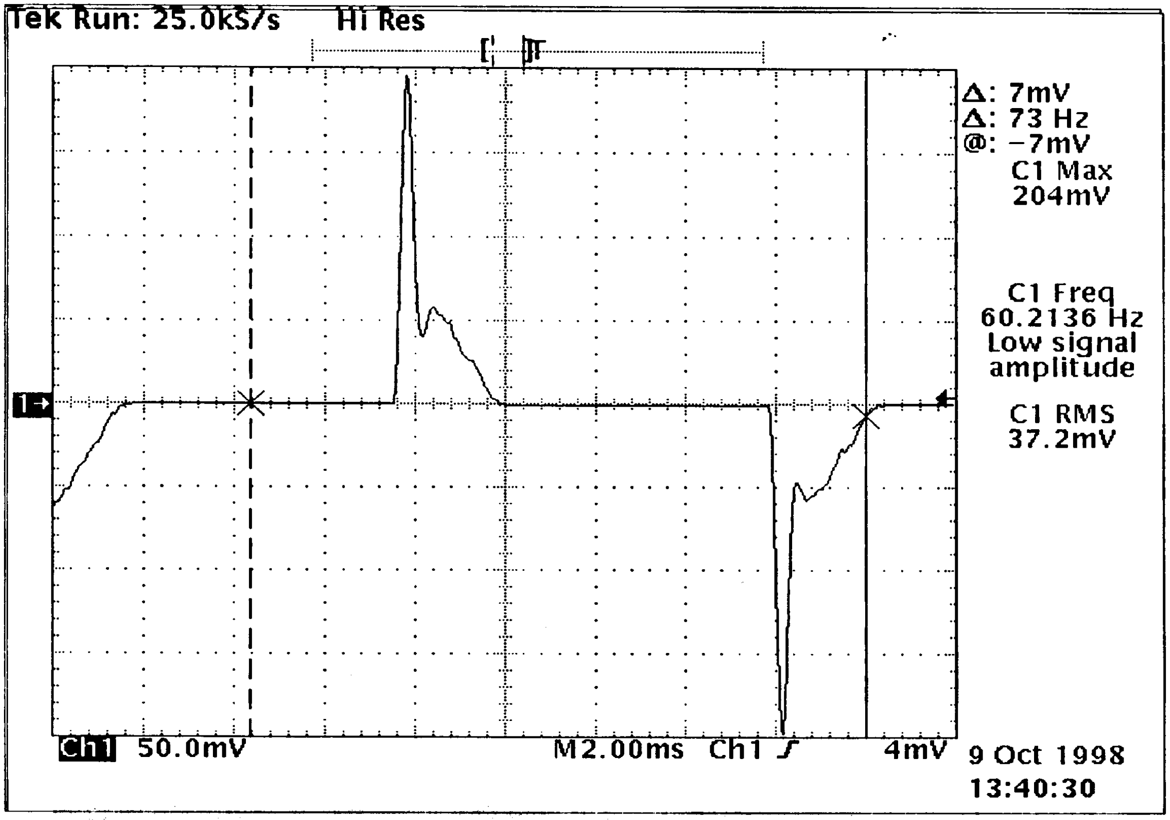

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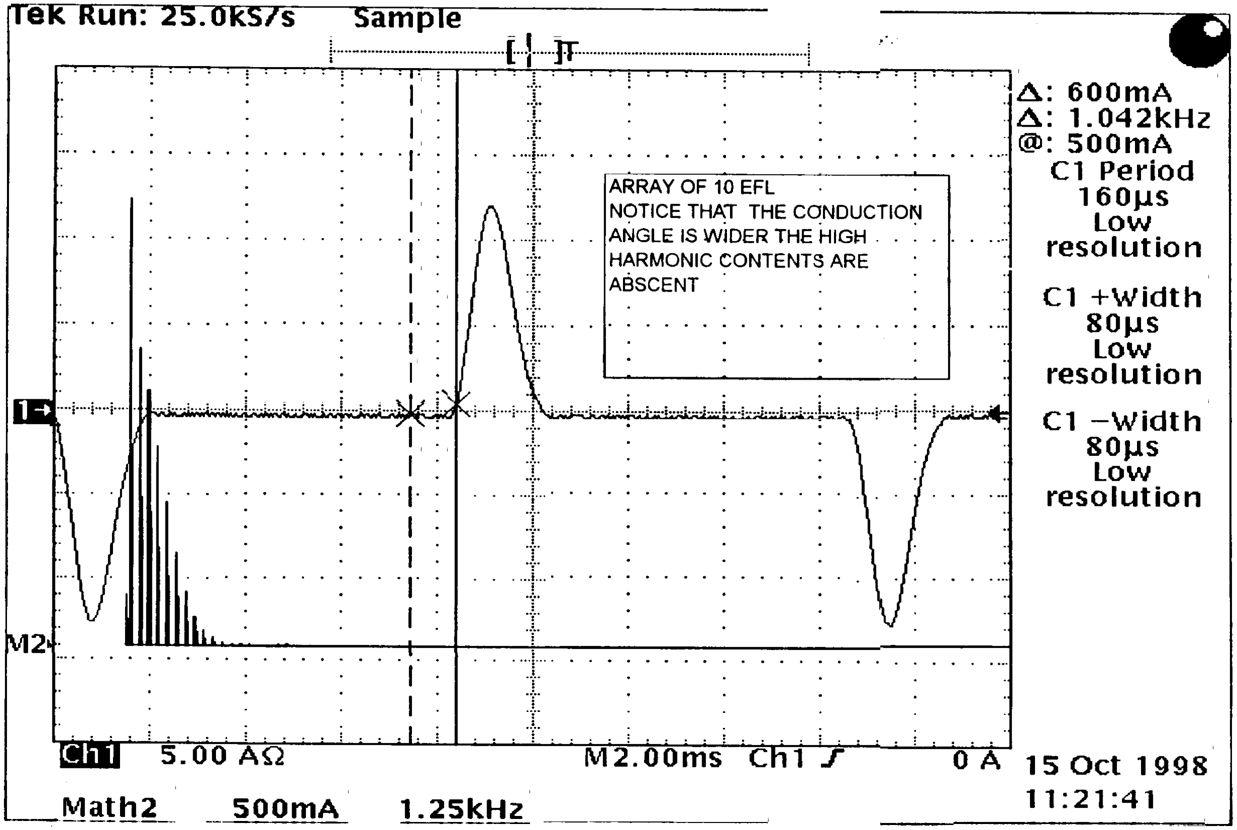
FIGURE 6

Ten 23W LPF GEL Genura EFLs 120V/60Hz



ARRAY OF 10 EFL
NOTICE THAT THE CONDUCTION ANGLE IS WIDER THE HIGH HARMONIC CONTENTS ARE ABSCENT

FIGURE 7

Ten 23W LPF GENURA EFLs + 250W Incandescent

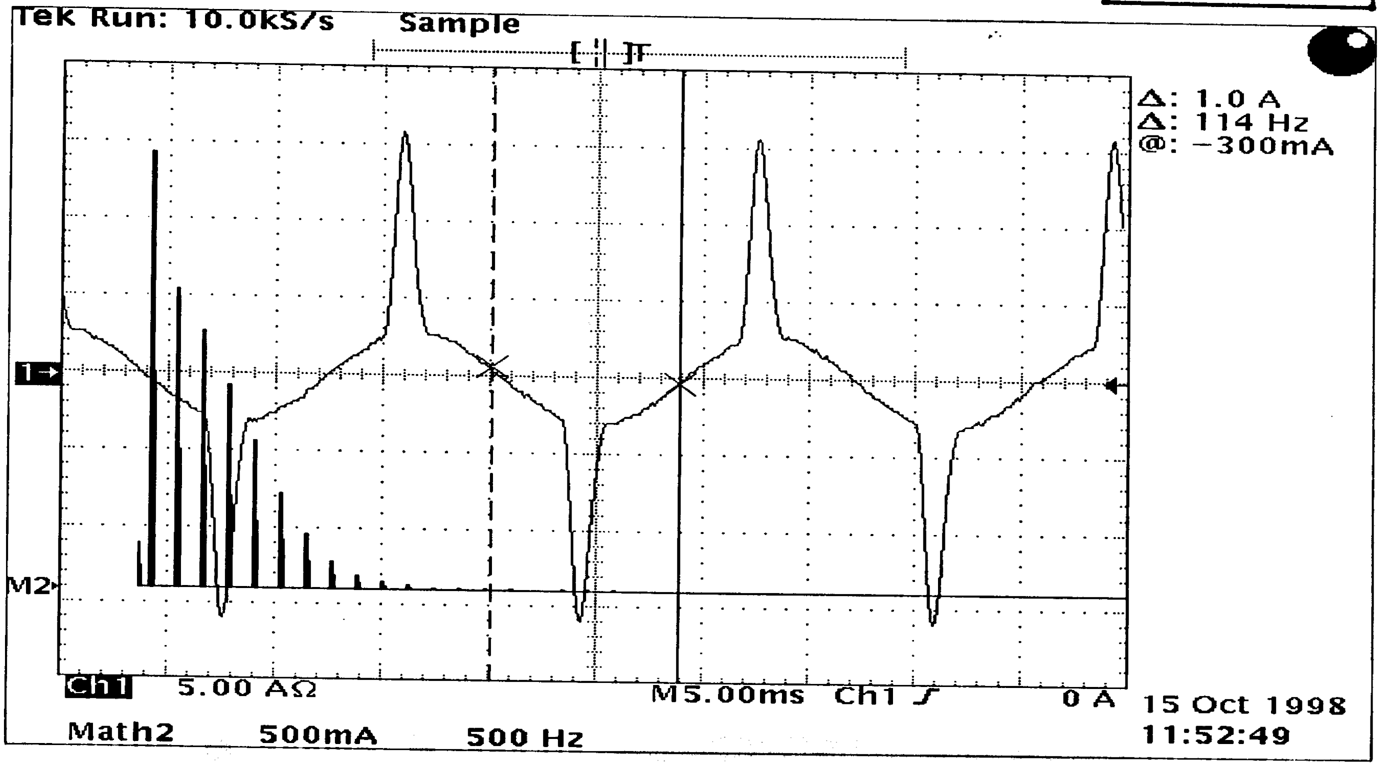


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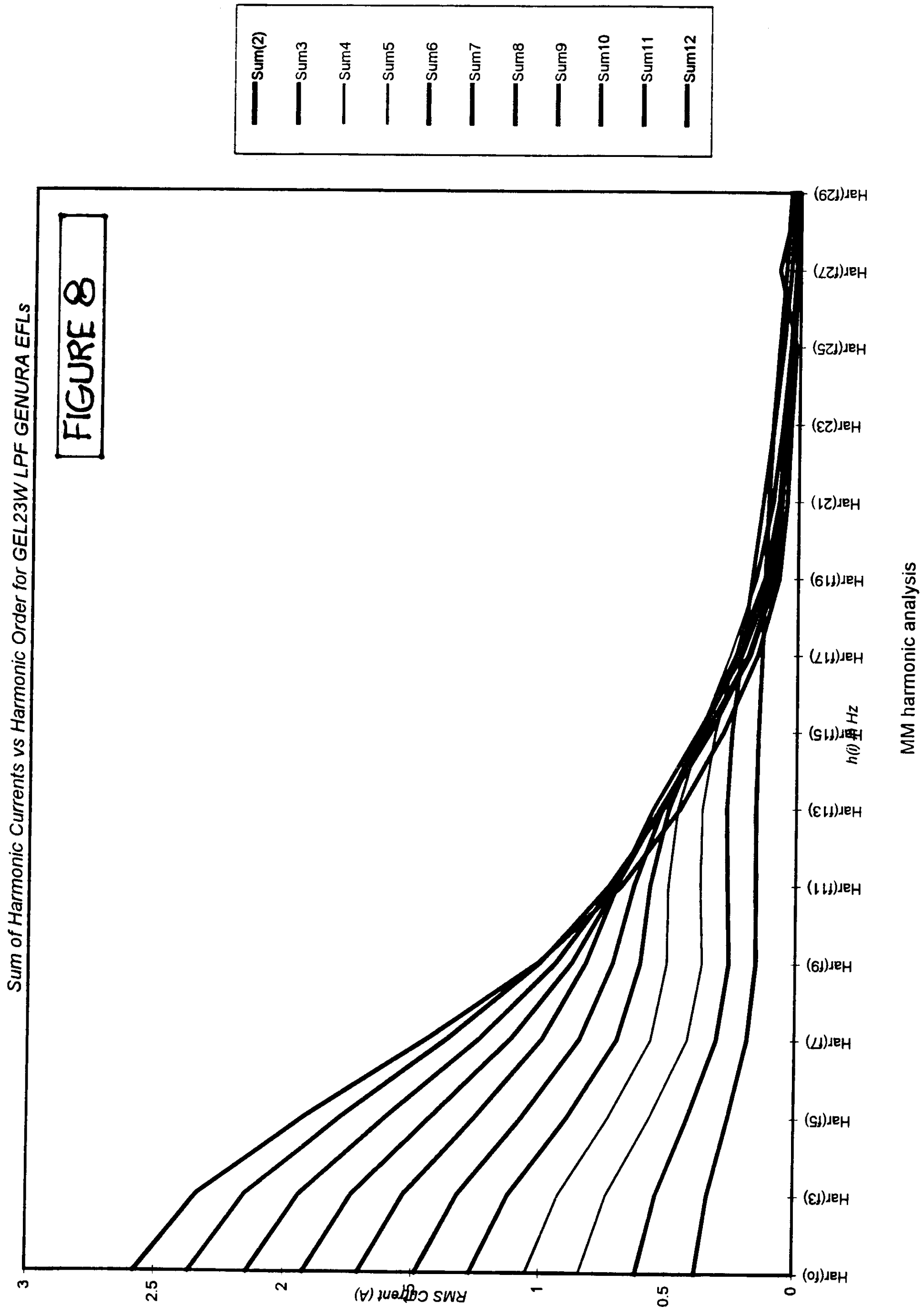
FIGURE 8


Sum of Harmonic Currents vs Harmonic Order for GEL23W LPF GENURA EFLs

Typical Lighting Load Characteristics

Aggregate Field Effect Implications and Typical System Mitigation

	% of 60 Hz Fundamental I										PF	THD
Load Control	3	5	7	9	11	13	15	17	19	21		
-1 LPF CFL @ LC	87	68	51	42	40	35	28	23	22	21	.51	153%
-8 LPF CFL @ LC	87	70	55	46	42	38	31	24	19	16	.52	154%
-1 Refrigerator	17	10	6	3	1						.94	21%
-8 LPF CFL 1st Floor Scattered Plus Refrigerator	32	18	10	7	7	7	5	4	3	3	.91	41%
-8 LPF CFLs Only, 1st Floor Scattered Plus Basement Lights	49	26	15	11	11	11	8	6	5	4	.84	62%
+Plus 2 Refrigerators	17	9	6	3	3	3	3	2	2	1	.90	22%
+Plus 1500W Space Heater	11	4	3	2	2						.99	13%
+Plus Clothes Dryer	6	3	2	1							.99	8%

Figure 9