Star configuration of power factor correction units in LED lighting systems

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As a result of rapid development of LED lighting solutions and taking into account the new international regulations (Energy Star® and EN61000-3-2:2006) regarding the power factor, the power factor correction unit should be a compulsory component in any system that uses this kind of illumination. The present paper covers the concept, design, fabrication and testing of a lighting system composed of one major PFC unit and the individual drivers that deliver the power to the LEDs. This new star architecture has certain advantages over the conventional parallel one used at the present time, such as the power factor value, overall system efficiency and cost. The presented configuration is designed with the purpose to be used "as it is", with almost zero modifications on the existing electrical connections in most households or institutions. The system is designed for a maximum absorbed power of 2kW, but virtually any power limit could be achieved, depending on the specific requirements of the space to be illuminated.

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1. Introduction

Until recently, power factor correction (PFC) units were mandatory devices only for large industrial consumers such as electric motors, but with the large scale implementation of lighting solutions which have their own ballasts and controllers, conditions started to emerge regarding the small consumer electronics too [**1**]. In short terms, the power factor is a dimensionless coefficient defined as the ratio of the real power absorbed by a load (Watts) to the apparent power (VA) and can take values from 0 to 1, giving an indication to the degree of distortion and phase-shift of the current waveform. In spite of their extreme inefficiency, incandescent light bulbs are still being used at the present time. These light sources have a power factor of 1 as they are purely resistive loads.

Also, an important problem in today's lighting community is that CFL lamps, which are being used on a very large scale, do not include circuits for power factor correction (typical power factor: 0.55), based on the idea that the power absorbed from the mains by each unit is of small value. This approach, yet even more its inference to the LED lighting domain, is wrong because such light sources have been implemented in a very large number and the effect of low power factors on the electrical grids is cumulative [2].

The new standard EN 61000-3-2 applies to all electronic equipment with current inputs up to 16A (per phase). This standard, which is a part of the European EMC-directive, superseded the EN 60555-2 standard as of 10.02.2001 and establishes four classes of electronic equipment, with different limit values [3,4]. The third class is related to lighting equipment and its conditions are shown in Table 1.

Table 1. EN 61000-3-2 conditions for class C electronic equipments.

	Active power >25W	Active power <25W
Harmonic order n	Maximum harmonic current as a percentage of the input current at the fundamental freq. (%)	Maximum permissible harmonic current per watt (mA/W) *
2	2	-
3	30xλ*	3.4
5	10	1.9
7	7	1.0
9	5	0.5
11<n<39	3	0.35
13<n<39	-	3.85/n
λ is the power factor		
** or the third harmonic current shall not exceed 86% and the fifth harmonic current shall not exceed 61% of the fundamental current*		

In response to the new International and European Standards, the LED luminaire manufacturers rapidly found a solution which generally consists of small PFCs implemented in each LED lamp, and usually integrated in the same chip with the current driver. This mainly leads to efficiency compromises, as in the low-cost market where complexity is to be kept at a minimum, it can only be increased at the cost of lowering the power factor, which is undesirable.

Currently used LED drivers can be divided in two main categories: without and with PFC. The first category includes passive current limiters and buck converters, and the latter usually consists of one-stage flyback converters and two-stage circuits. The drivers that provide PFC have certain disadvantages, including complexity, transient current regulation, voltage ripple and limited output power.

This paper presents a new architecture comprised of a main PFC unit, able to provide regulated power to all the LED fixtures in the building to be illuminated. The fixtures would then need to include only simplistic high-efficiency current limited drivers. The resulting configuration easily lends itself to optimization at reduced total costs for an increased number of light sources.

To the author's knowledge, only the bare concept of such a star configuration has been proposed in the past [**5**] for LED lighting, with certain differences regarding the LED individual drivers and the PWM (Pulse Width Modulation) dimming.

2. Design and fabrication

The main idea of the proposed concept (
Fig. ***1***) is to have one major PFC unit which can be easily integrated in most existing electrical grids with minimal modifications, and the individual current drivers integrated inside the LED luminaires. This not only reduces the cost of the system, but also allows for better power factor and overall efficiencies.

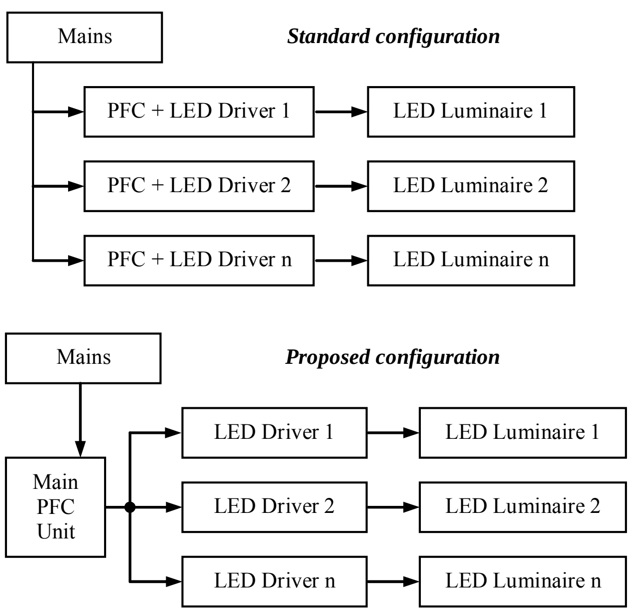

Fig. 1

2.1 The PFC unit

The main PFC unit is based on a heavily-modified design of a 1.2kW PFC board from Texas Instruments [6]. It is designed to function in the Europe at an input voltage of 176-264V, having an output voltage of 400V and a maximum output power of 2kW. For easier block and trace identification, the unit is divided into two parts, the power board and the control board respectively. The control circuit is based on the UCC28070 (Texas Instruments) integrated circuit, which is a continuous current mode interleaved PFC controller [7]. The schematic of the control circuit is presented in
Fig. ***2***. The UCC28070 is an advanced power factor correction device which allows for natural interleaved PWM operation on two MOSFETS that function 180º out of phase, at a switching frequency of 150 kHz.

For the reduction of input and output current ripple and thus easier compliance with electromagnetic interference limits, the frequency is dithered ±6.25kHz with a repetition rate of 1 kHz. The output voltage contains only a small low-frequency line ripple, which can be readily eliminated by the LED drivers. As shown in the circuit diagrams, J1 has the same connections on both the control and the power board.

The power board schematic is shown in
Fig. ***3***. It features common-mode and differential filtering for reduced radiated interference. The boost stages utilize IPW60R045CP CoolMOS™ power transistors from Infineon featuring 45mΩ R_{DS-ON}, 150nC gate charge and HFA25PB60 HEXFRED® ultrafast (23ns typical trr) ultrasoft diodes from Vishay. The boost inductors have an inductance of 121uH and a saturation point of 40A (-10%), are wound on two T200-2 cores each with AWG17 (~1.17mm diameter) wire, having 71 turns and provide small core losses in this application. Single-layer windings like this one provide the smallest capacitance and highest self-resonant frequency. The current transformers have a turns ratio of 1:100 and are wound with AWG25 (0.45mm diameter) on FT-140-43 ferrite cores; the primary uses AWG14 (~1.6mm diameter) wire. The secondary inductance is large (8.85mH), providing a small magnetization current and improved current sensing performance. Reset networks use ultrafast BAV102 diodes and resistors, calculated to allow duty cycles of up to 0.9 without saturating. For bulk storage we used three 470µF/450V BHC long life (15000h@85ºC) capacitors having a rated ripple current of over 4A. At the maximum estimated PFC enclosure temperature of 60ºC, the reliability of these components should exceed 94000h [8] providing a cost effective solution over increased periods of usage.

2.2 The LED current-limiting drivers

The LED drivers use a pulse-skipping configuration operating at 132kHz dithered ±4kHz with 1kHz. This configuration employs a small number of components and attains over 94.4% efficiency. The Power Integrations TNY268 integrated circuit offers simplicity in design as it contains all the small-power control circuitry and a 7Ω R_{DS-ON}, 700V internal MOSFET. It is also self-powered. Non-isolated continuous current mode buck converters allow for the use of off-the-shelf regular inductors, providing a cost effective solution but it should be noted however that the driver does not provide any insulation from the main circuit. The inductors used in this design are Panasonic parts, with a DC resistance of only 1.6Ω providing small core and copper loses. The current tolerance is determined by only 2 components (R2 and U2) and is better than ±10% using standard parts. The driver has a low cost, small footprint and, because of the high efficiency, an inherent good reliability. It should operate with ease even at ambient temperatures as high as 60ºC but it should be noted that increased losses occur at higher temperatures.

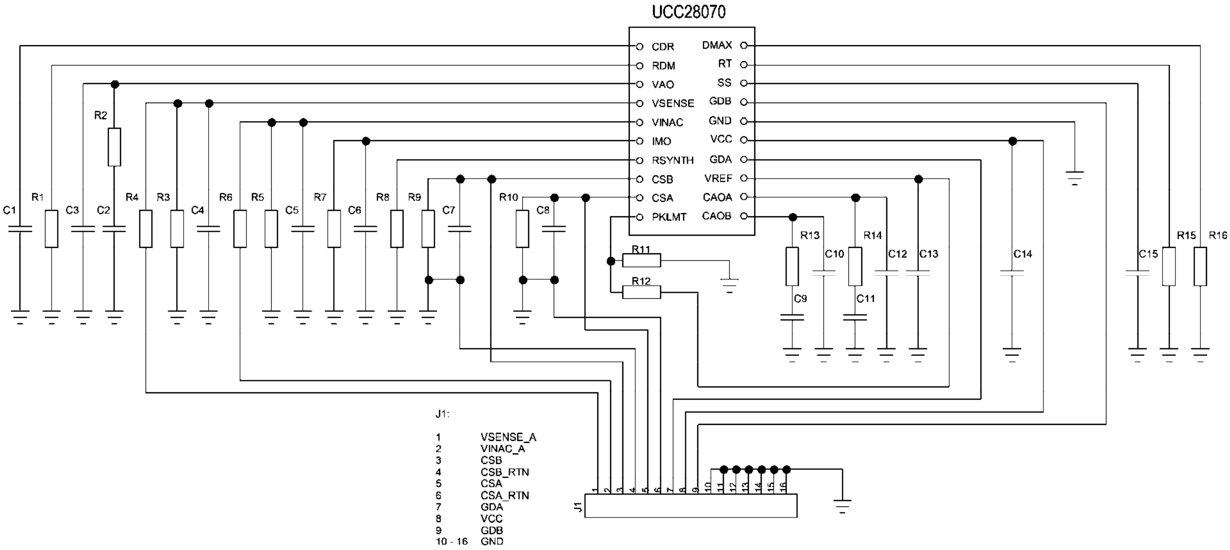

Fig. 2. UCC28070 control board circuit diagram. Parts: R1=R2=120kΩ, R3=R5=24kΩ, R4=R6=100Ω, R7=18kΩ, R8=47kΩ, R9=R10=20Ω, R11=16.5kΩ, R12=10kΩ, R13=R14=2.2kΩ, R15=100kΩ, R16=83kΩ, C1=10nF, C2=1.22uF, C3=122nF, C4=C5=330pF, C6=1nF, C7=C8=3.3nF, C9=6.8nF, C10=C12=2.2nF, C11=6.8nF, C13=C14=100nF, C15=3.3uF.

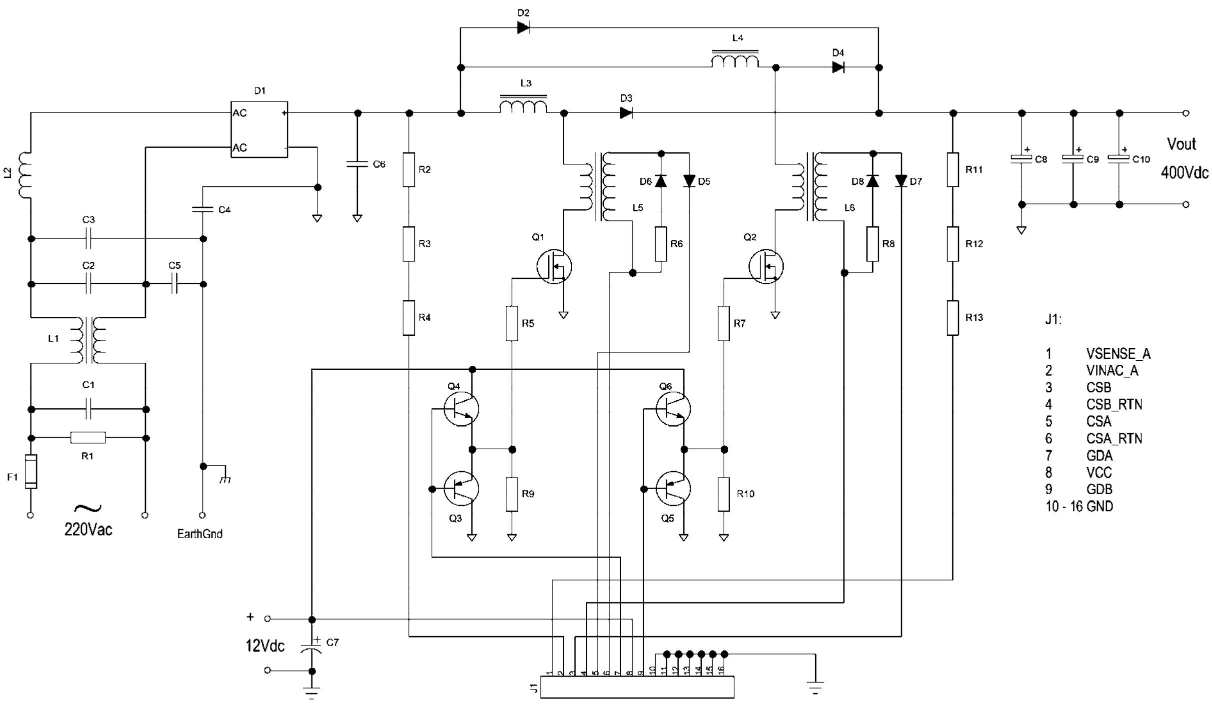

*Fig. 3. Power board circuit diagram. Parts: R1=820kΩ, R2=R3=R11=R12=1.5MΩ, R4=R13=180kΩ, R5=R7=3.9Ω, R8=220Ω, R9=R10=6.8kΩ, C1=C2=C6=2.2uF/305V, C3=C4=C5=2.2nF/2kV, C8=C9=C10=470uF/450V, D1=40A/1000V, D2=MUR460, D3=D4=HFA25PB60, D5=D6=D7=D8=BAV102, Q1 = Q2 = IPW60R045CP, Q3 = Q5 = BD140, Q4 = Q6 = BD139, L1 = 2*1.5mH/20A, L2 = 100uH/20A, L3=L4=130uH/20A on 2*T200-2, L5=L6=Current transformer 1:100 Lm = 10mH on FT140-43*

The LED drivers are fully protected against over-temperature and output over-voltage in order to prevent damage in case of LED matrix failure. The over-voltage threshold tolerance is determined mainly by the Zenner diodes used (standard -7% +5%). By controlling the stress ratio and using the minimum possible number of parts, the design can be expected to have a long operating lifetime.

Each fixture includes a total of 55 cool-white LEDs (NSDW570GS, Nichia Corporation). The operating voltage of each LED is 3.4V, corresponding to a current intensity of 76mA, at which the luminous efficiency is 121lm/W [**9**]. The projected lifetime of these LEDs at an operating temperature of 50ºC is 50000 hours. This model has been chosen due to its high luminous efficiency and, being a 5mm resin-capsule LED, it doesn't require a heat exchanger. In order to maximize the conversion efficiency of the driver stage, we chose a series connection for the LEDs, resulting in an operating voltage of 187V; as an added benefit, all the LEDs are functioning at the same forward current, leading to almost identical lumen output. The only drawback of this configuration is that the entire fixture will stop functioning in case of accidental failure of one LED. On the other hand, having mixed series-parallel groups presents the disadvantage that in case of failure of one series LED branch, the current regulator will force the same amount of current through only the remaining branches, thus exceeding the absolute maximum ratings of the LEDs. The driver schematic is depicted in

Fig. ***4***.

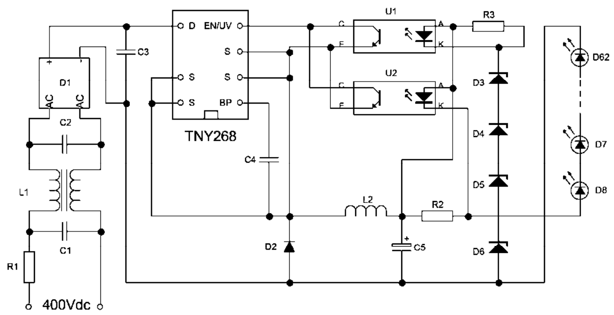

*Fig. 4. Driver board circuit diagram. Parts: R1=15Ω, R2=12Ω, R3=1.2KΩ, C1=C2=C3=100nF/500V, C4=1uF/10V, C5=22uF/250V, L1=2*2.2mH/0.5A, L2=2.4mH/0.8A, D1=B380S, D2=UF4007, D3=D4=MM3Z33VT1G, D5=D6=BZT55C75, U1=U2=HCPL-817-300E*

3. Results and discussion

The efficiency of the main PFC unit and overall system efficiency is depicted in

Fig. 5, for an input voltage of 230Vac. The efficiency peaks at 96.5% for the main unit and at 91.1% for the whole system when using a number of 85-108 fixtures.

At light load the efficiency declines, because switching losses become predominant, totaling 90.1% for 17 fixtures and 85.8% for 8 fixtures. At full load low line conditions, the PB4010 input bridge rectifier losses account for approximately 23% of the total circuit losses.

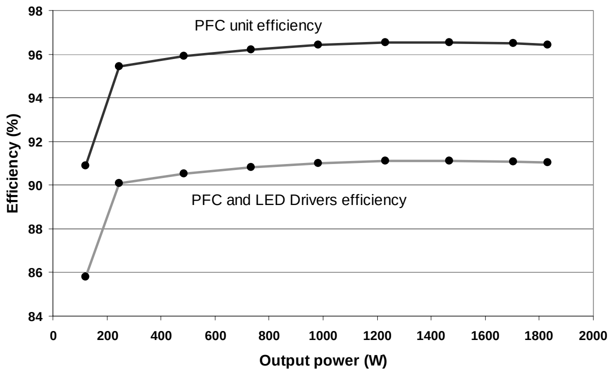

Fig. 5. PFC unit efficiency (upper curve) and overall efficiency (lower curve).

The measured output characteristic of the LED drivers in Fig. 6 shows the current and over-voltage limiting values at 76.6mA and 221V. The behavior of the drivers allows the use of a different number of LEDs (46-70) without any modification to the circuit. However, the efficiency is higher with a large number of LEDs. To accommodate an even larger number of LEDs the circuit's over-voltage limit can be easily modified.

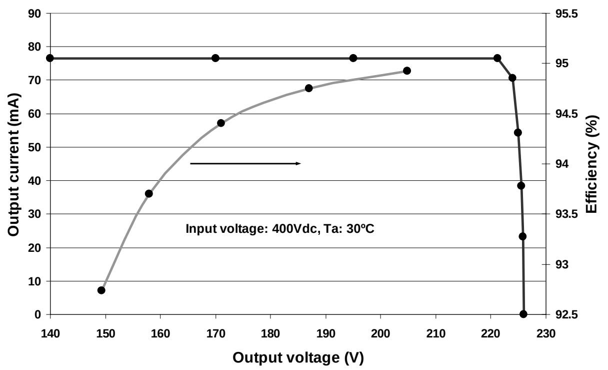

Fig. 6. Output characteristic of the LED drivers.

The graph in Fig. 7 shows the output current regulation at different input voltages for a LED string voltage of 171V. The variation is only 0.22mA (0.29%), translating into imperceptible luminous flux variations regardless of main PFC unit output voltage regulation.

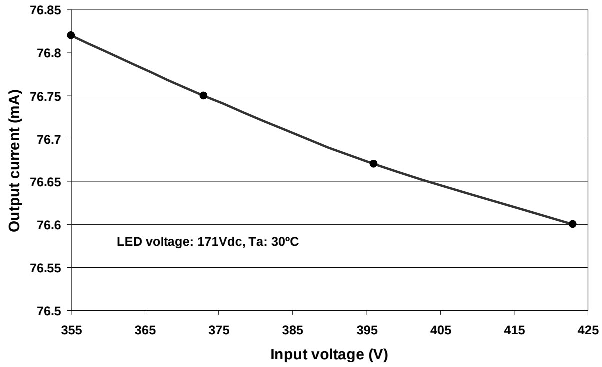

Fig. 7. Current intensity regulation versus the input DC voltage.

All the results can be summarized into the graph in Fig. ***8***, which shows the overall lumen efficiency as a function of the number of luminaires. It can be seen that the best results for this particular configuration are obtained for more than 20 fixtures. However even when using 10 fixtures, the overall efficiency exceeds 103.5 lm/W.

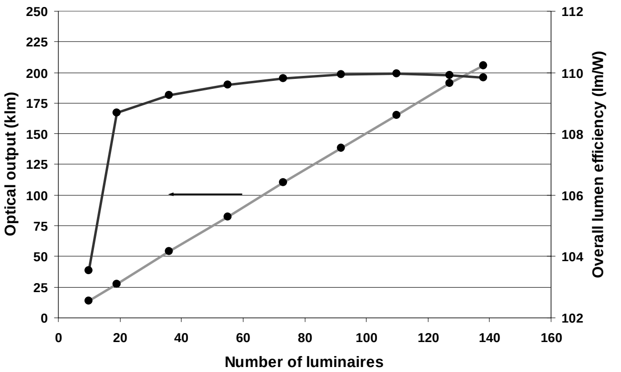

Fig. 8. Overall lumen efficiency and total optical output versus the number of luminaires.

4. Conclusions

A new configuration for power factor correction units in LED lighting has been proposed. We demonstrated the functionality and applicability of this concept by fabricating the main PFC unit and the additional current-limited drivers. The configuration surpasses the units available on the market in terms of overall efficiency and power factor, and meets the latest regulations regarding LED lighting sources. It has been found that the highest efficiency is achieved when using at least 12% of the power capability of the main PFC unit, and so the system must be scaled to fit the actual requirements of the space to be illuminated. Also the system can be easily integrated in most existing 230V electrical grids with minimal modifications and is inherently short-circuit proof because it includes an over-current protection on the main 400Vdc bus, thus basically eliminating the need for panel fuses.

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