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Optimization and Performance Evaluation of an AC-Chopper Ballast for HPS Lamps

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Abstract—Electronic ballasts for high-pressure sodium lamps based on an ac-chopper topology are proposed as a cheaper and less complex alternative to the industry-standard low-frequency square-wave ballasts. In this paper, the design process of the ac-chopper ballast is reviewed, and the design tradeoffs caused by the single-stage topology are discussed. The analytical and simulation results are verified with measurements of a 250-W prototype system, including a detailed list of the losses for the different circuit components and electromagnetic compatibility measurements. Due to the disadvantages of the single-stage topology, a comparison to a two-stage ballast using the inverter stage of the ac-chopper ballast with a separate power factor correction stage is provided.

Index Terms—High-pressure sodium (HPS) lamp, lamp ballast, single stage.

I. INTRODUCTION

HIGH-PRESSURE sodium (HPS) lamps see widespread use for public lighting applications due to their high luminous efficacy and long lifetime. Like other types of high-intensity discharge (HID) lamps, HPS lamps have a negative resistance characteristic and require a ballast to limit the lamp current during operation. Additionally, an igniter is required to start the lamp arc with voltage pulses in the range of several kilovolts. For reasons of cost and reliability, HPS lamps are usually operated with electromagnetic ballasts. However, electromagnetic ballasts have several disadvantages, including a poor power factor, relatively low efficiency, light flicker, and poor power regulation. Electronic ballasts avoid most or all of the problems depending on the employed circuit topology. The main challenge for using electronic ballasts with HID lamps is that the high-frequency (HF) operation can excite acoustic resonances in the lamp which can potentially lead to the destruction of the lamp. Even a small amount of current ripple can trigger a resonance if the switching frequency coincides with the frequency of a resonance mode [1].

Several approaches have been published to avoid acoustic resonances in HID lamps: The most common is supplying the

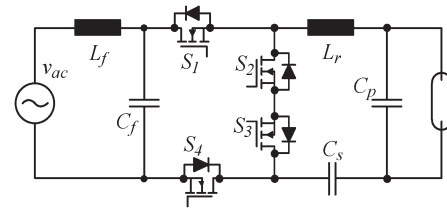


Fig. 1. AC-chopper ballast topology (complete EMC filter shown in Fig. 14).

lamp with a low-frequency square-wave (LFSQ) current [2], [3]. The main disadvantage is the circuit complexity of the two- or three-stage ballasts; however, several LFSQ ballasts with a reduced number of components have been proposed [4]–[7]. Alternatively, Tomm *et al.* [8] presented a ballast which supplies the lamp with a low-frequency sine-wave current. Further concepts include modulation schemes to avoid the excitation of the resonances [9] and operating the lamp above the resonance range. The last option is particularly interesting for HPS lamps due to the relatively low switching frequency around 120 kHz [10] compared to several megahertz for other lamp types [11].

An electronic ballast for HPS lamps based on an ac chopper (cf. Fig. 1) was presented in [12] and [13]. The converter topology has a reduced complexity compared to multistage ballasts, a high efficiency, and a potential longer lifetime because no electrolytic capacitors are required. The main disadvantage of the circuit is that, due to the missing dc-link capacitor, the sinusoidal input voltage causes a mains-frequency envelope of the HF-lamp current, resulting in light flicker and low quality of the input current due to the nonlinear characteristic of the lamp.

This paper further investigates the ac-chopper ballast to provide additional information for a potential industry application of the topology. New contributions are the investigation of a switching frequency modulation to improve the current waveforms, a detailed list of the component losses in the converter, electromagnetic compatibility (EMC) measurements, and a comparison of the losses to a two-stage ballast. Additionally, the switching frequency was increased to 120 kHz to avoid excitation of acoustic resonances. Section II explains the principle of operation for the ac-chopper ballast as presented in [12] and [13] and the effect of the nonlinear lamp characteristics on the circuit performance. In Section III, the design process for the resonant tank is shown. The input and output current waveforms can be influenced by a modulation of the switching frequency over a mains half cycle which is discussed in Section IV. Section V presents the hardware prototype including the losses for different components and EMC measurements. Finally, Section VI compares the ac-chopper ballast to a two-stage topology.

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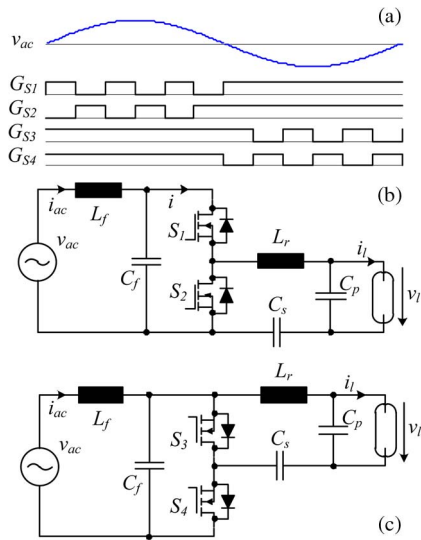


Fig. 2. (a) Gate signals of the switches for one mains cycle (low switching frequency shown to improve visibility) and equivalent circuits for (b) positive and (c) negative input voltages.

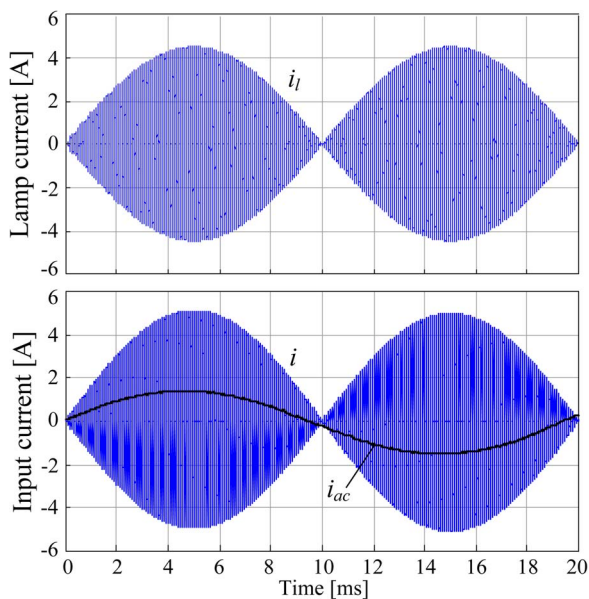


Fig. 3. Simulated output and input currents with a resistive load.

II. PRINCIPLE OF OPERATION

The circuit consists of two half bridges S_1/S_2 and S_3/S_4 and an *LCC* series–parallel resonant tank. Fig. 2(a) shows the gate signals over a mains period. For a positive input voltage v_{ac} , MOSFETs S_3 and S_4 are turned on constantly while S_1 and S_2 are operated as a half bridge with a duty cycle of 0.5 [cf. Fig. 2(b)]. For negative half cycles, S_1 and S_2 are on, and S_3 and S_4 form the switched half bridge [cf. Fig. 2(c)].

As a result of the resonant tank, the lamp current is approximately sinusoidal with a frequency equal to the switching frequency of the half bridge. In order to avoid excitation of the acoustic resonances, the switching frequency must be above the frequency range of the resonances. Fig. 3 shows the input and output currents for a resistive load. Since the currently active

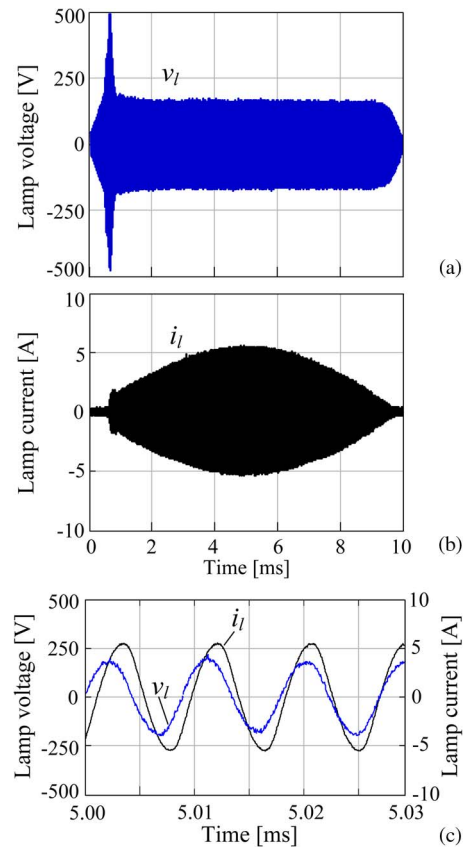


Fig. 4. Low-frequency lamp (a) voltage and (b) current waveforms with a 250-W HPS lamp and (c) HF waveforms around the peak of the mains voltage.

half bridge is supplied directly from the mains voltage, the output waveforms are modulated with the mains frequency.

The current–voltage characteristic of an HPS lamp shows a strong dependence on the operating frequency. At the mains frequency, the characteristic is highly nonlinear due to the variation of the lamp temperature over a mains half cycle. With increasing operating frequency, the lamp characteristic becomes more linear and finally shows a resistive behavior [14].

Fig. 4 shows the output voltage and current waveforms of the ballast supplying a 250-W HPS lamp. The lamp is extinguished near the zero crossing of the mains voltage until the voltage is large enough to reignite the lamp. The required voltage for reignition increases during the warm-up of the lamp. If the ballast is not able to supply the required voltage, the lamp will turn off completely.

Due to the nonlinear characteristic of the lamp, the envelope of the voltage is not sinusoidal. Fig. 5 shows the variation of the lamp resistance over a mains half period, which was calculated from the voltage and current waveforms. The decreased temperature in the lamp results in an increased resistance near the zero crossing of the mains voltage.

The impedance of the resonant inductor L_r limits the current through the lamp; therefore, no direct lamp current control is required. However, operating the lamp above the rated power has to be avoided since HPS lamps are filled with excess sodium amalgam to increase the lifetime of the lamp. Operation above the rated power evaporates additional amalgam which decreases the lamp resistance, potentially leading to a thermal runaway.

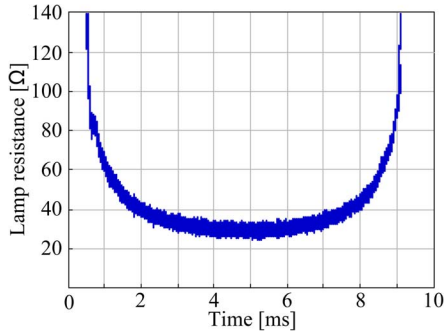


Fig. 5. Lamp resistance over a mains half cycle (calculated from the voltage and current waveforms).

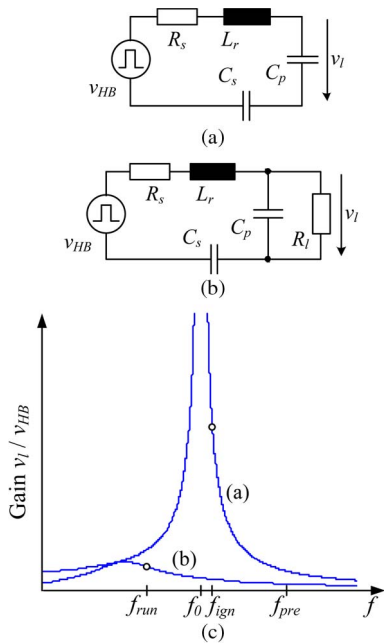


Fig. 6. Equivalent circuit of the resonant tank (a) before and (b) after ignition. (c) Calculated voltage gain curve in dependence on the equivalent lamp resistance.

III. DESIGN OF RESONANT TANK

The performance of the ac-chopper ballast is primarily determined by the design of the *LCC* resonant tank. Fig. 6(a) and (b) shows equivalent circuits of the resonant tank before and after the ignition of the lamp, respectively. When the lamp is off, the resonant tank is only damped by the resistor R_s , consisting of the resistance of the inductor L_r and the on-resistance of the MOSFETs [cf. Fig. 6(a)]. Using a switching frequency f_{ign} close to the resonance frequency f_0 , a high voltage can be created to ignite the lamp. The ignition sequence starts by operating the ballast at a switching frequency f_{pre} well above the resonance frequency. Close to the maximum of the mains voltage, an ignition pulse is then created by reducing the switching frequency to f_{ign} for 1 ms.

After the ignition of the lamp, the lamp resistance is in parallel to the capacitor C_p [cf. Fig. 6(b)] and damps the resonance. The resulting voltage gain curves are shown in Fig. 6(c). The average output current after ignition can be controlled by changing the switching frequency f_{run} .

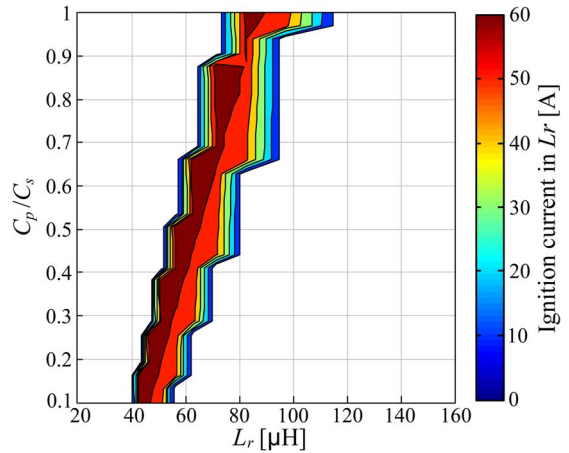


Fig. 7. Ignition current in the resonant inductor L_r for different combinations of the resonant tank components. Values exceeding the allowed current are shown in white.

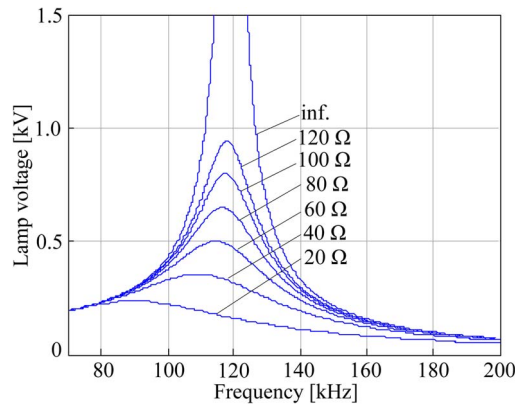


Fig. 8. Variation of the output characteristic of the resonant tank for different values of the load (cf. Fig. 5).

Due to the nearly sinusoidal waveforms, the currents and voltages in the resonant tank are calculated using the fundamental frequency analysis.

The design process starts with the definition of value ranges for the components L_r , C_p , and C_s and the generation of a number of discrete component values within the value range. For each combination of values, the currents and voltages at ignition and in normal operation are calculated. Finally, the valid combinations are selected using the following criteria.

- 1) The maximum ignition current has to be limited in order to avoid excessive losses in the MOSFETs and saturation of the inductor L_r . As shown in Fig. 7, a maximum value of 60 A reduces the valid combinations considerably.
- 2) The minimal switching frequency has to be over 110 kHz to avoid the excitation of acoustic resonances. Additionally, f_{run} needs to be higher than the resonance frequency of the *LCC* tank to ensure zero-voltage turn-on of the MOSFETs.
- 3) The difference between the resonant frequency before ignition and that at the lowest lamp resistance is limited to 20 kHz. Larger differences lead to increased variation of the output characteristic due to the variation of the lamp resistance during a mains half cycle (cf. Figs. 5 and 8)

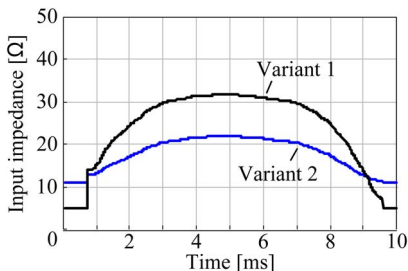


Fig. 9. Variation of the input impedance of the resonant tank over a mains half cycle. (Variant 1) $L_r = 80 \mu\text{H}$, $C_p = 35 \text{ pF}$, and $C_s = 55 \text{ nF}$. (Variant 2) $L_r = 55 \mu\text{H}$, $C_p = 53 \text{ pF}$, and $C_s = 84 \text{ nF}$.

which complicates the use of a switching frequency modulation.

- 4) The current in the parallel capacitor C_p has to be limited in order to avoid unnecessary losses in the switches and the resonant inductor. However, a larger capacitor decreases the variation of the input impedance over a mains half cycle (cf. Fig. 9). Therefore, there is a tradeoff between the input behavior and the efficiency of the ballast.

IV. SWITCHING FREQUENCY MODULATION

The behavior of the ac-chopper ballast for a given resonant tank can be influenced by a modulation of the switching frequency during a mains half period. The modulation function is implemented in the DSP as a table with 20 entries with linear interpolation in between. The modulation function allows changing the time for the lamp reignition after a zero crossing of the mains voltage by moving the switching frequency close to the resonance frequency. Furthermore, the shape of the input current can be controlled to a certain degree.

The main limitation is that there is only limited control over the lamp current close to the zero crossing of the mains voltage. Due to the high lamp resistance in this time interval, a change of the switching frequency mainly changes the current through the parallel capacitor. The second major limitation is the lack of lamp models describing the mixed low-frequency and HF operation used by the ballast. Therefore, the modulation function has to be adjusted empirically.

Fig. 10 shows measurements of the voltage and current waveforms for the prototype system with a modulation table which minimizes the length of the zero-current interval in the lamp current. The switching frequency is reduced close to the resonant frequency 0.5 ms after the zero crossing of the mains voltage to increase the voltage gain. Additionally, the switching frequency is also reduced before zero crossing to delay the extinction of the lamp as long as possible, resulting in a zero-current interval of approximately 1 ms. As shown in the input current waveform, this results in a heavy distortion of the current.

The limits of the input current harmonics for ballasts are defined in the standard IEC 61000-3-2 Class C as a percentage of the fundamental (see Table I). The diagram at the bottom of Fig. 10 shows that the limits are clearly exceeded.

Fig. 11 shows a modulation function which was modified to improve the input current shape. The reignition of the lamp is delayed which increases the zero-current interval of the lamp to about 2 ms. The input current shape is more sinusoidal than

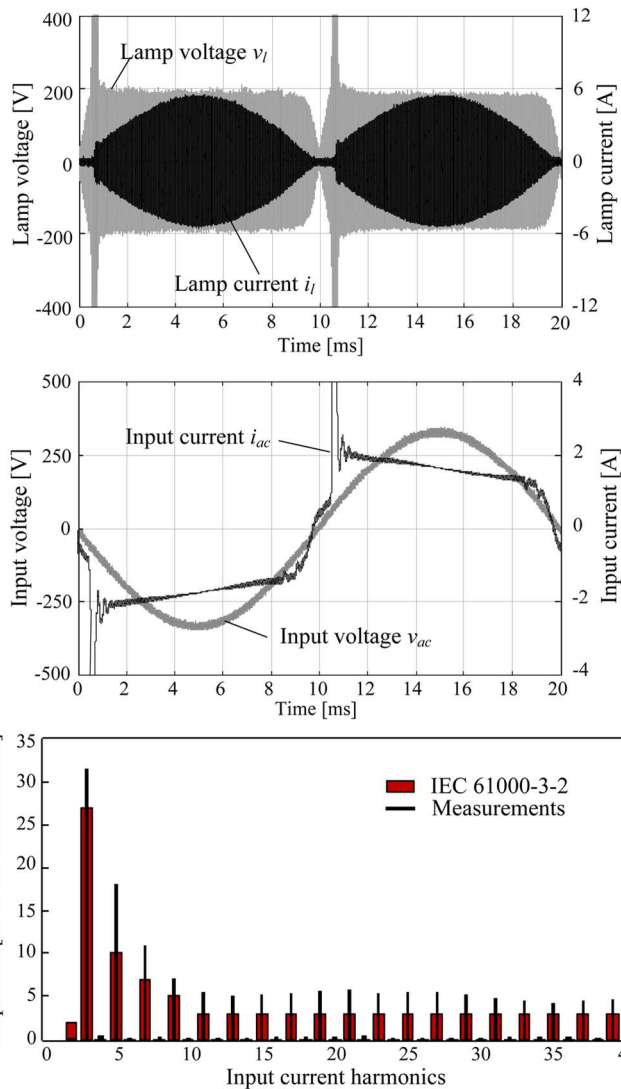


Fig. 10. Lamp and input waveforms and input harmonics for a modulation table which minimizes the zero-current interval in the lamp current to 1 ms.

TABLE I
LIMITS OF INPUT CURRENT HARMONICS ACCORDING TO IEC 61000-3-2 CLASS C. LIMIT OF THIRD HARMONIC IS 30 TIMES POWER FACTOR

Harmonic	2	3	5	7	9	11-39
Limit [%]	2	$30 \cdot \lambda$	10	7	5	3

that in Fig. 10, but the 11th and 13th harmonics still exceed the limits.

The modulation table and the input current are shown in Fig. 12. The table was tuned experimentally with the following goals for the different parts of the mains half cycle.

- 1) 0–1.5 ms: The switching frequency is well above the resonant frequency for the first millisecond before it is decreased to 124 kHz. This results in a delayed reignition of the lamp.
- 2) 1.5–2.5 ms: The switching frequency is increased again to avoid the high input current in this range observed in Fig. 10.
- 3) 2.5–8 ms: The modulation function follows approximately a sinusoidal function to shape the input current.

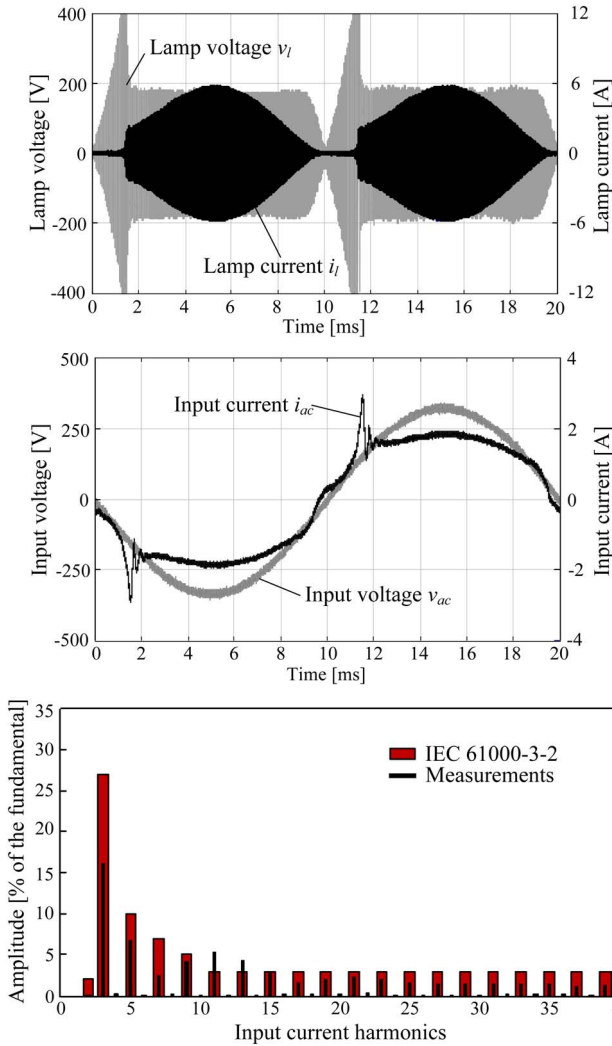


Fig. 11. Lamp and input waveforms and input harmonics for a modulation table which improves the input current shape.

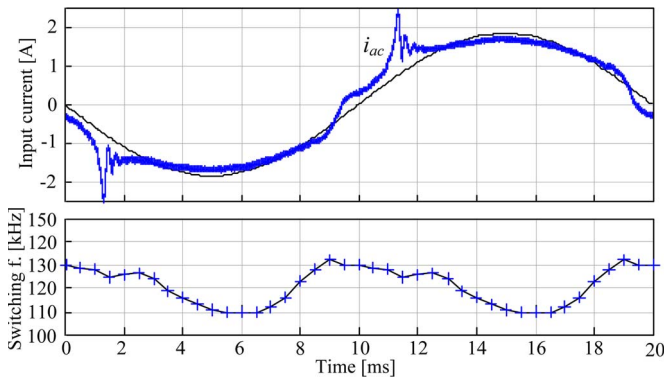


Fig. 12. Input current and modulation table. For the lower diagram, the change of the output characteristic with the lamp resistance has to be considered (cf. Figs. 5 and 8).

Due to the damping of the resonant tank, the switching frequency can be lower than the open-circuit resonant frequency.

- 4) 8–10 ms: The switching frequency is increased again for the next cycle.

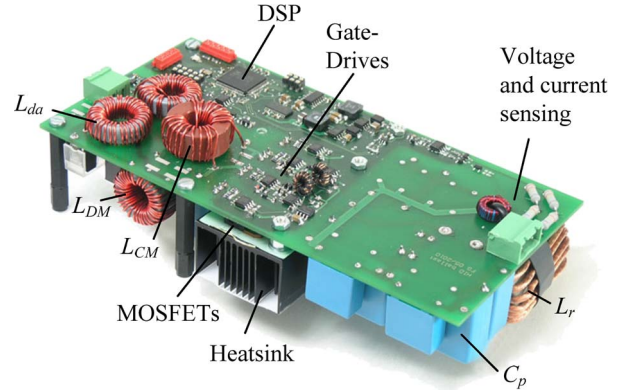


Fig. 13. Prototype of an ac-chopper ballast for a 250-W HPS lamp.

TABLE II
COMPONENT VALUES (CF. FIG. 1)

S_{I-A}	-	ST STP30NM60ND
L_r	82 μ H	N = 27, 4xMagnetics 55326
C_p	35 nF	2 Epcos B3265x 2000 V (in series)
C_s	55 nF	Epcos B3265x 2000 V

TABLE III
LOSSES IN BALLAST COMPONENTS

L_r core	3.6 W	EMC filter	0.3 W
L_r winding	0.9 W	DSP	1.2 W
S_{I-A} conduction	4.4 W	Gate-drives	0.4 W
S_{I-A} switching	4.5 W	Auxiliary PSU	0.4 W
C_p and C_s	0.2 W		
Total			15.9 W
Total (measured)			17.1 W

Apart from the reignition peak, the main problem for the input current harmonics is the zero crossing which cannot be influenced by the switching frequency modulation.

The average lamp current is controlled by changing the switching frequency between 2.5 and 8 ms. The lamp current is measured using a current transformer, rectified and filtered, before it is sampled with the A/D converter of the DSP. The measured average current is compared to the reference, and a proportional–integral controller is used to provide a switching frequency value that is added to the modulation table.

Additionally, the switching of the MOSFETs is stopped if the output voltage exceeds 800 V to protect the ballast in case the lamp extinguishes or fails.

V. HARDWARE

A prototype of the ac-chopper ballast for a 250-W HPS lamp was built to verify the simulations (cf. Fig. 13). A Texas Instruments TMS320F2808 DSP used for control provides flexibility for experiments with frequency modulation. The values of the most important components (cf. Fig. 1) are listed in Table II.

Table III shows the losses of the ballast components. The switching losses were approximately calculated from eight measured points during a mains half cycle. The core losses of the resonant inductor L_r were calculated for each switching

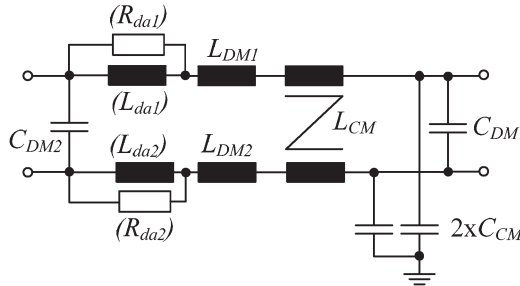


Fig. 14. Schematic of the EMC filter.

TABLE IV
COMPONENT VALUES OF EMC FILTER

$L_{DM1,2}$	250 μ H	C_{CM}	20 nF
L_{CM} (at 120 kHz)	2.9 mH	$(L_{da1,2})$	200 μ H
C_{DM}	2.2 μ F	$(R_{da1,2})$	3.5 Ω
C_{DM2}	690 nF		

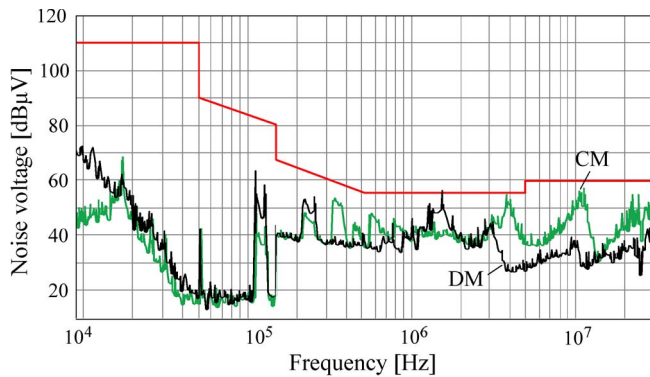


Fig. 15. Differential- and common-mode noise voltage spectra.

cycle in a circuit simulation using *GeckoCIRCUITS*, and the loss curves were provided by the core manufacturer *Magnetics*.

Additionally, the total losses were measured in a calorimeter [15]. Using the measured value, the efficiency of the ballast is 93.6%. The efficiency is reduced by the reignition of the lamp in each mains half cycle which increases the losses in the switches and the resonant inductor.

Fig. 14 shows the circuit diagram and Table IV presents the component values of the EMC filter used in the prototype, consisting of a *CLC* differential-mode filter and a *CL* common-mode filter. The relatively large value of C_{DM} is required to limit the voltage over the switches at the ignition of the lamp. Measurements showed that the input current has no significant components at the resonant frequency of L_{DM} and C_{DM} . Therefore, the damping resistors R_{da1} and R_{da2} and the bypass inductors L_{da1} and L_{da2} can be removed without affecting the performance of the ballast.

A reference ballast according to CISPR30-3 was used for the EMC measurements. Fig. 15 shows the differential- and common-mode noise components measured with a single-phase version of the noise separator presented in [16]. The relatively wide peak at the switching frequency is caused by the frequency modulation (120–130 kHz). The peak total noise voltage spectrum with automatic quasi-peak measurements shows that the requirements are fulfilled (cf. Fig. 16). For a commercial ap-

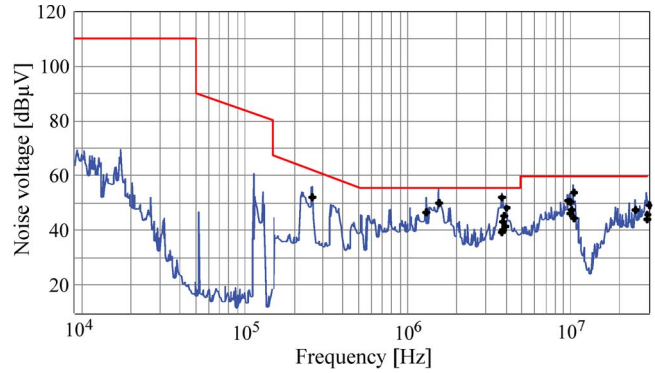


Fig. 16. Total noise voltage (peak) with (+) automatic quasi-peak measurements.

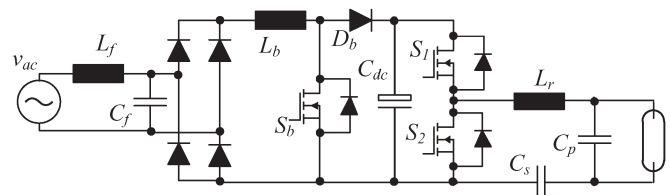


Fig. 17. Two-stage ballast topology.

TABLE V
PFC COMPONENT VALUES (CF. FIG. 17)

S_b	-	Infineon IPP60R385CP
L_b	0.42 mH	N = 66, Epcos EFD 30 N87
D_b	-	Fairchild RURD660S
C_{dc}	100 μ F	-

TABLE VI
LOSSES FOR TWO-STAGE BALLAST (PFC LOSSES
ARE SIMULATED RESULTS)

L_r core	3.1 W	EMC filter	0.3 W
L_r winding	0.6 W	DSP	1.2 W
$S_{1,2}$ conduction	1.5 W	Gate-drives	0.3 W
$S_{1,2}$ switching	3.8 W	Auxiliary PSU	0.4 W
C_p and C_s	0.2 W	S_b conduction	0.3 W
L_b core	0.5 W	S_b switching	1.2 W
L_b winding	0.3 W	D_b conduction	0.7 W
Bridge rectifier	3.6 W		
Total			18.0 W

plication, a larger safety margin would be required to allow for tolerances of the filter components.

VI. COMPARISON WITH TWO-STAGE BALLAST

The issues caused by the nonlinear behavior of the lamp in the ac-chopper ballast can be avoided, if the inverter stage is supplied from a dc voltage. Therefore, a two-stage ballast was investigated as a comparison, using measured data of the output stage and simulated data for the power factor correction (PFC) stage.

Fig. 17 shows the circuit diagram of the ballast combining the resonant output stage of the ac-chopper ballast with a PFC stage in boundary condition mode. Table V presents the most important PFC components used for the simulation.

The losses for the components of the two-stage ballast are shown in Table VI. Since there is no reignition of the lamp in every mains half cycle, the losses in the inverter stage are lower than those in the ac-chopper ballast. The total losses are slightly higher, but an efficiency in the range of 92%–93% should be achievable in a practical realization.

The main advantage of a two-stage ballast is that the dc-link capacitor removes the tradeoff between input and output current qualities seen in the ac-chopper ballast: With a separate PFC stage, the standards for the input current harmonics can be fulfilled, and the light of the lamp is flicker-free when the inverter is supplied from a dc-link capacitor.

Apart from the slightly higher efficiency, the main advantage of the ac-chopper ballast is that the relatively small capacitance values allow using film types for all capacitors in the power path. This can potentially increase the reliability and lifetime of the ballast, because the electrolytic dc-link capacitor is a limiting component for the lifetime of multistage ballasts [17].

VII. CONCLUSION

The main limitation of the ac-chopper ballast is the nonlinear characteristic of the lamp due to the mains frequency envelope of the output waveforms. This results in a tradeoff between the current quality at the input and output sides and the efficiency of the converter. Modulation of the switching frequency improves the current quality, but the input current harmonic regulations could not be fulfilled with the prototype.

The main advantages of the ac-chopper topology are an efficiency of more than 93% and the lack of electrolytic capacitors, which potentially increase the reliability and lifetime of the ballast.

A comparison with a two-stage ballast based on the resonant inverter stage of the ac-chopper ballast and a boost PFC shows that a similar efficiency can be expected with fulfilled input current harmonic standards and flicker-free light output.

Due to the disadvantages of the topology, the ac-chopper ballast is limited to applications where moderate input current and light quality is acceptable.

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