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Load Shedding Ballast Specification

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Sacramento, CA 95814

Submitted By:
Architectural Energy Corporation
2540 Frontier Avenue, Suite 201
Boulder, Colorado 80301

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Contact Information:

Subcontract Project Manager
 Andrew Bierman
 Lighting Research Center
 21 Union Street
 Troy, New York 12180
 518-687-7128 voice
 518-687-7120 fax
bierma2@rpi.edu

AEC Program Director
 Judie Porter
 Architectural Energy Corporation
 2540 Frontier Avenue
 Boulder, Colorado 80301
 303-444-4149 voice
 303-444-4303 fax
jporter@archenergy.com

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Load Shedding Ballast Specification

Introduction

This document, prepared by the Lighting Research Center, provides the specification for the load shedding ballast under the PIER LRP Project 3.2 Energy Efficient Load Shedding Technology.

- What:** A ballast specification for reducing power demand by dimming fluorescent lighting (T-8 lamps) from a centralized point of control.
- Why:** To manage load on the electrical grid. Used by electricity suppliers/grid operators as a substitute for power generating resources in times of critical peak system demand, and for managing demand at any time for more efficient system operation and risk avoidance.
- How:** Dimming and/or switching T-8 fluorescent lamps to reduce luminaire power input by 33 or 50 percent (%), and aggregating those loads via a building-wide signaling system. There are two scenarios for control of dimming:
- **Scenario 1.** Dimming is controlled by the electricity supplier/grid operator via remote signaling and distributed automatically to the luminaires (i.e., ballasts). Dimming times and payments are determined through negotiated contracts between the utility/grid operator and electricity customers. Payments to customers are based on minimizing the customer's electric demand while reducing operating risk for utility/grid operator.
 - **Scenario 2.** Dimming is controlled by the building owner/manager and used as a load management resource to limit peak electrical demand, resulting in lower electrical demand charges. An automated system that tracks electrical demand and initiates load shedding is envisioned.
- When:** As needed, up to a maximum of 100 hours per year of lamp operating time.
- Where:** The technology is applicable to all commercial/industrial (C/I) applications except where light-dependent critical tasks or processes are conducted (e.g., hospital operating rooms).

Performance Specification

Physical

- Same size and form factor as a standard ballast
- Wiring connections and number of wires identical to standard instant-start ballast

Energy and electrical

- Ballast efficiency factor
- Ballast factor: 0.77 to 0.9 (157 to 188 mA full output, 105 to 125 mA dimmed)
- Power quality: THD < 20%, PF > 0.9 for normal and dimmed operation

Dimming

- Dimming rate: -10% per second < Rate < -0.3% per second measured with a 50 Hz upper frequency response (basically, a ramp function dimming over a period of 3 to 120 seconds with no abrupt changes visible to the human eye)
- Always start lamps at full nominal power level (100%) and maintain that level for at least 20 seconds
- Default mode (in case of signaling error) is full nominal power level

Signaling

- Power line carrier (PLC) signal
 - ASK modulation with 100% modulation depth (carrier present/absent)
 - Modulation frequency: 7.5 Hz (1/8 of a.c. line frequency)
 - Modulation phase: synchronized to 60 Hz a.c. line frequency with phase shifting by one 60 Hz cycle (16.67 ms) every 4 seconds (In 3-phase systems, two of the phases will be a constant 120 degrees out of phase with the modulation frequency, and this is acceptable.)
 - Carrier frequency: 45 kHz \pm 3 kHz
- Begins and sustains load shed in the presence of signal triggers; sustains nominal light output in the absence of signal triggers. (The default condition with no signal present is, therefore, full light output.)
- Receiver characteristics
 - Sensitivity: Operates for signals in the range from 5 mV rms to 5 V rms (60 dB range)
 - Response time: 180 seconds
 - Noise/interference rejection
 - Guard against false triggering
 - Detection in the presence of noise (white, impulse and harmonic)

Justification and Discussion of Performance Specification

Physical size

To fully capitalize on load-shedding opportunities for fluorescent lighting, it is important for a load-shedding ballast to easily substitute for a standard ballast and fit within the confines of different luminaire styles. In the U.S., most ballasts for T-8 fluorescent lamps conform to two basic shapes: the standard “brick,” measuring 9.5x2.375x1.5 inches, and the smaller profile, measuring 9.5x1.7x1.18 inches. Both sizes have the same size mounting brackets, but many luminaires require the smaller, lower profile ballast size so the luminaire can have a smaller profile as well. The industry trend is toward making things smaller, and luminaire manufacturers are quick to capitalize on this trend when designing new luminaires. Any increase in the size requirements for a load-shedding ballast would limit its appeal and applicability for certain luminaire types.

The additional circuit components needed for load-shedding ballasts are small and would require less than 0.5 watt additional heat management. Instant-start ballasts have fewer components than other ballast types; therefore, if it is possible to make a four-lamp dimming ballast fit within the confines of a standard “brick” ballast case, it seems very probable that a four-lamp load-shedding ballast should fit comfortably into that same space.

Related to ballast size is the number of wiring connections that need to be made when ballasts are installed. Not only do extra wiring connections require extra labor and increase the probability of incorrect hookup, the wires and their points of attachment require space within the luminaire case and inside the ballast case as well. Instant-start ballasts require fewer wire connections between the lamp and the ballast than other ballast types, and a power line carrier (PLC) signaling method eliminates the need for any other wiring connections. Therefore, a load-shedding ballast can be identical in shape to standard ballasts and have identical installation requirements.

Energy and Electrical

Even though the primary point of the load-shedding ballast is to reduce power demand at certain times, minimizing energy use and maximizing efficiency are still important aspects of a commercially successful ballast.

The efficiency of full-dimming ballasts is lower than that of comparable non-dimming ballasts for two reasons. First, the design of lamps and ballasts can be optimized more easily for one specific power level than for a range of power levels. For example, lamp electrodes are designed to operate at a specific temperature and consequently, they are sized so that self-heating from the discharge current provides sufficient heating for normal operation. Changing the discharge current changes the amount of self-heating and the operation of the lamp.

Second, the electronics necessary for control/communication require power to operate. For large loads, the power required to operate the controls can be made a small percentage of the power required by the device under control, but as the load size

decreases, the power requirements of controls do not scale proportionally with the total system power requirements, and thus consume a larger percentage of the total power. Small, widely distributed loads, such as fluorescent lamp ballasts, require proportionally more power to control than large, centralized loads.

Given that controls require power to function, the design goal is to minimize that extra power requirement so the net energy use of the system, considering the proportion of time operated at dimmed levels, is equal to or less than systems without the control. Minimizing energy use is accomplished in three ways: 1) use of an efficient ballast design; 2) making sure the control has minimal impact on efficacy under normal, full power operation; and 3) minimizing the power requirements of the control gear.

Regarding ballast design, Table 1 shows the relative efficacies of the commercially available ballast types. Except where indicated, the data in Table 1 are the average values from a sampling of energy-efficient products from many different manufacturers, as reported by NLPIP Specifier Reports on electronic ballasts and dimming electronic ballasts (National Lighting Product Information Program 2000; National Lighting Product Information Program 1999).

Table 1. Relative efficacy of commercially available ballast types.

Ballast type	Ballast Efficiency Factor (BEF) (2-lamp)	BEF Standard Deviation	Relative Efficacy	Input Power for Equal Light Output
Instant-start	1.52	0.031	1.00	60.0
Rapid-start	1.45	0.048	0.95	63.2
Programmed-start	1.50*	NA*	0.99*	60.6*
Conventional Dimming Ballast	1.38	0.049	0.91	65.9

* based on one manufacturer's data

Instant-start ballasts have the highest efficacy. Programmed-start is nearly as high as instant-start, but slightly lower, most likely because of the power required for the extra circuitry involved with the programmed starting. Like instant-start, most programmed-start ballasts do not provide supplemental electrode heating, except during starting. However, measurements performed at the LRC show some residual electrode heating voltage remains after the lamps have started, which probably accounts for the slight decrease in efficiency compared to instant-start systems. Building a load-shedding ballast on an instant-start or programmed start platform permits high efficacy to be maintained. Rapid-start and traditional dimming ballast platforms that continuously provide supplemental electrode heating are not as attractive for load-shedding applications

because of the substantial increase in energy use for full light output operation. Because the ballast is operated at full output for the vast majority of the time, high efficiency under this condition is essential.

Adding the ability to dim potentially decreases the efficacy of ballasts, even when the ballast is operated at full power. This impact must be limited as much as possible since a load-shedding ballast operates at full power for the vast majority of the time.

Minimizing the power requirements of the control gear greatly affects overall system efficacy. The control gear consists of the PLC receiver in the ballast, circuitry in the ballast that engages dimming, and the central transmitter of the PLC signal. The power consumption of the transmitter is the least critical since one transmitter serves potentially hundreds of ballasts or more. The PLC receiver and other control circuitry inside each ballast, however, are critical since any power consumption and associated energy use directly subtracts from the efficacy of the ballast.

Ballast efficiency factor

Considering the above, the specification for a load-shedding ballast should ensure that adding load-shedding capability does not compromise overall energy savings. A load-shedding ballast must, therefore, have a ballast efficacy factor that nearly matches the widely used instant-start products on the market with a small allowance, or decrease in efficacy for the control aspect. The resulting increase in energy use for this allowance should be no larger than the energy savings expected from dimming the ballast during the brief load-shedding periods. In other words, the net energy use of a load-shedding ballast should not exceed that of the commonly used instant-start system. For example, dimming a three-lamp instant-start system (90 watts) that is operated 2600 hours per year (10 hours per day, five days per week) for a 33% power reduction, for 100 hours per year, saves three kilowatt-hours per year. This energy savings is equivalent to an efficacy reduction of 1.3%, or an allowance of 1.15 watts per ballast for the ability to control and dim the lighting.

Ballast factor

The choice of ballast factor provides lighting designers and specifiers the ability to fine-tune their lighting designs so that lighting objectives are met with the least amount of connected load. Choosing a load-shedding ballast should not take away this design flexibility. However, ballasts with low ballast factors already operate lamps at current levels well below the nominal operating currents, and further reducing the current to obtain the required power reduction might have a greater impact on lamp life than would occur for ballasts with higher ballast factors.

Present life test data indicates that dimming up to 50% for short periods of time has minimal impact on lamp life, so it appears safe to include low ballast factor ballasts. As more data is gathered on the impact on lamp life when operating lamps at reduced currents without supplemental cathode heating, the decision to include low ballast factor ballasts should be revisited.

Power quality

Similar to the argument for ballast efficiency factor, the power quality of a load-shedding ballast should be equal to or better than accepted industry norms to ensure widespread use of the technology.

Dimming

The amount of dimming is determined by three factors. First is the desire to reduce the power consumption of ballasts as much as possible so lighting load shedding can have the greatest impact. Second is the need to provide and maintain adequate illumination for the building occupants, and third is the technology limitation involved with cost-effective dimming with instant-start systems. Fortunately, the relationship between system power reduction and light output is nearly linear over most of the dimming range considered, and nearly proportional to near full light output. Because a portion of the power losses in lamps and ballasts are nearly constant regardless of dim level, the relationship between system power consumption and light output is not strictly proportional, but has a positive offset. For example, a 50% power reduction will result in a 60% to 70% reduction in light output. The offset, on the order of a few watts per lamp, becomes more significant at low power levels, but power reductions of up to approximately 30% correspond to roughly equivalent percentage reductions in light output.

Dimming Range

Previous work at the LRC on the detection and acceptability of temporarily reduced light levels (i.e., dimming for load shedding) (Akashi et al. 2002) showed that a reduction of 15% in illuminance levels is the approximate threshold for noticing changes under typical office lighting conditions. However, light level reductions that are deemed acceptable in an office environment range from approximately 33 to 50% depending on the office task and whether the occupants were informed of the purpose and benefits of dimming.

It is recognized that dimming all the lamps in a luminaire with a special load-shedding ballast is not the only way to participate in lighting load shedding. “Dimming” can be achieved by switching techniques, such as tandem wired ballasts where a fraction of the lamps in multi-lamp luminaires can be separately switched, or by having a multi-lamp ballast that can separately switch off a fraction of the lamps operated. With different techniques available to implement lighting load shed with varying amounts of demand reductions, it was recognized that the marketplace would likely be plagued by confusing claims about load-shedding products if any amount of dimming were to be called load-shed dimming. Therefore, through discussions with lamp and ballast manufacturers, a definition of load-shed dimming was tentatively agreed upon that took into account what was thought technically possible and worthwhile (Lighting Research Center 2002). Since it was deemed important to include both switching and dimming means of achieving power reductions, the levels 33% and 50% were chosen. A level of 33% is achievable through either dimming or switching off one lamp in three-lamp ballasts, while 50% is achieved by switching off lamps in two- and four-lamp ballasts. At the time when this was decided, dimming instant-start operated lamps to 50% was considered too detrimental to lamp life to be an option, but recent life test data indicates that acceptable

lamp life might be obtained for short dimming periods of up to 50%, at least for some high ballast factor ballasts.

Dimming transition

The transition from normal, full light output to a dimmed, load-shedding condition can be made less noticeable to occupants by dimming gradually over several seconds, thereby avoiding sudden fluctuations in light level. Previous work at the LRC (Akashi et al. 2002) investigated the effect of different dimming rates and transition profiles on occupants' acceptability of dimming. From these studies and the existing literature on this topic, it was concluded that the transition profile and the time over which dimming occurs has little or no effect on occupants' detection of illuminance changes. The dimming periods tested ranged from 3 to 120 seconds. The research pointed to memory of the initial brightness as being the primary factor in determining when a change in illuminance is detected.

Signaling

Cost-effective, reliable, and compatible with existing control systems are the main requirements of a lighting load-shedding system. Keeping the costs low for the receiver technology is perhaps the most challenging requirement due to the narrow price margins on fluorescent lamp ballasts. To make use of existing communication systems and to build on existing infrastructure, the signaling path for load shedding is divided into three domains: 1) utility/ISO to building or facility; 2) communication within the facility or building to major electrical distribution centers; 3) electrical distribution centers to the individual ballasts. Each of these communication domains has a different optimal solution based on the distances that are covered and available communication infrastructure and services. It is proposed that Internet web site posting and existing building automation/communication systems provide solutions for the first two domains. However, no cost-effective communication system exists for the last domain that distributes the signal to the individual lighting loads, i.e., ballasts.

Any signaling method that requires new wiring or physical linking of individual ballasts is considered too costly for a load-shedding lighting system. Of the available wireless techniques, optical signaling has too limited a range within buildings and, as with radio, would require a wave-guide or antenna to enable a metal-enclosed ballast to receive a signal. Wireless radio signaling has future potential, but presently the technology is too expensive as a system due to the need for sharing communication channels and regulation requirements.

While not exactly wireless, power-line-carrier (PLC) signaling techniques do not require any additional physical infrastructure. While a cost-effective, off-the-shelf solution using PLC technology could not be found, all the elements of a solution are present with PLC technology. Obtaining a solution for load shedding involves trading-off the high data rates of current systems for lower-cost systems that operate over relatively short intra-building distances. The challenge with using the power lines for signaling is coping with the line's variable and noisy characteristics. Signaling techniques that work well for radio and dedicated wire networks often have reliability problems when used in the power line

environment (Dostert 2001). However, a load-shedding signaling system that takes advantage of the unique requirements of load management by incorporating specialized modulation techniques can dramatically improve the reliability and cost-effectiveness of a PLC system (Bierman et al. 2003).

Noise and reliability problems with PLC

Perhaps the most difficult challenge with using the power lines as a communication medium is dealing with power line noise. Noise arises from both natural causes, such as corona discharges and lightning strikes, and man-made sources, such as radio and television stations, as well as from appliances and other devices that are connected to the power lines. Because of the diversity of appliances connected to the power lines, and the relatively high power levels at which they operate, noise problems when using the power line are potentially much worse than for other communication media.

Power line noise is classified into at least three types: background noise, narrow-band noise, and impulsive noise. Background noise, being similar in characteristics to noise in other communication media, presents no additional challenges for power line communication. Certain devices, however, produce large amounts of full-spectrum, background-like noise, which can affect nearby communication. Universal motors typically found in many household appliances, such as kitchen appliances, vacuum cleaners, and power tools, emit large amounts of this type of noise, which can jam nearby receivers.

Narrow-band noise is generated from both intentional transmitters and unintentional transmitters. Generally, narrow-band noise from intentional emitters, such as broadcasting stations and communication devices, can easily be avoided by selection of appropriate carrier frequencies. More problematic are narrow-band emissions from unintentional emitters, such as CRT monitors and switching power supplies (found in most commercial electronic equipment including electronic fluorescent lamp ballasts). If all appliances and power line devices operated at well prescribed frequencies, then interference from these devices would be easy to avoid, but power line operated devices operate over a wide range of frequencies making it hard to avoid all narrow-band emissions from these devices.

Impulsive noise is described as sporadic pulses, or disturbances, on the power lines. Impulsive noise usually arises from the switching of large loads. The noise from a switching transient is a brief, continuous spectrum that decreases with frequency. Impulsive noise is difficult to measure because its average power is low, but its peak power can be very large. Its effect on high-speed digital communication is typically the introduction of bit-errors, making the received data unreliable.

For load-shedding signaling purposes, as opposed to high-speed data transmission, randomly occurring impulsive noise can easily be overcome with receivers that have long signal integration times. Similarly, background noise can also be overcome to a large extent by long integration times, provided that the noise level is not so large that it exceeds the dynamic range of the receiver, effectively jamming it. With long integration

times, periodic impulsive noise can degrade performance in a similar manner as background noise, provided that the integration time is much longer than the period of the impulses. However, the magnitude of impulsive noise is typically much greater. Narrow-band noise is perhaps the trickiest to handle because of its potentially high power levels at a particular frequency. If the frequency of a narrow-band emitter happens to coincide with the PLC carrier frequency, the signal can easily be jammed. While narrowing the bandwidth of the receiver decreases the chances of a coincidence of frequencies, it increases the cost of the system and does not guarantee freedom from interference. Spread-spectrum modulation techniques offer the best solution to narrow-band interference originating from unpredictable, unknown sources; however, such techniques require sophisticated receivers, which add considerably to the cost.

Signal attenuation and the variable nature of the power line is another issue that complicates using the power lines for communication. Signal strength and the distance that signals will propagate along the power lines depends heavily on what other devices are connected, and the layout of the electrical distribution system. This type of problem, however, is encountered with other forms of “wireless” communication. For example, the distance that radio signals travel inside a building depends on the material and construction techniques of the walls, floors, and ceilings, and buildings that contain a lot of metal lath and sheeting material often have problems with radio communications.

Proposed PLC signaling method

A simple form of synchronous detection is proposed in the load-shedding ballast specification to overcome power line noise problems and to provide a cost-effective solution. Synchronous detection is a well-established technique for recovering signals in the presence of noise and other interfering signals. The basic technique is also called lock-in detection, or phase detection.

With synchronous detection, the transmitted signal is made periodic, such as by turning it on and off in a square wave pattern. The receiver is synchronized to the transmitted signal so that it positively integrates, or sums, the reception of the signal along with whatever noise is present when the signal is being transmitted, and negatively integrates (i.e., subtracts) the reception of the noise during periods when the signal is not being transmitted. Over the course of many cycles, the received noise nulls to zero because it is positively integrated for exactly half the time and negatively integrated for half the time. The signal, on the other hand, is not present when the negative integration occurs so its value builds over time. Noise cancellation becomes more complete and the signal strength grows as more cycles of the periodic signal are integrated. Therefore, receiver sensitivity and noise rejection is improved with longer integration times (i.e., slower data rates).

Applying synchronous detection to a widely distributed signaling system is complicated by the need for the transmitter and receiver to be precisely synchronized. After all, if a synchronizing clock signal could easily be sent between transmitter and receiver, what would be the point of using synchronous detection in the first place? Fortunately, the electrical distribution system has a “built-in” clock: the 60 Hz a.c. line frequency.

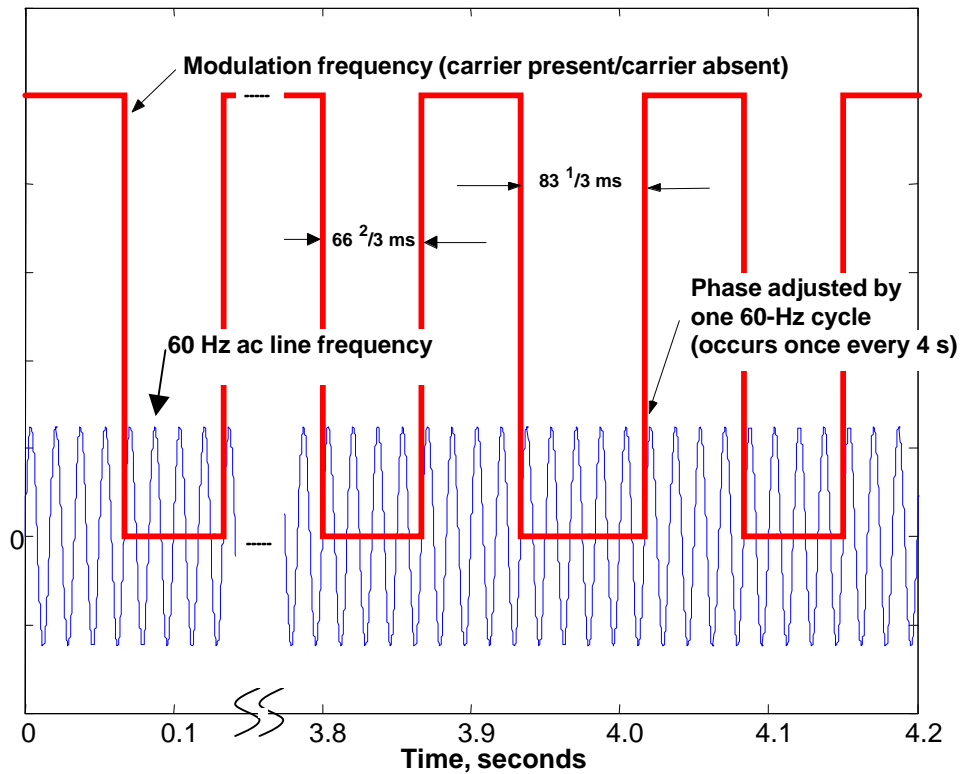
However, using 60 Hz, or a multiple of it, for the modulating frequency does not isolate the transmitted signal because most noise on the power lines, especially impulsive noise, is also periodic with the 60 Hz fundamental frequency of the line, or a multiple of it. Using a modulating frequency lower than 60 Hz is effective for reducing power line noise, and if the modulation frequency is a subharmonic of 60 Hz, the 60 Hz associated noise is completely canceled over one integration period. A subharmonic is a frequency that can be divided into another an exact number of times; thus, 7.5 Hz is a subharmonic of 60 Hz, being exactly 1/8 the frequency. The relatively slow modulation rates associated with 60 Hz subharmonics limit the rate at which information, or data, can be transmitted to what is considered extremely slow by today's standards (on the order of one bit per second), but the slow information rate is perfectly acceptable for a load-shedding system with a required response time of up to several minutes.

Synchronizing signals that are subharmonics to the synchronizing clock signal does not guarantee that the signals will be matched in phase. Because the synchronizing clock is a multiple of the operating frequency, two devices can phase align to any one of the clock cycles occurring within one period of their own frequency. For example, the eighth subharmonic contains eight cycles of the clock waveform, and so separate devices have a 1/8 probability of aligning to the same clock cycle.

A solution to this problem is to have one of the devices, say the transmitter, advance or delay its phase by one clock cycle every so often. Eventually the two devices will phase align for a period of time. When the devices are phase aligned, the received signal will be at maximum amplitude. When the two devices are exactly 180 degrees out of phase, the signal amplitude will be at a minimum negative value. At a 90-degree phase difference the received signal will be zero, and so on. The received signal amplitude will trace out a sine wave pattern as the phases go in and out of alignment. The period of this sine wave pattern is equal to the time period that the transmitter lingers at a particular phase angle multiplied by the inverse of the subharmonic used for modulation. For example, lingering at each phase interval of the clock frequency (60 Hz) for four seconds and using a modulation frequency at the 1/8 subharmonic of 60 Hz produces a received sine wave with a period of 32 seconds. Figure 1 shows the timing of the modulation.

The low frequency received sine wave signal resulting from this method of subharmonic synchronous detection is a unique, highly noise resistant signal that is suitable for triggering the ballast to go into and out of the load shedding condition.

Appendix A contains documentation of a prototype circuit for PLC-signaled load shedding that employs the above modulation technique. In addition to demonstrating the effectiveness of the method, the prototype demonstrates that a circuit can be achieved at extremely low cost from common electrical components. The cost of the components (quantity = 1000) for the PLC prototype receiver is less than \$3.00. Further substantial cost reductions are possible by using custom integrated circuits.

Figure 1. Timing diagram for subharmonic synchronous detection of PLC signals.

Triggering load shed and the default condition

It is highly important to avoid false triggering in and out of the load-shed condition. Such false triggering is detrimental to the life of the lamps and could unnecessarily annoy occupants. The default condition of the ballasts shall be full light output. Full light output is necessary during the starting of the lamps and for normal operation of ballasts in the presence of no PLC signal. Therefore, if a customer decides not to participate in load-shedding practices, the ballasts will provide full light output by simply disabling the signaling system.

Triggering of load shed must be refreshed approximately every ten minutes so lighting loads switched on after the initial load-shed signal is broadcasted will be able to go into the load-shed condition. Periodically refreshing the signal also prevents people from manually exiting the load-shed condition by cycling the lights off and on.

To address the above issues, the triggering of load shed shall be based on the presence or absence of the PLC signal; the presence of the signal triggers and maintains load shed, while the absence of a signal triggers and maintains normal, full light output operation. Signal conditioning shall be provided so the ballast is not sensitive to momentary

interruptions of signal. For example, triggering that requires a sustained signal, or lack of one, for several minutes would limit the possibility of false triggering.

Receiver characteristics (sensitivity, noise rejection, false triggering, etc.)

To avoid false triggering of load-shed operation and to ensure reliable power reductions when load shedding is initiated, the receiver must operate in the presence of power line noise and other environmental conditions to which electronic ballasts are subject. Metrics for these conditions and performance levels are highly important so that a minimum level of quality and reliability is maintained for load-shedding ballast products. These metrics and the corresponding performance levels are yet to be determined. Testing and demonstration experiments of prototype devices and pre-production products are needed to help set these performance specifications.

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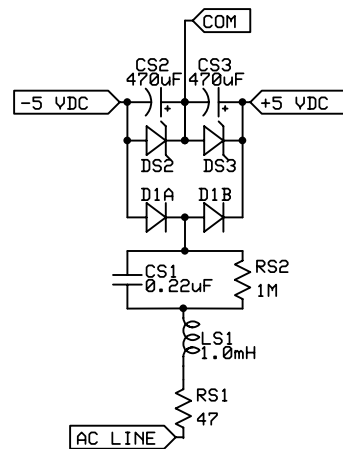
Appendix A

Parts List

5-Jan-04 Loadshed Receiver Costs

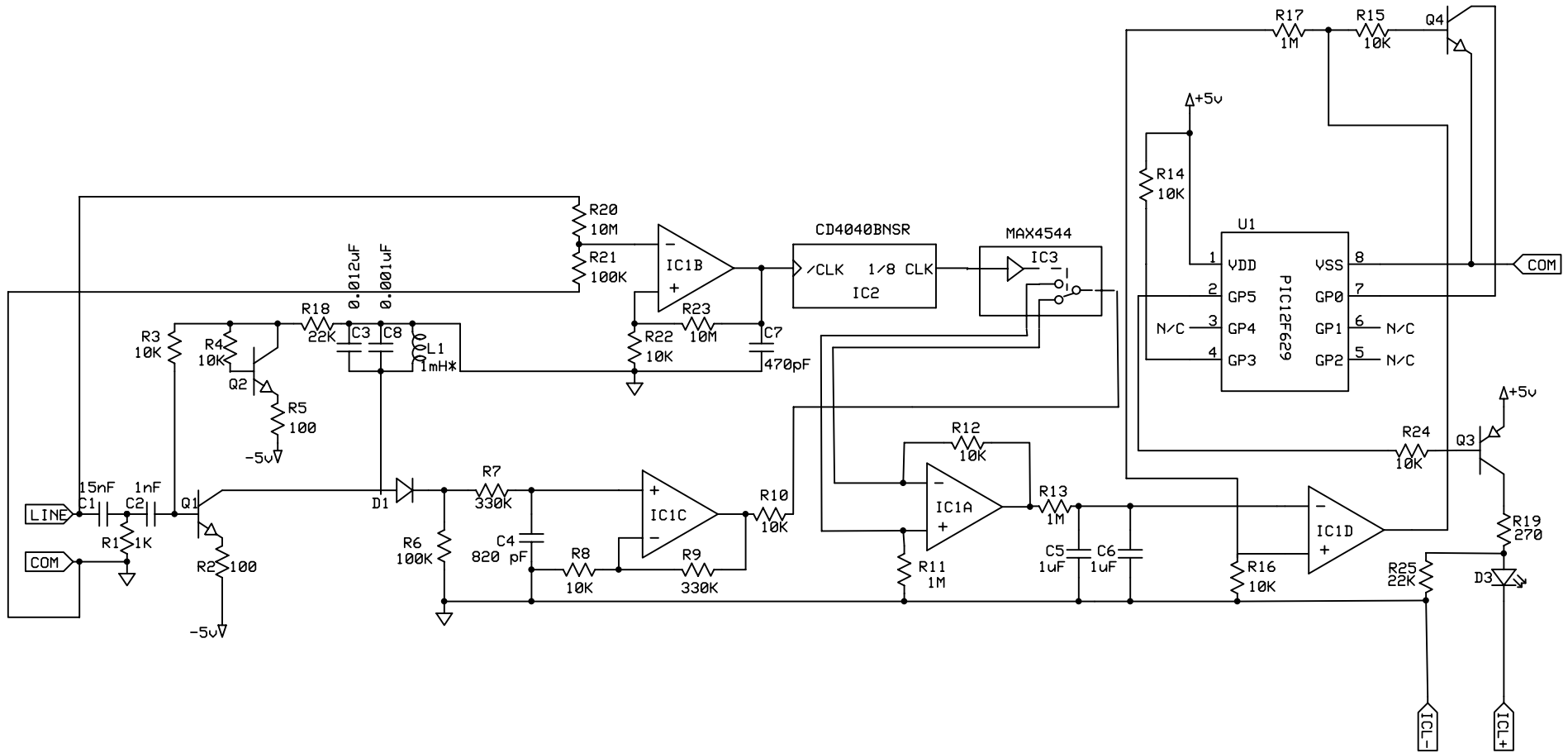
QTY	REF DES	DESCRIPTION	SUPPLIER PN	QTY 10	QTY 1000	Total Count	w/ 10 piece price	w/ 1000 piece price	SUPPLIER	
1	C1	CAP FILM MKP .015UF 275VAC X2	BC1604-ND	0.352	0.1761	1	\$0.35	\$0.18	DIGIKEY	
1	CS1	CAP FILM MKP .33UF 275VAC X2 20%	BC1609-ND	0.462	0.23085	1	\$0.46	\$0.23	DIGIKEY	
1	C2	CAP 1000PF 250VAC CERAMIC Y2/X1	P11418CT-ND	0.209	0.10198	1	\$0.21	\$0.10	DIGIKEY	
1	C3	CAP .012UF 50V PPS FILM ECH-S	PS1H123G-ND	0.834	0.416	1	\$0.83	\$0.42	DIGIKEY	
2	CS2, CS3	CAP 470UF 10V ELECT NHG RADIAL	P5520-ND	0.28	0.112	2	\$0.56	\$0.22	DIGIKEY	
1	C7	CAP 470PF 50V CERAMIC X7R 0805	BC1281CT-ND	0.058	0.01378	1	\$0.06	\$0.01	DIGIKEY	
1	C4	CAP 820PF 50V CERAMIC X7R 0805	311-1194-1-ND	0.077	0.0182	1	\$0.08	\$0.02	DIGIKEY	
2	CL1, CL2	CAP 1500PF 1000V DISC	P4130-ND	0.371	0.1484	2	\$0.74	\$0.30	DIGIKEY	
2	C5, C6	CAP 1.0UF 25V CERAMIC F 0805	PCC2230CT-ND	0.229	0.08798	2	\$0.46	\$0.18	DIGIKEY	
1	C8	CAP .001UF 50V PPS FILM ECH-	PS1H102G-ND 1029	0.687	0.343	1	\$0.69	\$0.34	DIGIKEY	
2	D1, D2	DIODE ULTRAFast HI COND SOT-23	BAS16FSCT-ND	0.119	0.03564	2	\$0.24	\$0.07	DIGIKEY	
1	DS1	DIODE LOLEAK 100V 250MA SOT-23	FLLD261CT-ND	0.338	0.15	1	\$0.34	\$0.15	DIGIKEY	
2	DS2, DS3	DIODE ZENER 5.1V 0.35W SOT-23	BZX84C5V1FSCT-ND	0.14	0.04212	2	\$0.28	\$0.08	DIGIKEY	
1	F1	FUSE FAST 100MA IEC SHORT TR5	WK4927BK-ND	1.17	0.5655	1	\$1.17	\$0.57	DIGIKEY	
2	L1, LS1	INDUCTOR FIXED 1.0MH TYPE 8RB	TK4312-ND	1.661	0.548	2	\$3.32	\$1.10	DIGIKEY	
1	IC1	IC QUAD OP AMP 14-SOIC	296-14597-1-ND	0.42	0.1365	1	\$0.42	\$0.14	DIGIKEY	
1	IC2	IC COUNTER/DIVIDER BINRY 14-SOIC	296-14258-1-ND	0.39	0.108	1	\$0.39	\$0.11	DIGIKEY	
1	IC3	IC SW DUAL ANLG LV SPDT 8-SOIC 2:1 MUX	MAX4544CSA	0.89	0.51	1	\$0.89	\$0.51	MAXIM IC	
2	ICL1, ICL1	MOS Output SS RELAY 400V	AD4C312	5.99	3.99	2	\$11.98	\$7.98	DIGIKEY	
3	Q1, Q2, Q4	TRANSISTOR GP NPN AMP SOT-23	MMBT5088CT-ND	0.19	0.04212	3	\$0.57	\$0.13	DIGIKEY	
1	Q3	TRANSISTOR GP PNP AMP SOT-23	MMBT5087CT-ND	0.19	0.04212	1	\$0.19	\$0.04	DIGIKEY	
1	RS1	RES 47 OHM 1/8W 5% 0805 SMD (AXIAL Cur)	P47ACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
2	R2, R5	RES 100 OHM 1/8W 5% 0805 SMD	P100ACT-ND	0.08	0.01682	2	\$0.16	\$0.03	DIGIKEY	
1	R19	RES 270 OHM 1/8W 5% 0805 SMD	P270ACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
1	R1	RES 1.0K OHM 1/8W 5% 0805 SMD	P1.0KACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
10	R3, R4, R8, R10, R12, R14, R15, R16, R22, R24	RES 10K OHM 1/8W 5% 0805 SMD	P10KACT-ND	0.08	0.01682	10	\$0.80	\$0.17	DIGIKEY	
1	R18	RES 22K OHM 1/8W 5% 0805 SMD	P22KACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
2	R6, R21	RES 100K OHM 1/8W 5% 0805 SMD	P100KACT-ND	0.08	0.01682	2	\$0.16	\$0.03	DIGIKEY	
1	R7	RES 330K OHM 1/8W 5% 0805 SMD	P330KACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
1	R9	RES 330K OHM 1/8W 5% 0805 SMD	P560KACT-ND	0.08	0.01682	1	\$0.08	\$0.02	DIGIKEY	
3	R11, R13, R17	RES 1.0M OHM 1/8W 5% 0805 SMD	P1.0MACT-ND	0.08	0.01682	3	\$0.24	\$0.05	DIGIKEY	
1	RS2	RES 1.0M OHM 1/4W 5% CARBON FILM	1.0MQBK-ND	0.056	0.0087	1	\$0.06	\$0.01	DIGIKEY	
2	R20, R23	RESISTOR 10M OHM 1/8W 5% 0805	P10MACT-ND	0.08	0.01682	2	\$0.16	\$0.03	DIGIKEY	
4	TVS1-4	TVS 400W 350V Bi-directional	P4KE350CA	0.23	0.23	4	\$0.92	\$0.92	DIGIKEY	
1	U1	MICROCHIP MICROCONTROLLER PIC	PIC12F629	0.99	0.99	1	\$0.99	\$0.99	DIGIKEY	
							TOTAL COST	\$28.19	\$15.21	

Prototype schematic: Power supply



Lighting Research Center		
Transformerless Power Supply		
+/- 5 VDC		
N. Skinner	Rev 2.0	Page 1 of 1
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Prototype schematic: Powerline carrier receiver



Lighting Research Center

Load Shed Ballast
Powerline Carrier Demodulator

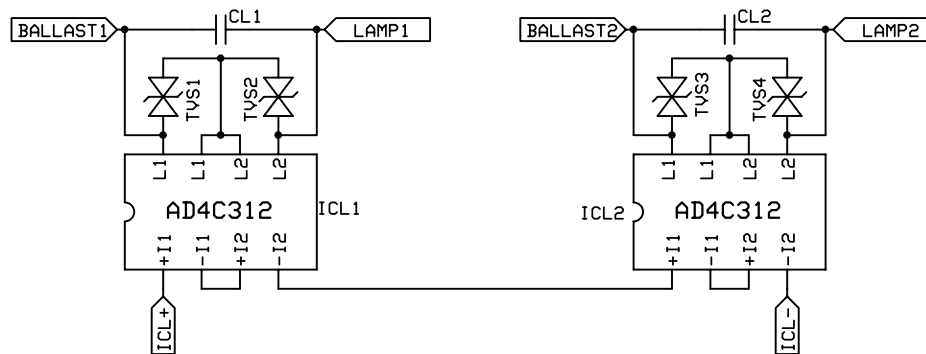
A. Bierman

Rev 3.0

1/02/2004

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Prototype schematic: Lamp dimming circuit



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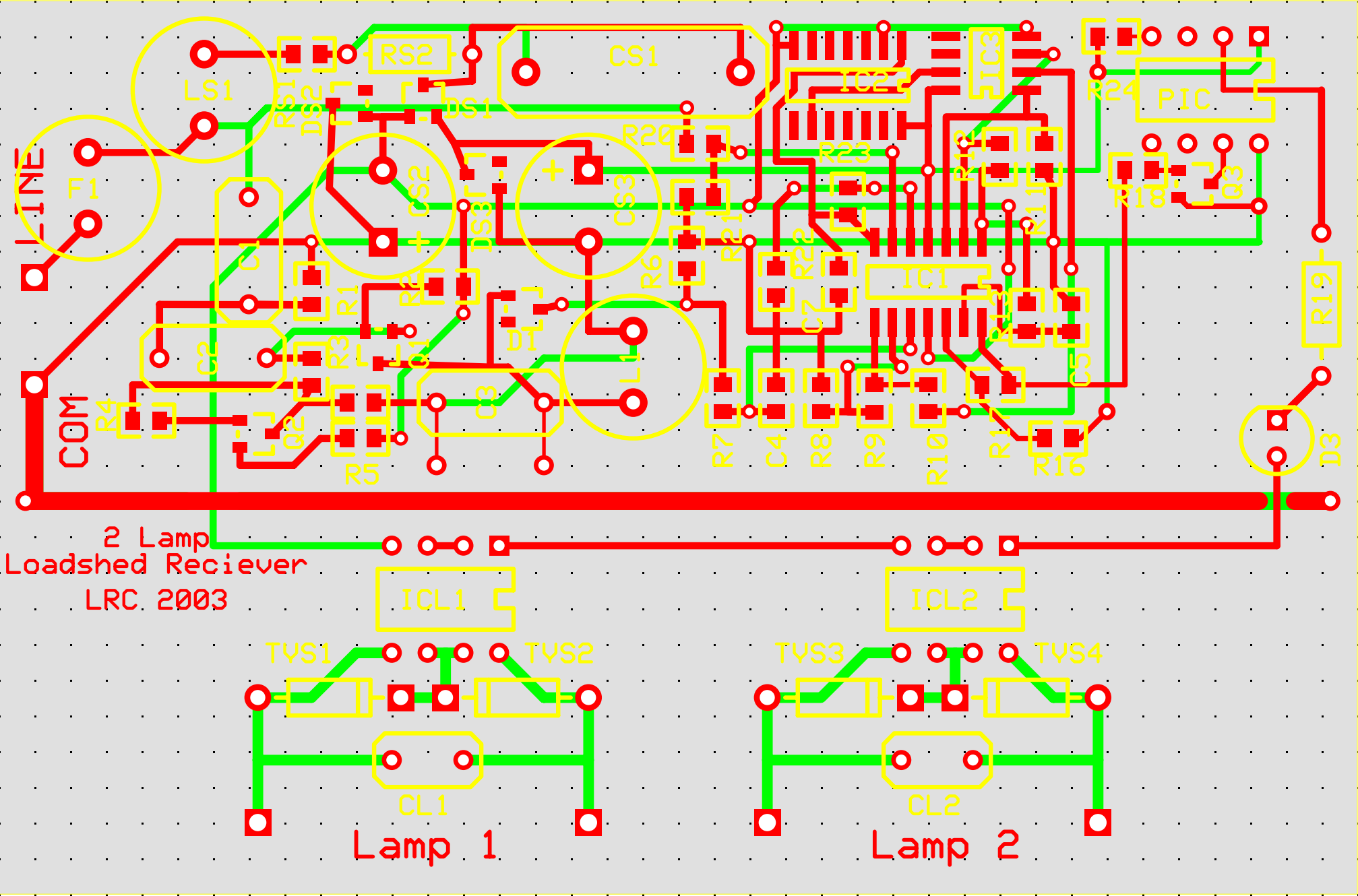
Lamp Dimming Circuit

N. Skinner

Rev 1.0
7/31/2003

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Prototype: Printed circuit board layout



Program code: Part U1 Microchip Microcontroller

```

;=====LSxmtr===== 09/08/03, revised
09/08/03, rmp =====
; LSxmtr code - PicBASIC Pro Compiled
;-----
CMCON=7 'PIC12F629 in digital, not analog,
mode
OPTION_REG.7=0 'GPIO Pull-Ups are enabled by individual
port latch values
TRISIO=%00001001 'Set I/O directions (GP0/GP3-IN;
GP1/GP2/GP4/GP5-OUT
SIGin var GPIO.0 'INPUT: 60 Hz square wave on SIGin
MSTRclr var GPIO.3 'INPUT: Master Clear from pullup to vdd
CLKout var GPIO.4 'OUTPUT: Clock Out from internal RC clock
SIGout var GPIO.5 'OUTPUT: Signal Out
Phase var GPIO.1 'OUTPUT: Toggles ON phase delay

index var byte
SIGprev var bit
cycles var word

SIGout=0 'Initialize SIGout to low
while 1=1 'Loop forever
    For index=1 to 60
        SIGprev=SIGin
        For cycles=1 to 8
Loop:    If SIGin=SIGprev Then Loop 'wait for change in SIGin
            SIGprev=SIGin
        Next
        SIGout=Not SIGout 'Completed 8 cycles; toggle
    Next
    Pause 20
    Phase=Not Phase
wend
End
```