A SPICE Compatible Model of High Intensity Discharge Lamps

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Abstract — A SPICE compatible model of High Intensity Discharge (HID) lamps was developed and verified against experimental results. The model is based on fundamental physical-thermal principles and applies lamp parameters and universal constants. The model was found to faithfully emulate the static and dynamic electrical responses of a High Pressure Sodium (HPS) lamp under low frequency (50Hz) and high frequency (30kHz) excitation.

I. INTRODUCTION

High efficacy (Lumen/Watt), long life and good color rendition have made the High Intensity Discharge (HID) lamp one of the most useful light sources [1,2]. The present range of application of HID lamps is broad: from large space lighting such as streets, sports arenas and industrial production halls to specialized applications such as LCD video projectors. The main difficulty with this family of lamps is the need for special electrical circuits (ballasts) to drive them [1,2]. In some applications, electronic ballasts offer important improvements over the traditional electromagnetic ballasts [2]. The main advantages of the electronic ballasts are: higher electrical efficiency and lower weight and size. For this reason there is presently a considerable scientific and engineering interest in the development of electronic ballasts.

A SPICE compatible model of HID lamps could be a useful tool in the investigation and design of electronic ballasts for HID lamps. Several studies proposed SPICE compatible models of fluorescent lamps [1,3-10] but the authors are unaware of earlier studies that present a SPICE compatible model of HID lamps. A number of earlier papers presented mathematical models of High Pressure Mercury, High Pressure Sodium (HPS) and Metal-Halide Lamps [11-17], but they are not readily adaptable to the environment of common SPICE simulators.

The objective of the present study was to develop a simple SPICE compatible model that emulates the electrical behavior of HID lamps. The model are derived from the arc's physics and therefore should be valid over a wide range of operating conditions. The present investigation did not probe into the process of ignition, warm up and the intricate subject of acoustic resonance [2].

II. GENERAL

The fundamental approach in developing the SPICE compatible model this study is to represent the lamp as a behavioral dependent current source (Fig. 1) having the following general definition:

$$i_{lamp} = \frac{v_{lamp}}{R_{lamp}} \qquad (1)$$

where v_{lamp} is the voltage across the lamp and $R_{lamp} = \int_V \frac{1}{\sigma_\Sigma} \frac{L}{S} dV$ is the non-linear resistance of the lamp, σ_Σ is the global specific conductance of the plasma, V is the volume of the plasma, L is the length of plasma and S is the cross section.

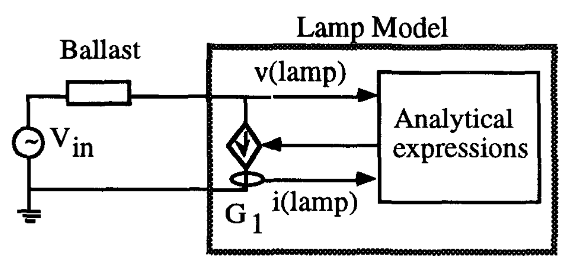

Fig.1. The proposed SPICE compatible model of an HID lamp. G_1 is a behavioral dependent current source.

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In general, the global specific conductance equals the sum of all conductances σ_i of the plasma's gas components :

$$\sigma_{\Sigma} = \sum \sigma_i . \qquad (2)$$

For weakly ionized plasma, the specific conductance σ_i depends on the temperature [18]:

$$\sigma_i = \sigma_{oi} \frac{T^{0.75}}{\sqrt{p}} exp\left(-\frac{E_i}{2kT}\right) \qquad (3)$$

where σ_{oi} is a constant of each gas component, T is the arc's active part (core) temperature, p is the pressure of the gas, E_i is the ionization energy of each component i and k is Boltzmann's constant.

To describe the electrical processes of the lamp one has to describe its thermodynamic state. This description of the discharge lamp state is based on the power balance equation. At any given time, the incremental increase in the arc's heat (dQ) can be described by the following equation :

$$dQ = (P_{in} - P_{out})dt \qquad (4)$$

where: P_{in} - input power; P_{out}- power removed from the lamp (radiation plus heat conduction); dt - time increment.

The present study was conducted under some simplifying assumptions of a channel model:

1. The arc is in the High Pressure Lamp is confined to a plasma cylinder.
2. The plasma is in a Local Thermal Equilibrium (LTE) state.

The next conventional simplification step is the assumption that some arc's parameters are constant:

3. The arc is composed of a two-layer cylinder:
   - the radius of the internal layer (core) is equal to the electrode's radius,
   - the external radius of the external layer (periphery) is equal to the arc's tube internal radius,
   - the arc's length is equal to the gap between the electrodes.
4. All physical properties in each layer are constant.
5. Electrical current runs only in the internal layer - core.
6. The losses are due to radiation and heat conduction from the core's surface.
7. The energy losses of the arc's active part run only in the radial direction.
8. The influence of the arc's tube, electrodes and bulb on the heath balance are neglected.

Additional assumptions are stated in Appendix A in conjunction with other aspects of the model.

Under those assumptions, the incremental increase in heat for a unit length of the arc can be expressed by :

$$dQ = [c_{core}\rho_{core}\pi R_{core}^2 + k_{Tred}c_{per}\rho_{per}\pi(R_{tube}^2 - R_{core}^2)]dT \qquad (5)$$

where: c_{core}, c_{per} - heat capacity of the internal and external layers respectively; ρ_{core}, ρ_{per} - density of the internal and external layers' medium. R_{tube}, R_{core} - arc cavity and core's radius (Rcore=Rel, where Rel - electrodes radius), k_{Tred} - the ratio between average periphery temperature and average core temperature.

The input power to the lamp per unit length (P_{ind}) is:

$$P_{ind} = \frac{v_{lamp}\, i_{lamp}}{L_g} \qquad (6)$$

where: L_g - distance between electrodes.

The radiated energy P_{rad} can be expressed as:

$$P_{rad} = 2\pi R_{el}\varepsilon(T) \qquad (7)$$

where: $\varepsilon(T)$ -arc's surface emissivity, defined in Appendix A.

The heat conduction losses P_{con} is described by the law:

$$P_{con} = \kappa\ (T - T_{amb}) * 2\ \pi\ R_{el}, \qquad (8)$$

where : $\kappa = \kappa(T)$ – coefficient of heat transfer defined in Appendix A.

By replacing the energy components of (4) by expressions (5)-(8) we obtain a fundamental differential equation that describes the arc's state:

$$\frac{dT}{dt} = \frac{\frac{v_{lamp}\, i_{lamp}}{L_g} - 2\pi R_{el}[\varepsilon(T) + \kappa(T)(T - T_{amb})]}{\pi\ [c_{core}\rho_{core}R_{el}^2 + k_{Tred}c_{per}\rho_{per}(R_{tube}^2 - R_{el}^2)]} \qquad (9)$$

III. STRUCTURE of SOLUTION

To solve (9) one has to evaluate the numerical values of the medium parameters $c_{core}, c_{per}, \rho_{arc}, \rho_{per}$ and ε in the numerator and denominator. The procedure adopted in the study is summarized in Fig. 2.

The required parameters of gas mixture, partial pressures, gas temperature at the axis and wall temperature, radiant power efficiency and nominal voltage and current values were estimated from the data given in [2] for 400-W HPS lamps. Some geometric sizes: arc tube's length, diameter, wall thickness, electrode's diameter and etc. were determined by direct measurements (see Appendix A).

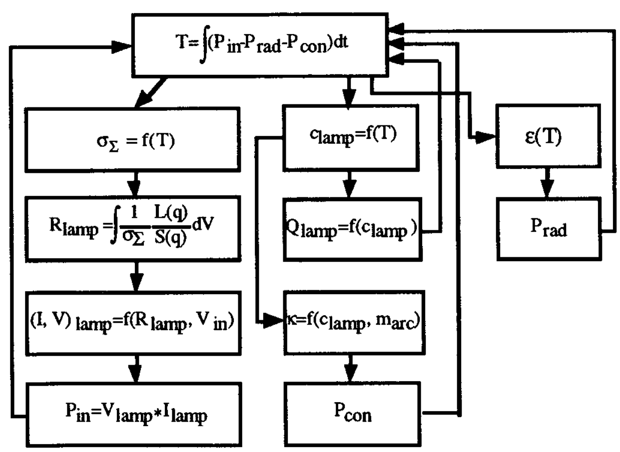


Fig.2. Solution structure of lamp state equation.

IV. SPICE ADAPTATION

The thermodynamic phenomena in the arc are described by the differential equation (9). This expression has the appearance of a first order differential equation but it is, in fact, a nonlinear differential equation. This is due to the fact that the values of all equation coefficients are a functions of temperature *(T)* which, according to the above assumptions, are associated with the average core temperature. The approach taken in this study is to emulate the thermodynamic phenomena by an equivalent circuit and to apply an electronic circuit simulator to solve this equation numerically. We have used PSPICE (MicroSim Inc., Irvine, USA), but any other simulator that includes behavioral dependent source is equally applicable.

To solve (9) one has to obtain the running value of the temperature and apply it to calculate all temperature dependent parameters. This can be done by using the right side of (9) to define a behavioral dependent current source(Fig.3). The output of this current source (I_{th}), which equals to $(\frac{dT}{dt})$, can now be integrated by feeding it to a capacitor C_{th}. Hence, the voltage across the capacitor (V_C) represents the arc's temperature at any given time:

$$V_C = \frac{1}{C_{th}}\int I_{th}\,dt \equiv T \qquad (10)$$

If we select $C_{th} = 1F$ than there is no need for scaling.

The SPICE adaptation of (10) is depicted in Fig. 3.

Resistor *R* is needed for technical reason, to provide a galvanic path to ground as required by some simulators. The value of R should be chosen such that:

$$R >> \frac{1}{\omega C_{th}} \qquad (11)$$

where ω is the highest angular frequency expected when the model is applied. It should be pointed out that the maximum value of *R* is limited only by the numerical range allowed by the simulator.

The calculation of all parameters as shown schematically in Fig. 2 can be carried out by interconnecting behavioral dependent sources. That is, the variables are coded into voltage or currents and the equations are evaluated by behavioral expressions. A general description of the SPICE compatible equivalent circuit is given in Fig. 4 that is PSPICE Version 7 (MicroSim Inc.) compatible.

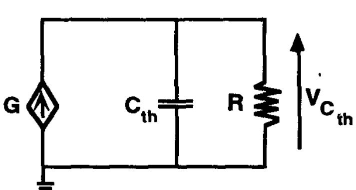


Fig.3. Method used to solve (9). G is a behavioral dependent current source defined by the right side of (9). V_{Cth} represents the (voltage coded) temperature of the arc.

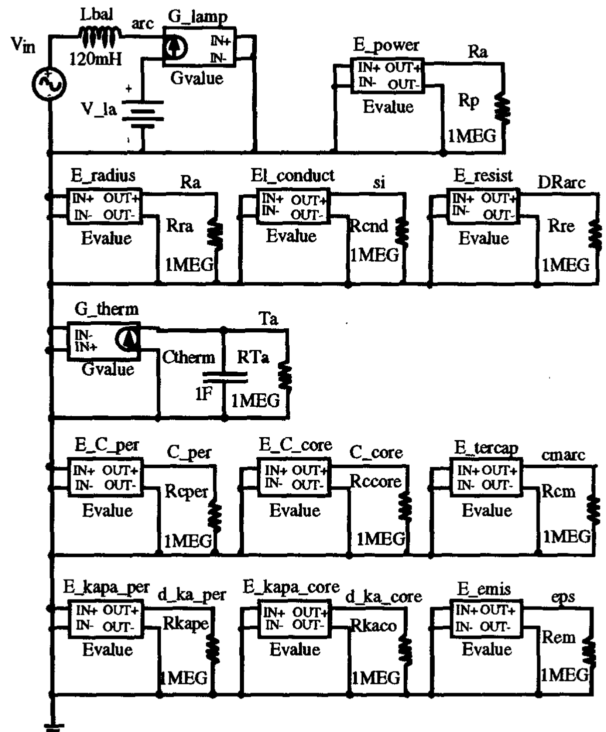


Fig. 4.SPICE model. See text for definitions of dependenent voltage sources (EVALUE) and current source (GVALUE)

The values of the parameters are given in Appendix B. The definition of the devices and dependent sources are as follows:

Vin - VSIN-type independent voltage source (IVS), that powers the ballast/lamp system. The values of the attributes: VAMPLitude=*{Vin}*, FREQuency= *{F_in}* are given in the "PARAMETERS" box (see Appendix B).

Lbal - Ballast inductor.

The combination Vin -Lbal represents a particular case of driver (source plus ballast inductor). Any other sources and ballasts are of course possible.

G_lamp = *V(lamp)/(Rarco-V(DRarc))*: Gvalue-type dependent current source that emulates the lamp corresponding to (1), except that it includes an additional term in the denominator to avoid division to zero in the first iterations. *Rarco* - arbitrary number, *Rarco*>> R_{nom} - lamp nominal resistance.

V_la -zero-voltage Vdc-type IVS; used to measure the instantaneous lamp current *I(V_la)*.

E_power =*V(lamp)*I(V_la)* - Evalue-type dependent voltage source that creates voltage V(Power) numerical equal instantaneous lamp power.

El_conduct=*sia_Na*PWR(V(Ta)*,0.25)*EXP(*-Ek_Na/ V(Ta)*)/5.244- Evalue-type according to (3) creates voltage *V(si)* that is equal the lamps conductivity.

This expression takes into consideration the relationship:

$$p = \frac{\sum p_i}{T_{core}} T; \quad (12)$$

where p_i is the initial partial pressure magnitude, T_{core} is the initial average core temperature (Appendix B).

E_resist-*Rarco-Lg/(sio+V(si))/Pi/((Rao+V(Ra)) *(Rao+V(Ra)))*. Evalue-type source that produces a voltage V(DRarc) equal to the lamp's resistance, *Rarco* is added to ffset the factor added at the denominator of G_value (see above).

E_radius- *Rat.* Evalue-type source that produces a voltage *V(Ra)* equal the arc's radius.

It was found that emulating the radius as *V(Ra)*, rather that applying it as a parameter help convergence.

G_therm=*(V(power)/Lg-(V(eps)+(kapa_o+ V(d_ka_core)) *(V(Ta)-Tamb))*2*Pi*(Rao+V(Ra)))/V(cmarc)-* Gvalue-type source, that is the analog of (9). It produces the voltage *V(Ta)* that is equal to the arc's core average temperature.

E_C_core=*Co+V(d_ka_core)*dD/ro_core** .732/*Lmfp_core* SQRT*(mHg/k/V(Ta))*- Evalue-type source that produces a voltage *V(C_core)* equal to the heat capacity of core.

E_C_per =*Co+V(d_ka_per)*dD/ro_per** 1.732/*Lmfp_per* *SQRT*(mHg/k/(k_tred*V(Ta)))*;-Evalue-type source that produces a voltage *V(C_per)* equal to the heat capacity of arc's periphery as above.

E_tercap=V(C_core)*Pi*(Rao+V(Ra))*(Rao+V(Ra))* ro_core+V(C_per)*Pi*(Rtu-V(Ra))*(Rtu-V(Ra))* ro_per - Evalue-type source that produces a voltage *V(cmarc)* equal to the arc's heat capacitance (per unit length).

E_kapa=k0*(Eef/k/V(Ta))*(Eef/k/V(Ta))*EXP(-Eef/k/ V(Ta)) - Evalue-type source that produces a voltage *V(d_kapa_core)* equal to the heat transfer coefficient increment.

E_eps=eps_0*(Eef/k/V(Ta))*(Eef/k/V(Ta))*EXP(-Eef/k/ V(Ta))- Evalue-type that produces a voltage *V(eps)* equal to the emissivity increment.

Each source is loaded by a resistor to avoid flouting node situations. All global constants, internal and input date are defined in PSPICE "PARAMETERS" (APPENDIX B).

V. EXPERIMENTAL VERIFICATION

The proposed model was verified against experimental data for low frequency (50Hz), high frequency (30kHz) and small signal modulation (carrier frequency 30kHz at modulation frequency range 50Hz - 5000Hz). Experiments were carried out on a 400W HPS lamp (OSRAM VIALOX NAV-T-400). The experimental and simulated dynamic responses (Figs. 5 and 6) were found to be in good agreement

VI. CONCLUSIONS

A HID lamp model, based on the arc's thermodynamics, was shown to emulate the electrical static and dynamics responses of a HPS lamp operating at high and low excitation frequencies. The model was implemented by an equivalent circuit that includes behavior dependent sources. It is thus compatible with general purpose electronic circuit simulators such as PSPICE (MicroSim Inc.). The main shortcoming of the model is the difficulty of getting the many parameters of the lamp. In particular those dependent on the composition and pressure of inner gases. Consequently, future use of this approach for any given lamp will be conditioned on the availability of this data. The suggested solution to the problem is to follow the practice already adopted by vendors of electronics components. Namely, having the SPICE related parameters published by lamp manufacturers.

APPENDIX A

TABLE 1

400-W Sodium-lamps data [2]

No	Parameter	Magnitude
1	Partial gas pressure P_i in operating lamp,	Na......$1*10^4$ Pa Hg......$8*10^4$ Pa Noble gas (Ar, Kr, Ne, Xe) $2*10^4$ Pa
2	Gas temperature at axis, T_{ax}	4000 ^oK
3	Arctube wall temperature, T_w	1500 ^oK
4	Radiant power efficiency, η_{rad}	56 %
5	Lamp current, I_{rms}	4.4 A
6	Lamp voltage, V_{rms}	105 V
7	Arctube inner diameter, D_{tu}	8 mm
8	Arctube inner long, L_{tu}	102 mm
9	Electrode diameter, D_{el}	1.35 mm
10	Electrode spacing, L_g	82 mm

*The values in lines 7,8,9 come by from real lamp mesurement.

The electro and thermo-physicals parameters of the arc tube's medium were derived under the auxiliary assumptions:

9. The mixture in the arc tube is treated as a perfect monoatomic [2] gas.
10. The mass of the noble gasses was calculated from the total partial pressure of the noble gasses mixture [2] assuming average mixture's atom mass of 69a.u.
11. The radial temperature distribution in the arc tube has a parabolic profile:

$$T_r = T_w + (T_{ax} - T_w)\left(1 - \frac{r^2}{D_{tu}^2/4}\right) \quad (A1)$$

where r is a radial coordinate.

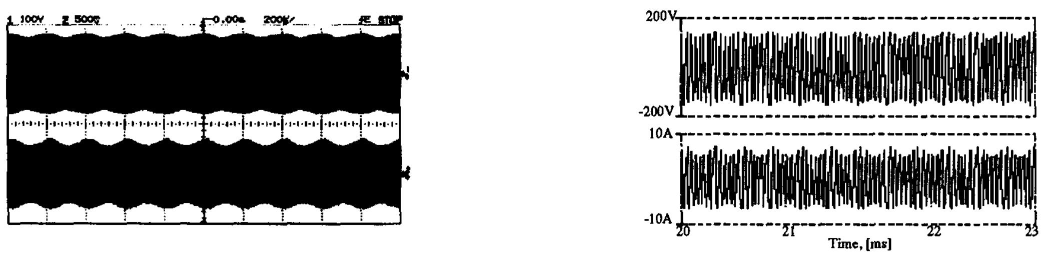
12. Since the arc's steady-state ionization is governed by the species with lowest ionization potential, the arc's conductivity was been calculated by considering (in the HPS lamp) Na only.

(a) (b)

Fig.5. Dynamic characteristics of the HPS lamp (NAV-T-400, OSRAM) at 50 Hz: (a) experimental. (b) model simulation. Upper trace - voltage. Lower trace - current. In (a): voltage - (100V/div), current - (5A/div).

(a) (b)

Fig.6 Dynamic characteristics of the HPS lamp (NAV-T-400, OSRAM) at 30 kHz: (a) experimental. (b) model simulation. Upper trace - voltage. Lower trace - current. In (a): voltage - (100V/div), current - (5A/div).



(a) (b)

Fig 7. Response of the HPS lamp to low frequency modulation. Carrier frequency 30kHz, modulation frequency 5kHz. (a) experimental. (b) model simulation. Upper trace - voltage.Lower trace - current. In (a): voltage - (100V/div), current - (5A/div).

APPENDIX B

PSPICE Model "PARAMETERS" data

INPUT DATA

PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
F_in	50Hz	Ltu	102m	Dtu	8m	ro_core	0.55
Vin	320V	Lg	82m	Del	1.33m	ro_per	0.7
Tamb	310	Tcore	3792				
PARAMETERS:		**PARAMETERS:**		**PARAMETERS:**		**PARAMETERS:**	
N_core	22E+16	sia_Na	3.1E+6	k0	7286	k_tred	0.756
Co	80	sio	300	Eef	43.83E-20	eps	0.045
				kapa-o	3.6		

INTERNAL PARAMETERS

PARAMETERS:		PARAMETERS:		PARAMETERS:		PARAMETERS:	
eVi_Na	5.139	m_aNa	23	Q_Na	37E-20	Pi	3.14159
eVi_Hg	10.437	m_aHg	200	Q_Hg	31E-20	ga	56.703n
eVi_Sc	6.561	m_aSc	45	Q_Na_i	43E-20	k	1.381E_-23

PARAMETERS:		PARAMETERS:	
mNa	{m_aNa*1.67495E-27}	No_core	{N_core/(Pi*Del*Del/4*Lg)}
mHg	{m_aHg*1.67495E-27}	No_per	{No_core*ro_per/ro_core}
mSc	{m_aSc*1.67495E-27}		

PARAMETERS:		PARAMETERS:		PARAMETERS:	
Ei_Na	{eVi_Na*1.6E-19}	Lmfp_core	{0.707/(Q_Hg*No_core)}	Rat	{Del/2}
Ek_Na	{Ei_Na/2/k}	Lmfp_per	{0.707/(Q_Hg*No_per)}	Rao	0.1m
		dD	{(Dtu-Del)/2}	Rtu	{Dtu/2}

PSPICE FILE

To make possible the application of proposed model by other workers, the PSPICE file is available for down load . Please check the WEB site: http://www.ee.bgu.ac.il/~pel - Downloads Section.

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