Design and Performance of an Electronic Ballast for High-Pressure Sodium (HPS) Lamps

Shmuel Ben-Yaakov, *Member, IEEE*, and Michael Gulko, *Student Member, IEEE*

***Abstract*—An electronic ballast for high-pressure sodium (HPS) lamps was designed and evaluated, theoretically and experimentally. The ballast is based on the half-bridge topology and includes a high-voltage ignitor and dimming capability. It was used to drive and examine the high-frequency characteristics of a commercial HPS lamp (NAV-T 150W (SON-T), OSRAM). The experimental results reveal that, for the frequency range of this study (27–75 kHz), the lamp is free of the acoustic resonance problem. It was also found that, for the present experimental conditions, the lamp is purely resistive, and the resistance is practically independent of the power level and operating frequency. The lamp exhibited stable operation over a very large dimming range, down to about 7% of nominal power. The 2.8-kV ignition pulse was found to be sufficient for both cold and hot startup under the proposed operating conditions.**

***Index Terms*—Acoustic resonance(s), dc–ac power converter, dimming, electronic ballast(s), high-pressure discharge lamp(s), light sources, lighting, power electronics.**

I. Introduction

Low- and high-intensity discharge lamps [1] are universally recognized as the most efficient method of illumination. They require, however, extra circuitry (ballasts) to regulate the current through the lamps. Electronic ballasts [1]–[3] can reduce the overall size and weight of the "ballast," facilitate dimming, and eliminate line frequency flickering [4].

High-pressure sodium (HPS) lamps belong to the class of high-pressure discharge lamps [5], [6], in contrast to fluorescent lamps, which are low-pressure lamps [1]. The main difference in the electrical characteristics between the two groups are related to the ignition voltage requirements and the susceptibility of the high-pressure discharge lamps to acoustic resonance. The acoustic resonance is associated with the physical dimension of the arc and the internal pressure. This problem was investigated in previous studies [7]–[11] that considered the design of electronic ballasts for high-pressure metal halide discharge (MHD) lamps. Little, however, is known about the characteristics of HPS lamps when driven by high-frequency electronic ballasts. Recent studies suggest that, similar to the fluorescent and MHD lamps, the HPS lamps should exhibit a resistive nature when driven at high frequency [12]. Still, other key questions related to ignition, dimming, and the possibility of acoustic resonance disturbances are yet open.

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The authors are with the Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel.
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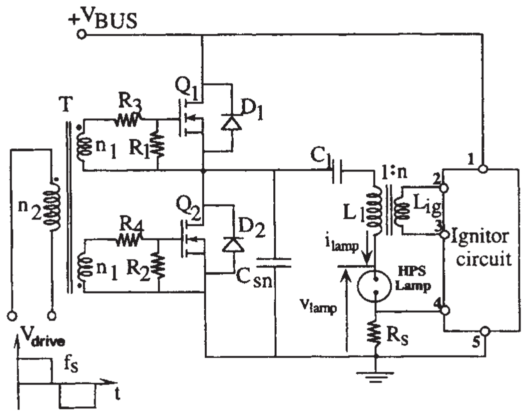


Fig. 1. The proposed HPS lamp electronic ballast.

The objective of this paper is to explore the design prerequisites for an electronic ballast suitable for driving HPS lamps. This was carried out by designing a high-frequency inverter and associated ignitor and applying these to study the electrical characteristics of a commercial HPS lamp (NAV-T 150W (SON-T), OSRAM).

II. Power Stage Design

The power stage was built around a half-bridge inverter (Fig. 1) fed by a high-voltage bus. The bus voltage of the present design was chosen to be 400 V to make it compatible with an "universal" active power-factor correction (PFC) front end. The half bridge is driven by a square wave of variable frequency, to facilitate dimming. The drive signal includes dead time that, along with the lossless snubber C_{sn}, helps to ensure zero-voltage switching (ZVS) of the main switches. The square wave generated by the inverter is coupled to the lamp via a blocking capacitor C_l and a series inductor L_l that control the current of the lamp.

The power delivered to the lamp can be estimated by considering the equivalent circuit presented in Fig. 2. The power delivered to the lamp (P_l) was found to be (see Appendix)

$$P_1 = \frac{2V_{\rm BUS}^2 R_1}{\pi^2\left[\left(\omega_s L_1 - \dfrac{1}{\omega_s C_1}\right)^2 + R_1^2\right]} \tag{1}$$

where $V_{\rm BUS}$ is the inverter's bus voltage, $\omega_s = 2\pi f_s$, f_s is the switching frequency, and R_l is the lamp resistance.

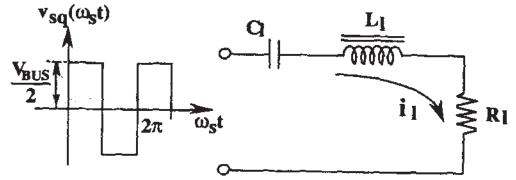


Fig. 2. Simplified equivalent circuit of the proposed ballast.

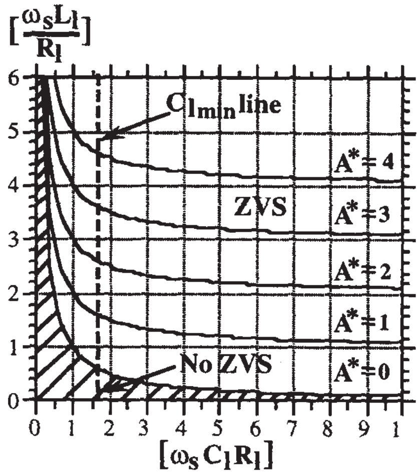


Fig. 3. Graphical presentation of (3).

Equation (1) assumes that the lamp represents a pure resistance (R_l), as suggested previously [14], and verified in this study (see Section IV-B). To retain ZVS, the switching frequency should be above the resonant frequency. That is,

$$\omega_s L_1 > \frac{1}{\omega_s C_1}. \tag{2}$$

The blocking capacitor C_l and the series inductor L_l, connected in series, control the current through the HPS lamp. However, the values of C_l and L_l, for a given series impedance, are not unique. In practical cases, there are normally additional constraints, such as minimizing the magnetic components. This optimization objective can be explored by rewriting (1) in the form

$$\frac{\omega_s L_1}{R_1} = A^* + \frac{1}{\omega_s C_1 R_1} \tag{3}$$

where A^* is defined in terms of known design parameters:

$$A^* = \sqrt{\frac{2V_{\rm BUS}^2}{\pi^2 R_1 P_1} - 1} \tag{4}$$

Equation (3), presented graphically in Fig. 3, reveals that minimum values of L_l are obtained from points to the right of the dashed line ($C_{l_{\min}}$ line) of Fig. 3, i.e., a reasonable operating point is when $\omega_s C_l R_l \approx 1.6$ and when $\omega_s L_1/R_1$ is chosen according to the required A^*. Little is gained, in terms of minimizing L_l, if C_l is increased beyond this value. The dashed area in Fig. 3 marks the operating points that do not fulfill the ZVS conditions of (2).

The simplified relationship (1) implies that the power level can be easily controlled by changing the switching frequency.

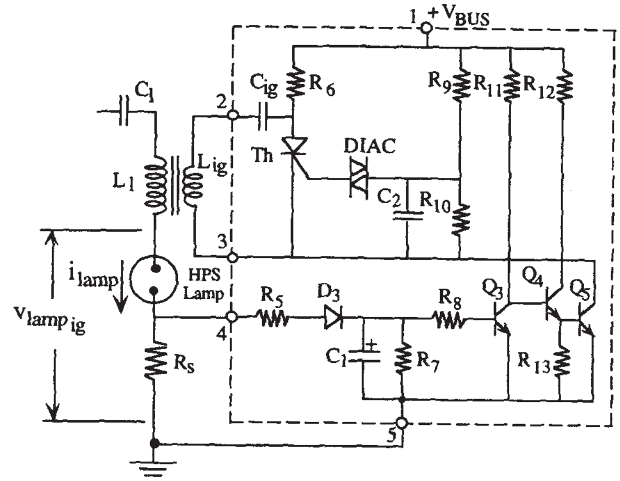


Fig. 4. The detailed ignitor circuit.

The higher the frequency, the lower the power delivered to the lamp.

III. Ignitor

The high-voltage spikes, necessary for ignition, are fed to the lamp serially via the inductor L_l (Fig. 1). The spikes are generated by a pulser (Fig. 4) that delivers a high-voltage excitation to the $L_{\rm ig}$ wound around the core of L_l. The turns ratio between the two windings was chosen to be about 12. That is, for a 400-V excitation, the secondary should reach, theoretically, peak levels of about 4.5 kV. In practice, the spike voltages will be lower due to various voltage drops, such as the overall resistance of the primary (taking into account the skin effect), the ESR of $C_{\rm ig}$, stray inductances of the wiring, and the coupling between the primary and secondary. Ignition pulses of the experimental ballast were measured to be about 3 kV, which is ample for ignition of the lamp under study.

The ignitor (Fig. 4) comprises a pulser [thyristor Th driven by a bidirectional breakdown device (DIAC)], a lamp current detector (D_3), and switches (Q_3–Q_5)). The fundamental features of the ignitor circuit will be described by considering the startup sequence. Before the HPS lamp is ignited, the voltage drop on the lamp current-sensing resistor (R_s) is zero, and the output voltage of the active peak detector (R_5, D_3, C_1, R_7) is low. Consequently, the transistor Q_3 is cut off, the emitter follower Q_4 is on, and the transistor Q_5 connects the pulser (point 3, Fig. 4) to the ground (point 5, Fig. 4). The ignition capacitor ($C_{\rm ig}$) is charged faster through the resistor R_6 up to $V_{\rm BUS}$ voltage, building up the voltage of the thyristor before the DIAC pulse is delivered. At the same time, the capacitor C_2 is charging through the parallel-connected R_9 and R_{10}. The time constant $R_6 C_{\rm ig}$ was chosen to be shorter than the time constant $((R9 \| R_{10})C_2)$. When the voltage of the capacitor C_2 is raised to forward breakover voltage ($V_{BR(F)}$) of the DIAC, the DIAC "fires," or turns on, allowing a flow of short pulse of capacitor C_2 current through the thyristor gate, i.e., the capacitor C_2 is discharged through the DIAC into the gate of the thyristor (Th). The thyristor is switched on and the ignition capacitor ($C_{\rm ig}$) is connected in parallel to the ignition inductor (L_{ig}). The high-voltage spike will be generated and delivered to the HPS lamp through L_{ig} wound around the core L_l. When the HPS lamp ignites, the lamp current produces a voltage drop across the lamp and current-sensing resistor (R_s), and transistor Q_5 disconnects the pulser from ground (point 3, Fig. 4). This will stop the pulser from generating high-voltage pulses. If the first high-voltage pulse does not ignite the HPS lamp, the discharge current of the ignition capacitor (C_{ig}) will drop and reduce the thyristor's current to below the holding current. As a result, thyristor will revert to its off state, and the pulse generation cycle will repeat itself until the lamp carries a steady current.

The pulse repetition rate was chosen to be about 200 pps, which was found ample to ignite the lamp within a fraction of a second, both for a cold and hot lamp. The duration and shape of the ignition pulses are controlled by two processes, the resonance interaction of L_{ig}, C_{ig} and saturation of the core. The resonance frequency of the ignitor circuit

$$f_{r_{ig}} = \frac{1}{2\pi\sqrt{L_{ig}C_{ig}}} \quad (5)$$

will prevail as long as the core does not saturate. Saturation could be easily reached, considering the fact that the number of turns of L_{ig} will be small ($L_{ig} = L_l/n^2$).

The time duration that the core can sustain a pulse is given by

$$t_s = \frac{2NA_eB_s}{V_S} \quad (6)$$

where

t_s time to saturation, s;
A_e effective area, m^2;
N number of turns of L_{ig};
B_s flux density at saturation, T;
V_s inductor voltage, V ($V_s = V_{BUS}$).

The holding time (t_s) should be long enough to strike the arc. Our experience shows that, for the lamp under study, a 1-μs pulse will suffice.

It should be noted that the instantaneous primary current will reach rather high values. Assuming a sinusoidal waveform and that the parasitic resistances are negligibly small (lossless case), the upper limit of this current (I_{limit}) can be estimated by

$$I_{limit} = V_{BUS} \Big/ \sqrt{\frac{L_{ig}}{C_{ig}}}. \quad (7)$$

IV. Experimental Results

The design parameters of the power stage for the experimental electronic HPS ballast were derived by the proposed design procedure given in Section IV-D. The HPS lamp was an NAV-T 150 W (SON-T), (OSRAM), of a nominal power $P_l = 150$ W and nominal rms lamp current $I_{l_{rms}} = 1.8$ A (OSRAM's catalogue AB 300 E 2/91). $V_{BUS} = 400$ V; $f_{s_{nom}} = 26.7$ kHz; $R_l = 46.3\ \Omega$ (from nominal P_l and $I_{l_{rms}}$ data); $A^* \approx 2; \omega_s C_l R_l \approx 1.6; C_l = 0.22\ \mu$F$; \omega_s L_1/R_1 \approx 2.5; L_l = 700\ \mu$H$; n = 12; L_{ig} = 6.6\ \mu$H$; f_{s_{dimm}} = 26.7$–$75$ kHz. The inductors L_l and L_{ig} were built around Kool Mμ toroid core

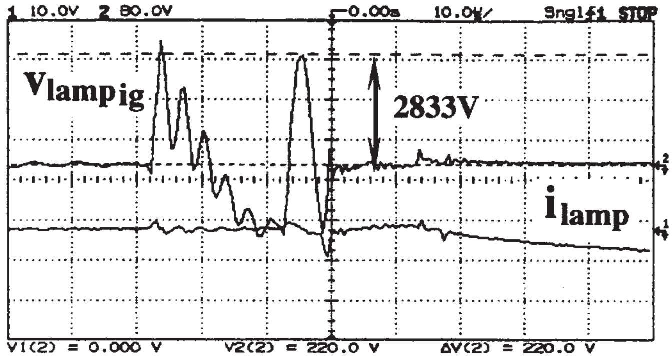


Fig. 5. Measured waveforms of the ignition peak voltage ($v_{lamp_{ig}}$) and the lamp current (i_{lamp}) of the experimental HPS lamp (NAV-T 150 W (SON-T), OSRAM) during lamp startup when driven by the proposed electronic ballast. Vertical scales: 1030 V/div, 1.0 A/div. Horizontal scale: 10 μs/div.

(Magnetics, part number: 77083-A7, $\mu = 60, B_{max} = 1$ Tesla) $N_{Ll} = 84$ turns, $N_{Lig} = 7$ turns; Q_1, Q_2 – IRF840, $R_s = 0.1\ \Omega, C_{ig} = 0.22\ \mu$F.

A. Ignition

The typical ignition record of Fig. 5 illustrates the startup sequence. The high-voltage pulse excites the lamp until an arc is established. Once ignited, the low impedance of the lamp shunts the high-voltage pulses and the lamp's current starts to build up. Applying the approximate expression (7), the upper limit of the current of L_{ig} (I_{limit}) is 73 A. In practice, current levels of 40 A were found in the experimental ballast. The somewhat large discrepancy between the theoretical upper current limit and the experimental value is due to parasitic resistances of the $L_{ig}C_{ig}$ circuit, which were ignored in the present theoretical analysis (7).

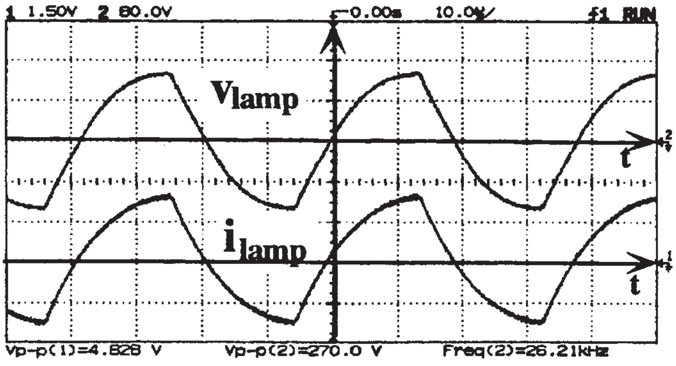
B. The Electrical Characteristics of HPS Lamps at HF

The typical waveforms of Fig. 6 suggest that, under the present operating conditions, the lamp is resistive. This was further verified by registering the V-I characteristic [Fig. 7(a)] for different power levels. These experimental data reveal that the resistance of the lamp under study is independent of the power level. This is in contrast to the resistance of a low-pressure lamp, that decreases as the power level is increased [Fig. 7(b)].

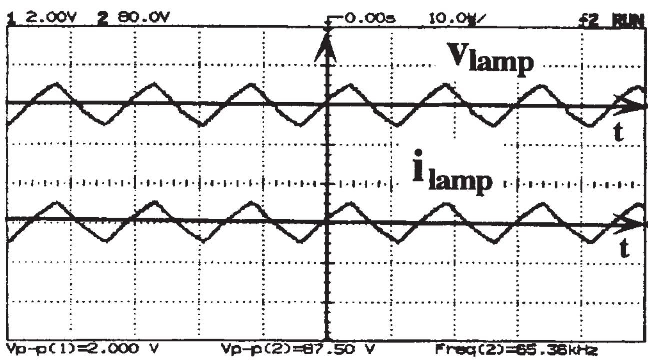
The resistance of the lamp under study, NAV-T 150W (SON-T), OSRAM, was found to be about 45 Ω (Fig. 8), very close to the value calculated from the manufacturer's 50/60–Hz data (46.3 Ω). The measured power levels were close to the ones calculated by the approximate equation (1).

C. Dimming

Dimming was controlled by varying the switching frequency over the range 27–75 kHz. The range of a stable dimmed light was found to be extremely large, extending down to about 7% (9 W) of the experimental power level (130 W). Light stabilization time between a dimmed conditioned and nominal power was found to be dependent, as one would expect, on the initial power level (Fig. 9).

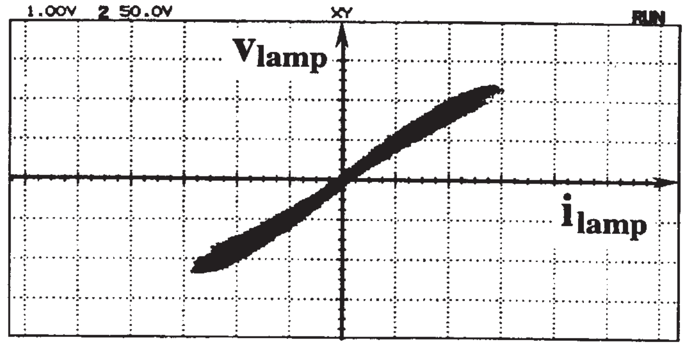


(a)

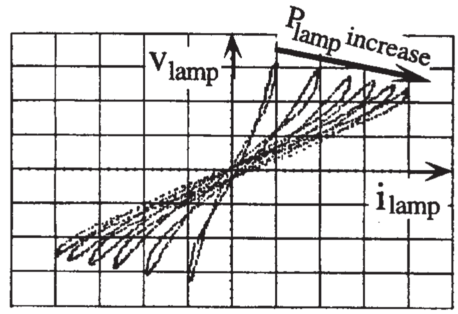


(b)

Fig. 6. Measured waveforms of the experimental HPS lamp (NAV-T 150 W (SON-T), OSRAM) (a) when driven by proposed electronic ballast at nominal lamp power of 150 W and (b) at 10% (15 W) of nominal lamp power. Vertical scales: 80 V/div, 1.5 A/div. Horizontal scale: 10 μs/div.



(a)



(b)

Fig. 7. Measured V-I characteristic of (a) HPS lamp (NAV-T 150 W (SON-T), OSRAM) as a function of the lamp power ($P_{\rm lamp}$). Superimposed curves are for lamp power in the range 54–130 W. Vertical scales: 50 V/div. Horizontal scale: 1 A/div. Switching frequency range from 27 to approx. 65 kHz. (b) V-I characteristic of a fluorescent lamp (General Electric type F40D/2) as a function of the lamp power ($P_{\rm lamp}$). Vertical scale: 50 V/div. Horizontal scale: 0.2 A/div. Switching frequency range from 150 to 300 kHz.

V. Design Guidelines

The following procedure is suggested for the practical design of the proposed power stage for an HPS electronic ballast. It is assumed that the following parameters are given: bus voltage of the power stage ($V_{\rm BUS}$), lamp current ($I_{l_{\rm rms}}$), nominal lamp power (P_l), and the recommended ignition lamp voltage ($V_{{\rm lamp}_{\rm ig}}$).

1) Select the nominal switching frequency ($f_{s_{\rm nom}}$) according to the desired operating range and the availability of transistors and magnetic materials, taking into account the dimming range (see Section IV-C).
2) Calculate the resistance of the HPS lamp (R_l) from the 50/60 Hz data:

$$R_1 = \frac{P_1}{I^2_{1_{\rm rms}}}. \tag{8}$$

3) Calculate the parameter A^* by (4).
4) Choose $\omega_s C_l R_l$ from Fig. 3 such that it will be on the right-hand side of the dashed line ($C_{l_{\rm min}}$ line). $\omega_s C_l R_l \approx 1.6$.
5) Calculate the blocking capacitor C_l from the chosen $\omega_s C_l R_l$.
6) Select $\omega_s L_l / R_l$ from Fig. 3 for the chosen $\omega_s C_l R_l$ and the calculated A^*.
7) Calculate the inductance L_l from the selected $\omega_s L_1 / R_1$.

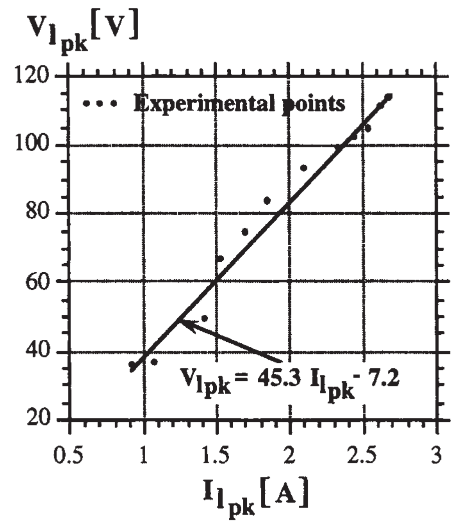


Fig. 8. Relationship between the peak HPS lamp voltage ($V_{l_{\rm pk}}$) and the peak current ($I_{l_{\rm pk}}$) through the lamp for lamp power (P_l) of 11–130 W (Switching frequency range from 27 kHz to approximately 75 kHz). HPS lamp: NAV-T 150 W (SON-T), OSRAM.

8) Calculate the turns ratio n:

$$n = \frac{V_{\rm ig}}{V_{\rm BUS}} \tag{9}$$

where $V_{\rm ig} \approx 1.3\ V_{{\rm lamp}_{\rm ig}}$ because, in practice, the spike

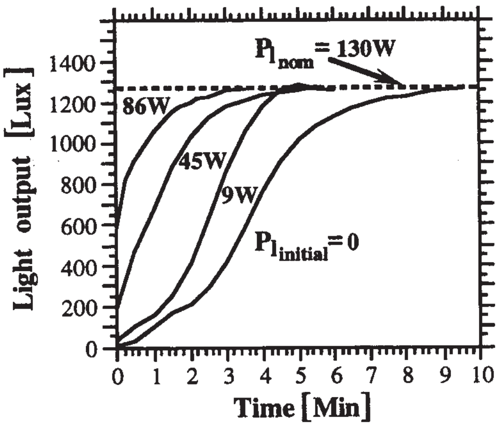


Fig. 9. Light output of the HPS lamp (NAV-T 150 W (SON-T), OSRAM) when driven by proposed electronic ballast as a function of time required to achieve nominal power under different initial conditions. The nominal power ($P_{l\text{nom}}$) is the final reference power used in all experiments.

voltage will be lower than theoretically expected (see Section III).

9) Calculate the ignition inductance L_{ig}:

$$L_{\text{ig}} = \frac{L_1}{n^2}. \tag{10}$$

VI. Discussion and Conclusions

This paper examined and evaluated the performance of an electronic ballast for a commercial HPS lamp. The experimental prototype ballast, which included a PFC front end, was found to be effective and highly repeatable in behavior. The proposed ignitor was proven to be sufficient for cold ignition. The ignitor was found to be sufficient for instant hot ignition of a lamp that was previously run dimmed. For nominal power, ignition was possible after several seconds of cooling. The easy-to-implement dimming option could be useful in cases where full output power is not required at all times. In such cases, the lamp can be left dimmed to save energy and returned to nominal power after a relatively short warmup time.

The results of this study reveal that a commercial HPS lamp can be characterized as a pure resistance when driven at high frequency, but, unlike the case of fluorescence lamps, the resistance is independent of the switching frequency or power level. Consequently, the resistance can be calculated from the 50/60-Hz data given by the manufacturer. The constant resistance characteristic manifests itself by a rather large change of the voltage across the lamp between nominal and dimmed conditions. It would, thus, appear that dimming could be realized by dropping the input voltage, while keeping a constant frequency. This, and other issues, will be explored in a subsequent paper.

Appendix
Derivation of (1)

The Fourier series corresponding to the square-wave signal generated by the inverter ($V_{\text{sq}}(\omega_s t)$, Fig. 2) is

$$v_{\text{sq}}(\omega_s t) = \frac{4a}{\pi}\left[\sin(\omega_s t) + \frac{\sin(3\omega_s t)}{3} + \frac{\sin(5\omega_s t)}{5} + \cdots\right] \tag{A1}$$

where $a = V_{\text{BUS}}/2$ is an amplitude of the square-wave signal $V_{\text{sq}}(\omega_s t)$.

The square-wave signal $V_{\text{sq}}(\omega_s t)$ is coupled to the lamp via a blocking capacitor C_l and a series inductor L_l that is a bandpass filter, where its resonant frequency (ω_o) is

$$\omega_o = \frac{1}{\sqrt{L_1 C_1}}. \tag{A2}$$

To retain ZVS, the switching frequency (ω_s) should be above the resonant frequency (ω_o). That is,

$$\omega_s > \omega_o. \tag{A3}$$

Consequently, the higher harmonics of the square-wave signal [$3\omega_s t, 5\omega_s t, \cdots$, (A1)] will be filtered out by the resonant circuit L_1C_1 and their amplitudes will be negligibly small, as compared to that of fundamental frequency component ($v_{(1)}(\omega_s t)$)

$$v_{\text{sq}}(\omega_s t) \approx v_{(1)}(\omega_s t) = \frac{2V_{\text{BUS}}}{\pi}\sin(\omega_s t) \tag{A4}$$

where $V_{(1)\max} = 2V_{\text{BUS}}/\pi$ is an amplitude of fundamental frequency component ($v_{(1)}(\omega_s t)$).

The power delivered to the lamp (P_l) can be expressed as

$$P_1 = I_{\text{rms}}^2 R_1. \tag{A5}$$

The amplitude of fundamental harmonic of the lamp current ($I_{(1)\max}$) is found to be

$$I_{(1)\max} = \frac{2V_{\text{BUS}}}{\pi\sqrt{\left(\omega_s L_1 - \dfrac{1}{\omega_s C_1}\right)^2 + R_1^2}}. \tag{A6}$$

Applying now (A5), (A6), and the fact that the effective value of the lamp current (I_{rms}) is approximately $I_{(1)\max}$ divided by $\sqrt{2}$, the lamp power (P_l) is expressed as

$$P_1 = \frac{2V_{\text{BUS}}^2 R_1}{\pi^2\left[\left(\omega_s L_1 - \dfrac{1}{\omega_s C_1}\right)^2 + R_1^2\right]}. \tag{A7}$$

References

[1] W. Elenbaas, Ed., *Fluorescent Lamps*. London, U.K.: Macmillan, 1971.

[2] J. Spangler, B. Hussain, and A. K. Behera, "Electronic fluorescent ballast using a power factor correction techniques for loads greater than 300 watts," in *Proc. Applied Power Electronics Conf.*, 1991, pp. 393–399.

[3] W. R. Alling, "Important design parameters for solid-state ballasts," *IEEE Trans. Ind. Applicat.*, vol. 25, pp. 203–207, Mar. 1989.

[4] E. E. Hammer, "High frequency characteristics of fluorescent lamp up to 500 kHz," *J. Illum. Eng. Soc.*, vol. 16, no. 1, pp. 52–61, Winter 1987.

[5] J. M. Stork, "High pressure sodium lamps: practical design model," *Lighting Res. Technol.*, vol. 24, no. 3, pp. 149–154, 1992.

[6] J. M. Stork, "A model for the high pressure sodium lamp characteristic curve," *J. Illum. Eng. Soc.*, vol. 20, no. 1, pp. 70–76, Winter 1991.

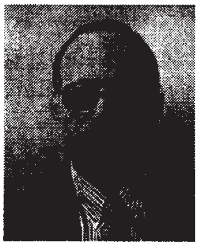
[7] H.-J. Faehnrich and E. Rasch, "Electronic ballasts for metal halide lamps," *J. Illum. Eng. Soc.*, vol. 17, no. 2, pp. 131–140, Summer 1988.

[8] J. F. Waymouth, *Electric Discharge Lamps*. Cambridge, MA: MIT Press, 1971.

[9] S. Wada, A. Okada, and S. Morii, "Study of HID lamps with reduced acoustic resonances," *J. Illum. Eng. Soc.*, vol. 16, no. 1, pp. 162–175, Winter 1987.

[10] M. Gulko and S. Ben-Yaakov, "Inductor controlled current sourcing resonant inverter and its application as a high pressure discharge lamp driver," in *Proc. Applied Power Electronics Conf.*, 1994, pp. 434–440.

[11] L. Laskai, P. Enjeti, and I. R. Pitel, "A unity power factor electronic ballast for metal halide lamps," in *Proc. Applied Power Electronics Conf.*, 1994, pp. 31–37.
[12] J. Malis, "Ballast curves for HPS lamps operating at high frequency," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1992, pp. 1908–1914.



Shmuel (Sam) Ben-Yaakov (M'87) received the B.Sc. degree from the Technion, Haifa, Israel, in 1961 and the M.S. and Ph.D. degrees from the University of California, Los Angeles, in 1967 and 1970, respectively.

He is currently a Professor with the Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel, where he is also Head of the Power Electronics Group. He is involved in research, design, and development of switch-mode and resonant systems in both academic and industrial environments and serves as a consultant to commercial companies on power-electronics-related issues, including electronic ballasts for HID lamps.

Michael Gulko (S'96) was born in Moscow, U.S.S.R., in 1965. He received the B.Sc. degree in 1988 from the Communication Institute of Moscow, Moscow, U.S.S.R., and the M.Sc. degree in 1994 from Ben-Gurion University of the Negev, Beer-Sheva, Israel, where he is currently working toward the Ph.D. degree.

His current research interests include high-frequency switch-mode converters, electronic ballasts for high- and low-pressure discharge lamps, computer modeling, and engineering education.