A versatile power source for HID Lamps

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***Abstract*— One of the results of the EU COST action n°529, "Efficient Lighting for the 21^{st} century", is a standard HID lamp with prototypes available since January 2005. As one of the purposes of this lamp is its use as a research tool, various solutions to supply the lamp with electrical power can be used. A versatile power source will be presented, permitting to operate and study HID lamps under a variety of driving conditions, including current control. The most important properties of this device are discussed in this paper.**

I. Introduction

High Intensity Discharge (HID) lamps are a "hot" topic, both from a research and commercial point of view. Key properties [1], [2] include higher energy efficiency, compact size, good color rendering, whiter light (higher color temperature), and longer lifetime. Typical applications range from car headlamps, greenhouse lighting, to interior lighting and projection systems.

Unfortunately, their inner operation still requires some work to be better understood. The electric discharge occurs in a high pressure plasma, so the modelling implies to take into account a broad range of coupled phenomena: electrical properties, chemical reactions, temperature distribution, particles convection, electrodes interactions, radiative transfers, ...

Given the high level of complexity, various members of the European COST 529 action [3] are performing research on specific aspects: materials; diagnostic and modelling; associated power electronic supply; and novel concepts like Hg-free lamps and organic LEDs. But, at the time of writing, there is still no link between the field variables and the global electrical behaviour.

In order to make data exchange possible between the research teams involved in this action, a reference HID lamp has been designed by Philips Lighting, Eindhoven. At the same time, there is a need for a flexible power source, where the waveforms global parameters can be easily varied.

A general-purpose switching power source developed at the K.U.Leuven can be used for this purpose, permitting to operate and study the lamp under a variety of driving conditions. After a review of the specificities of the I-U characteristic and of the requirements put on the power supply, the main characteristics of this source will be presented in this paper, together with results obtained on commercially available HID lamps.

This paper is organised as follows: the context of lamp modelling is exposed in sec. II. Sec. III is about the specific requirements of HID lamp testing. The main characteristics of the proposed power source are explained in sec. IV, and the test circuit is illustrated in sec. V. Further test capabilities are discussed in sec. VI.

II. HID lamp modelling

A. Context

There is a demand for specialised models of an HID lamp from different sides:

1) lighting designers require photometric characteristics such as color rendering and radiation diagram;
2) engineers in charge of the power supply need both the lamp efficiency (lm/ W) and the voltage-current characteristic in order to predict the amount of harmonics generated by the lamp and its supply;
3) scientists studying the inner working of the lamp obtain results expressed as fields values, *i.e.* spatial distribution of ions and electrons temperature, ion density, gas speed, ...

There is thus a need to link and validate models across these levels, which involves going from local, distributed values to global variables.

To perform tests and validate such methodology, a common reference HID lamp is now available. Its purpose is two-fold:

1) as a reference lamp, to assert findings in one laboratory at another laboratory, working on an identical data source;
2) as a research lamp, to provide a common tool in order to study particular aspects of the model.

In the first situation, the lamp has to be operated on standardised and well defined conditions. In the second situation, a flexible power source is required to permit experimenting on various aspects.

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B. Plasma modelling

HID lamps generally contain, when operated:

1) Mercury, both at liquid and vapor state; the global pressure inside the lamp being a function of the coldest temperature of the bulb where mercury condensates;
2) Metal Halide molecules, which are minor species but have a major influence on light properties;
3) atoms;
4) electrons and ions.

Modelling [4]–[6] generally implies to numerically solve the state equations resulting from the following processes:

1) the temperature field results from a power balance between the electrical power dissipated into the arc and the heat evacuated to the outside;
2) momentum and mass balance permits to compute the bulk flows: in HID lamps, the plasma is generally considered as a fluid rather than as a gas;
3) elemental densities are coupled with species flows, governed by diffusion and reaction rates;
4) the electrical field is solution of the Laplace or Poisson equation;
5) the chemical composition is obtained from the Saha or Gibbs equation;
6) the radiation transport is more difficult to take into account, as it occurs non-locally: one possible way to compute it is to use ray-tracing techniques [7];
7) the cathode and near-cathode area often require a specific approach [8]–[10].

For computational feasibility, the various models tend to focus on some particular aspects, and require appropriate simplifications or linearisations. Computation is performed either on own-developed software, or on commercial environment, but taking into account all the involved processes is in general a daunting task. The final result consist of maps of the variables.

C. Global model

Such detailed models are too heavy for simpler tasks such as ballast design [11], [12], or evaluating the influence of HID lamps on power distribution networks [13]. There are a number [14] of ways to express the non-linear voltage-current characteristic of discharge lamps through simpler models.

In such cases, a description of the lamp by an equivalent electric circuit is needed, which on the one hand possesses the required structure to fit the framework used to simulate electric circuits (*e.g.* Spice and PS-CAD), and on the other hand describes correctly the lamp operation without being restricted to a too limited domain of validity.

A dynamic conductance model [13], [15] satisfying those requirements goes as follows:

$$\frac{dG(t)}{dt} = a_2 I^2(t) - [b_3 G^3(t) + b_2 G^2(t) + b_1 G(t)] \qquad (1)$$

where $G(t) = I(t)/U(t)$ is the lamp conductivity and a_2, b_1 to b_3 are parameters that have to be obtained through a fitting procedure on real lamp data.

This model is a good compromise between accuracy and complexity. It describes the change of the global conductance over time during one voltage cycle, and can even describe the I-U hysteresis.

One drawback is that, under this form, it becomes ill-defined around the voltage zero crossings, this problem is currently under investigation.

III. HID lamp testing

Due to the complexity of the I-U characteristic, and in particular the negative dynamic resistance around the normal operating point, some stabilising device has to be associated with the lamp to maintain a stable operating point and to avoid lamp failure.

An inductor (ballast), or a combination inductor/capacitor is usually applied, although a resistor can also play this role but should be avoided due to the high losses.

In combination with a conventional power source (transformer), this is a simple, yet effective solution to power the lamp. But the parameters of the voltage waveform can only be adjusted by modifying the value of the associated elements.

Most commercially available power amplifiers behave as voltage source, so the current has to be taken "as is". But HID lamps requires a tight current control:

- due to the high working temperature, the housing is already under high mechanical and thermal stress. Increasing the current beyond 1.5 times the nominal value can lead to a lamp failure.
- reducing the current and hence the temperature means that the mercury pressure will decrease, leading first to a drift of the operating point, and later to lamp extinction.
- sometimes, a maximum crest factor is also specified.

Furthermore, HID lamps may be subject to a phenomenon known as "acoustic resonance" [16]: if the voltage waveform spans some specific frequency range, static pressure waves may occur inside the lamp. Such waves hinder the normal flows of species, and the arc can no more be sustained.

A last particularity is that those lamps generally need to cool down before being restarted, as the initial breakdown voltage increases quickly with the internal gas pressure. For a hot lamp, the required initial voltage pulse may be greater than the maximal allowed values determined by the dielectric strength of the wiring system. Great care has thus to be taken to avoid such extinction.

A general purpose inverter [17]–[19] permits to provide flexibility with regard to waveform parameters and to implement simultaneously current control, as explained in the next section.

(a) raw waveforms

(b) averaged current and voltage

Fig. 1. Experimental setup, scope screen capture.

IV. Setup

The control, measurement and inverter unit are components of a flexible rapid prototyping platform already used in numerous other applications [17], [18]. The inverter unit consists of up to four independent half bridge power stages, controlled by a digital signal processing core containing a DSP (TI ’C6711) and an FPGA (Altera EP1K100).

In order to achieve increased output frequencies up to 60 kHz, this particular inverter unit is equipped with power MOSFET devices (APT5020), giving it an output voltage and current rating of 400 V and 16 A.

Due to the highly nonlinear operating current of a HID lamp, digital hysteretic current control is applied.

A high-speed (500k samples/s) analog to digital converter provides current measurements to the FPGA, in which the value is compared to the upper and lower limit of the current band. Then, the appropriate inverter switches are selected to keep the output current inside the hysteresis band. After a switching operation, blanking is used to avoid detection of unavoidable oscillatory transients.

By proper selection of the current bandwidth, the output frequency is limited during normal operation. Nevertheless, as the HID lamp is in series with the output inductor, there may be – especially during the ignition phase with ignitors using the ballast to generate the starting voltage – a very high voltage across the inductor, making it impossible to guarantee a frequency limit.

Therefore, a frequency discriminator, which forms part of the inverter protection unit [19], is needed, which turns off the system if a switching frequency in excess of 30 kHz is detected.

As a current is imposed on the lamp, control of the lamp power requires a measurement of the output voltage being applied to it by the hysteretic current regulator. This voltage is derived from the DC bus voltage measurement and the average duty cycle of the output stage, which is easily obtained with a digital counter in the FPGA.

The DSP performs the lamp power control and provides the FPGA with a reference current value based on the acquired output voltage. The bandwidth of the lamp power control loop is currently 1 Hz and well below the power supply frequency, which can be varied.

Obviously, it is possible to program any arbitrary lamp current, provided that the serial inductor is not too large to allow the hysteretic current controller to follow the reference with the available internal DC bus voltage (400 V).

For the experiments described in the next section, a serial inductor of L = 0.7 H has been used, resulting in a current ripple below 50 mA peak. A smaller inductance was also used (L = 150 mH) which allows higher lamp current frequencies, but with increased current ripple levels (150 mA peak).

The DSP software was generated using the MatLab / Simulink Real Time Workshop, which also allows on-line parameter changes using the External Mode feature.

V. Experimental setup

Off-the-shelf components, in conjunction with the general purpose power source, have been used to operate a HID lamp similar to the reference lamp:

1) a ferromagnetic ballast (inductor);
2) a lamp ignitor to provide a high voltage pulse for the initial plasma breakdown.

Pictures of the global setup are illustrated on Fig. 2 and 3. The lamp was operated with sinusoidal current at 50 Hz, a scope screen capture can be viewed on Fig. 1. The top trace is the current and the bottom trace the voltage.

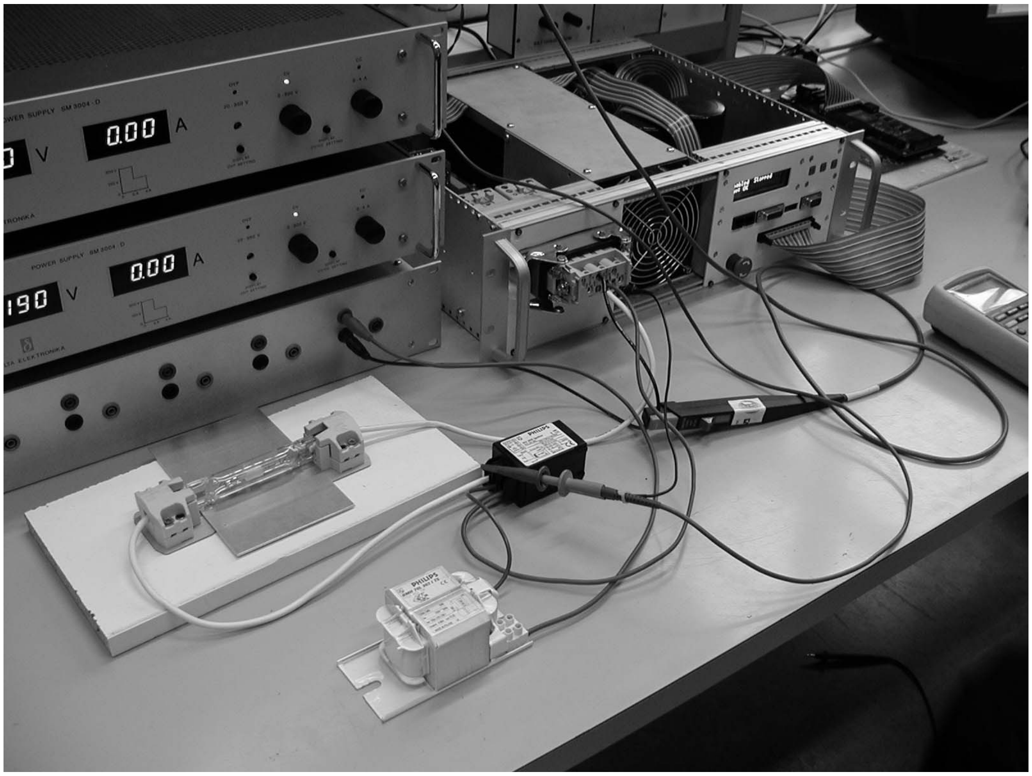

Fig. 2. Experimental setup, components.

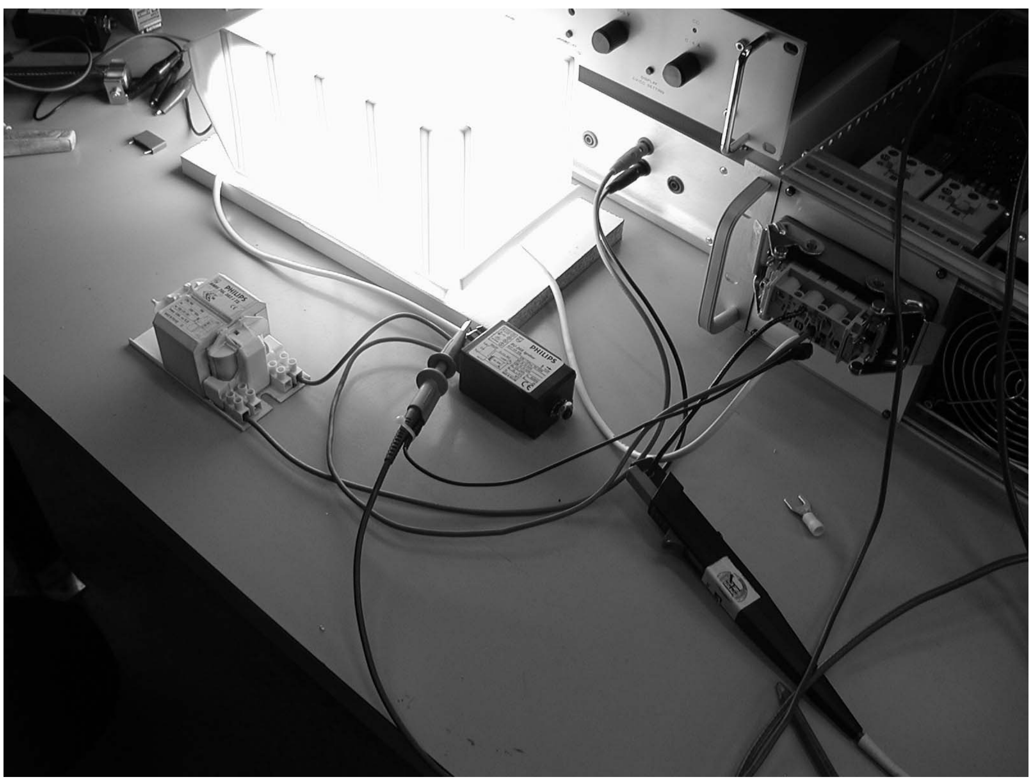

Fig. 3. Experimental setup, operated lamp.

Both the current and the voltage have been measured directly across the lamp with appropriate probes. The high frequency noise is due to the switching of the control circuit and to the coupling through the ground connection. Averaging on sixteen runs results in a much cleaner picture, as illustrated on Fig. 1(b).

The lamp was operated at a current of 0.7 A RMS and a power level of around 50 W. The voltage plateau is approximately at 80 V. It may be noticed that a very high dV/dt is applied around the current zero-crossing, where the arc gets extinct and the lamp requires some over-voltage to re-ignite in the opposite direction.

VI. System capabilities

Given the high flexibility of the system, it is possible to implement more complex setups, such as:

1) to test other current waveforms like triangle, square, multi-sines, …;
2) to add pseudo-random binary signal during the stable part of a square wave in order to identify the lamp frequency response or time constant around its operating point;
3) to implement other control schemes, f.i. adjusting the current magnitude to operate the lamp at some given power;
4) to study specific topics such as the power efficiency or the relationship between the waveform and problems like the electrodes blackening or the end-of-life properties through specific waveforms.

VII. Conclusions

A high performance and programmable power supply has been presented, permitting to cope with the specificities of HID lamp. Such device can be used to apply various current waveforms across the lamp, and implementing at the same time the required current control, with a very short dead-time.

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