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Optimizing parameters for a dynamic model of high-frequency HID lamps using genetic algorithms

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Abstract
This work is carried out to optimize the basic parameters of a dynamic model of high-frequency high intensity discharge lamps, which includes the effect of the phenomenon of acoustic resonance on the electrical parameters of the lamps. Hybrid modeling techniques are used, taking as their starting point the energy balance equations inside the lamp. The optimization of parameters is carried out using techniques based on genetic algorithms, included in the global optimization toolbox of Matlab. The implementation of the model is performed in Matlab R2011a. The result is a dynamic model for HID lamps at high frequency, validated for a high-pressure sodium lamp.

Keywords: genetic algorithms; high-frequency HID lamps; hybrid modeling; acoustic resonance.

Optimización de parámetros de un modelo dinámico de alta frecuencia de lámparas HID mediante algoritmos genéticos

Resumen
En este trabajo se lleva a cabo la optimización de los parámetros fundamentales de un modelo dinámico de alta frecuencia para lámparas de descarga de alta intensidad, que incluye el efecto del fenómeno de la resonancia acústica sobre los parámetros eléctricos de las lámparas. Para el modelado se emplean técnicas híbridas, teniendo como punto de partida las ecuaciones de balance de energía en el interior de la lámpara. La optimización de los parámetros se realizó mediante técnicas basadas en Algoritmos Genéticos, incluidas en la caja de herramientas de optimización global de Matlab. La implementación del modelo se realiza con el software Matlab R2011a. Como resultado se obtiene un modelo dinámico para lámparas HID en alta frecuencia, validado para lámparas de alta presión de sodio.

Palabras clave: algoritmos genéticos; lámparas HID en alta frecuencia; modelado híbrido; resonancia acústica.

1. Introduction

Rational use of energy has become a priority for most countries. Lighting systems consume a quarter of the world's energy, therefore it is an important task to find more efficient lighting systems [1]. High intensity discharge (HID) lamps are an attractive source of illumination for their compact size, high luminous efficacy and good color quality. However, their use has been limited to low frequency operation, as at high frequency (where they are more efficient) they are affected by the phenomenon of acoustic resonance (AR), which may even end up destroying the lamp [2]. Designers of electronic ballasts for stable operation of HID lamps, prefer to move their designs to areas of low frequencies, to avoid this phenomenon, sacrificing the lamp's performance [3].

Some models have been developed to emulate the high frequency operation of HID lamps, which are characterized by a complex dynamic and highly nonlinear behavior [4]. One of the biggest challenges is to optimize the modeling parameters, since lamp manufacturers regularly do not provide this information [5]. Genetic algorithms are an optimization technique successfully used to obtain the simplest model parameters of HID lamps [5], the aim of this work is to use these techniques in a dynamic model for these lamps, collecting a number of characteristics of the lamps that usually are not taken into account to simplify the solution. Such is the case for example of the drop on the electrodes of the lamps and the effect of the acoustic resonance phenomenon on the strength of these lamps.

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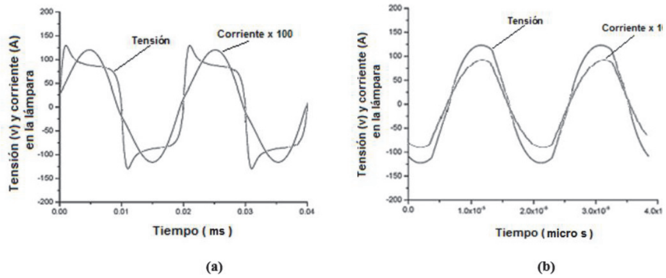

Figure 1. Waveforms of voltage and current in HID lamps. a) at low frequencies. b) high frequency.
Source: The Authors

A good optimization of the parameters of a lamp model with the mentioned features would be very useful for designers of ballasts, enabling new control systems for their power stages, with the comfort of having appropriate responding models to the presence of phenomena that affect high-frequency lamps.

The parametric identification for discharge lamps including the phenomenon of acoustic resonance mathematical model is proposed, which allow researchers to raise ballast electronic control systems aimed at the operation of this type of acoustic resonance free lamps.

2. HID Lamps

HID lamps base their operation on the light emission produced by the discharge that occurs in the gas constituent in the lamp upon application of an electric current [6]. Ballasts are devices that are responsible for feeding the lamps, making them work in a stable regime [7].

Various physical phenomena of thermal nature occur during operation of HID lamps, which determine its electrical characteristics [6]. Over its lifetime, several factors, both external and own internal operating condition, produce changes in the parameters required by the ballast to make variations to the energy delivered to the lamps as these get older [7].

The low frequency operation (Fig. 1a) causes reignition peaks during each line half cycle on the voltage waveform of the lamp, which produces the zero crossing of the current and the thermal phenomena that occur during this process. This feature of the low-frequency operation reduces the life of the lamps by surges that are exposed [6].

At high frequency, both waveforms of voltage and current are sinusoidal, as shown in Fig. 1b, reignition peaks disappear due to the rapidity with which the current crosses zero in each half cycle. The drawback, ballasts designers found for HID lamps operating at high frequency, is the phenomenon of AR, which usually occurs while HID lamps operate at these high frequencies.

Acoustic resonance is a tilting electric arc produced by the gases inside the lamp [2,6]. If the deviation of the arc is significant, it could reach the wall of the discharge tube, permanently damaging the lamp [2].

There are several techniques to prevent acoustic resonance in HID lamps, the most interesting include measuring the voltage and current waveforms of the lamp and observe the behavior of the resistance of the lamp, once a trend is detected, the system should be move to an area of acoustic resonance, and change the power frequency change in the ballast inverter stage, trying to keep the power constant in the lamp [1].

3. HID lamps model

Currently there are a variety of models for HID lamps. Some of them consider the lamp as a dynamic resistance with delays, which are associated with the thermal constants of the lamp and represented in the model by RC networks [8].

Other models are based on the conductance of the lamp, taking into account their voltage-current characteristics [9], associating conductance density of free electrons within the discharge tube [3] or the pressure, temperature of the arc, the ionization energy gas filling and constants that depend for example on the geometry of the discharge tube [3].

HID lamps can be modeled by implementing hybrid techniques based on a priori knowledge about the physical processes that occur in it. The model can be extended to strangers and great uncertainty of the lamp due to some assumptions made about its operation areas. From the balance equations in the lamp, an understanding of the physical processes that govern its properties can reach. However some parameters derived directly or indirectly from these equations, can be difficult to obtain because the manufacturers do not release these, as already mentioned, but also because cumbersome and expensive determination by experimentation is required in order to obtain these parameters. [5].

In this type of process, the optimization technique based on genetic algorithms has been applied with good results for some types of HID lamps of mercury, which suggests to experts that it can also be applied to other HID lamps [4].

The study model was determined so that it should contain the keywords related to the energy balance equation of the lamp, since its performance and properties are closely related to the photo-thermal phenomena that occur in it. Also, the drop in the electrodes should be taken into account since the high frequency behavior of the lamp's resistance is supported at this end of the model [6, 10]. Finally, the influence of the characteristics of the lamp on its resistance should not be ignored, since they are the reasons for the occurrence of acoustic resonance phenomenon affecting high frequency lamps [11].

The energy balance given by eq. (1) estates that from the power delivered by the power supply to the lamp [12], part is dissipated in the electrodes and the rest in the discharge column. Within column discharge the heat dissipated by heat conduction, convection, radiation and distribution, but usually the diffusion and convection losses are disregarded when the lamp is operated vertically.

$$\frac{\mathbf{dT}}{\mathbf{dt}} = \mathbf{a_1}(\mathbf{P_{in}} - \mathbf{P_{con}} - \mathbf{P_{rad}}) \qquad (1)$$

Where:
$\mathbf{a_1}$ is a parameter that allows a better fit to the model
$\mathbf{P_{in}}$ is the power consumed by the lamp
$\mathbf{P_{con}}$ are conduction losses
$\mathbf{P_{rad}}$ is the radiation losses
$\mathbf{T}$ is the gas temperature of the lamp
Also we know:

$$\mathbf{P_{in} = i^2 R} \tag{2}$$

Where:
i is the current of the lamp.
R is the resistance of the lamp's arc

$$\mathbf{P_{rad} = a_2 e^{-ea_3/kT}} \tag{3}$$

Where:
e is the electron charge
k is the Boltzmann constant
$\mathbf{a_2}$ is a parameter that allows a better fit to the model
$\mathbf{a_3}$ is linked to the average excitation potential of the lamp parameter

$$\mathbf{P_{con} = a_4(T - T_0)} \tag{4}$$

Where:
$\mathbf{T_0}$ is the temperature of the discharge tube wall
$\mathbf{a_4}$ is a thermal conductivity related parameter

Based on the prediction methods of the natural frequency of a lamp and confirmed by experimental observations, the resistance of the lamp's arc given by eq. (5) can be represented as the sum of a certain resistance by Saha's equation, expressing the resistance steady state arc discharge lamp and a series of frequency dependent coefficients, taking into account the influence of acoustic resonance on that resistance [11].

$$\mathbf{R = a_5 T^{-3/4} e^{e\,a_6/2kT} + \sum_{i=1}^{n} \frac{1}{(f-f_i)^2/A_i + B_i} = \boldsymbol{K} + \sum_{i=1}^{n} \frac{1}{(f-f_i)^2/A_i + B_i}} \tag{5}$$

Where:
f is the operating frequency of the lamp
$\mathbf{f_i}$ is the set of self-frequency of the lamp
$\mathbf{a_5}$ is an on resistance of the lamp parameter
$\mathbf{a_6}$ is related to the average ionization potential of the lamp parameter

$\mathbf{A_i}$ and $\mathbf{B_i}$ are constants related to vectors influence acoustic resonance modes on the resistance of the lamp.
K medium weight stable lamp

The current through the lamp can be determined in the equivalent circuit of the ballast-lamp system by formulating Kirchhoff voltage law.

$$\mathbf{v(t) = i(R + r) + V_{ele}} \tag{6}$$

Where:
$\mathbf{v(t)}$ is the voltage of the lamp
r is the equivalent resistance of the circuit formed by the ballast and ignitor lamp
$\mathbf{V_{ele}}$ is the voltage drop across the lamp electrodes

Since until now a numerical model for $\mathbf{V_{ele}}$ is not available, an empirical model that can be easily implemented in software design was used as proposed in [13], by eq. (7). The same is developed from experimental observations of the waveform in $\mathbf{V_{ele}}$ lamps specially designed for these measurements.

$$\mathbf{V_{ele} = Ae^{-Bt} sen(2C\pi f) + Dt} \tag{7}$$

Where:
A controls the amplitude of the signal
B controls the amplitude and the asymmetry of the signal
C and **D,** were obtained by measurements at different frequencies and using linear regression techniques, as well as A and B.

Table 1, shows the system of equations obtained by linear regression techniques for calculating the constants related to the generation of the model waveform $\mathbf{V_{ele}}$.

Implementation of the ballast-lamp model presented in Fig. 2 was performed with functions *m-file* type developed with the Matlab-Simulink tool.

Table 1.
System of equations for the calculation of the constants of the empirical model $\mathbf{V_{ele}}$.

Related constants with Vele	
A=70	B=8.3f+1090
$C = \begin{cases} 6 & \text{if } f = 60\text{Hz} \\ 1 & \text{other case} \end{cases}$	D=4.8f+761

Source: The Authors

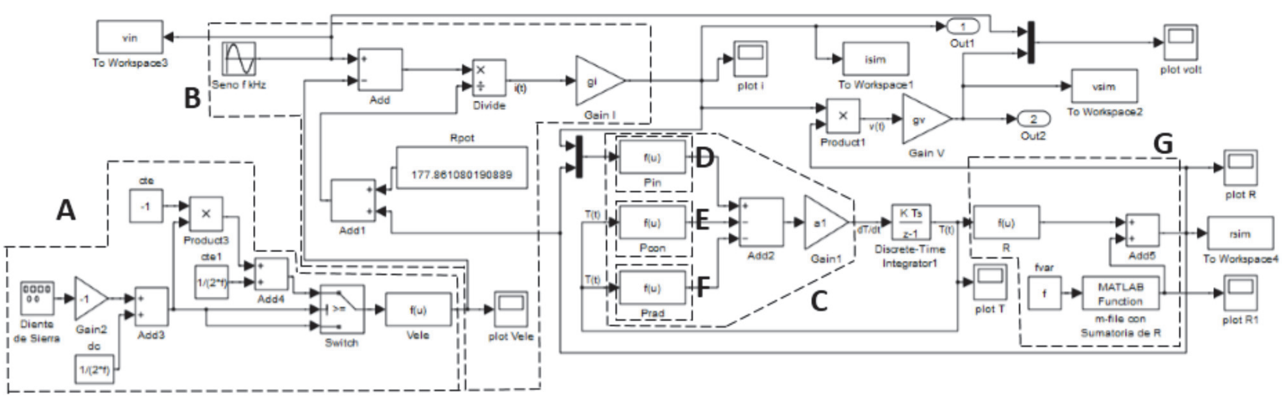

Figure 2. Model for high frequency of a 70 W HPS lamp, developed in Simulink.
Source: The Authors

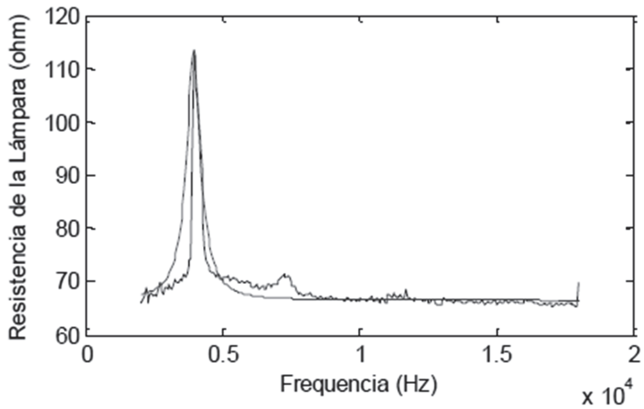

Figure 3. Resistance of 70 W HPS lamp vs frequency.
Source: The Authors

To perform the tests, an experimental facility was implemented in order to perform electrical measurements on HID lamps operating at high frequency and to collect data in both stable operation and when acoustic resonance occurs in the lamp in order to allow appropriate identification of the parameters.

During the experiments, a data set of 2500 record measurements were obtained for a 70W HPS lamp, in 50 Hz supply frequency intervals, in a range from 2 to 18 kHz. Data analysis confirmed that both the excitation and the output signals have an adequate quality for performing the identification tasks.

3.1. Model parameterization

During the parameterization stage, the values of the constants and model parameters were adjusted. With the values collected of voltage and lamp current, its equivalent resistance was calculated to identify possible areas of acoustic resonance. As result, a significant point of increased resistance was identified at 3.95 kHz which suggests that this is a frequency point where the energy is sufficient to excite the resonant mode in the lamp, as shown in the Fig. 3. With this value of auto-frequency ($\mathbf{f_i}$) and the frequency where the lamp operates at steady state, the constants $\mathbf{a_i}$ and $\mathbf{b_i}$ are calculated using the respective vectors **Ai** and **Bi** from eq. 5, by numerical methods. The values obtained for $\mathbf{a_i}$ was 2301847.5432, while for $\mathbf{b_i}$ a value of 0.0212 was obtained.

Other universal physical constants are defined, as in the case of the Boltzmann constant (**k**: $\mathbf{1.38 \times 10^{-23}}$) and the electron charge (**e**: $\mathbf{1.6 \times 10^{-19}}$). The adjustment of key model parameters was performed at this point, once all the constants and the model implemented in Simulink were available. The global optimization toolbox based on Genetic Algorithms in MATLAB was used for purpose. The objective function was developed as defined in eq. (8) in a Matlab file and the parameters were also defined. The Genetic Algorithm was set in the working window, limiting the range of the search space and initial conditions were imposed.

Objective function **(@FO)**:

$$\mathbf{J(a1, a2, a3, a4, a5, a6) = min[\sum(V_{real} - V_{sim})^2 + \sum(I_{real} - I_{sim})^2]} \qquad (8)$$

Parameters of Genetic Algorithm amending:
Function optimization: @ FO Variable #: 6
Limits of the Universe:
Bottom: [8000 1000 0.5 0.001 50 1]
Top: [10000 4000 10 10 500 12]
Initial Population:
[10000 2513.4959 3.7821 0.0164 66.8994 4.7467]
Population Size: 50
Feature selection: Roulette.
Function Mutation: Uniform.
Mutation rate: 0.1
Crossover function: Intermediate
Radio crossing: 0.9
Hybrid Function: fminsearch
Stop criteria:
• Number of Generations (Number of Iterations): 100
• Tolerance function: 1x10-20
• Tolerance linearity restrictions: 1×10^{-20}

Other initial conditions required by optimization algorithm were also specified in the model implemented in Simulink, such as the temperature of the discharge tube wall lamp ($\mathbf{T_0}$), which was set to 1200 K, according to what is expressed by [10] for this type of sodium lamps. Similarly the initial temperature of the lamp was adjusted to 4500 K.

The number of iterations was set based on several experimental runs, in which a standard deviation less than 1% was obtained

After several runs, where the stopping criterion that prevailed was the preset number of iterations reached as mentioned above, the results for the optimization process was found the optimum value, for a given objective function, was $\mathbf{1.57905 \times 10^5}$. Finally, the adjusted parameters are shown in Table 2.

4. Resolution model and validation of results

The resolution of the model shows that the graphics obtained are in line with the expectations for both amplitude and waveform. The model outputs for temperature and the resistance of the lamp are also in the range values and behavior similar to the real system, as shown in Fig. 4. Note that the resistance value is approximately equal to the corresponding value in the real system at 9 kHz, which can be seen in the graph of Fig. 3.

Table 2.
Parameters obtained by Genetic Algorithm optimization for high-frequency model.

Parameter	Adjusted value
a1	9990,76837
a2	2539,05449
a3	5,44916
a4	0,01914
a5	74,01949
a6	4,83055

Source: The Authors

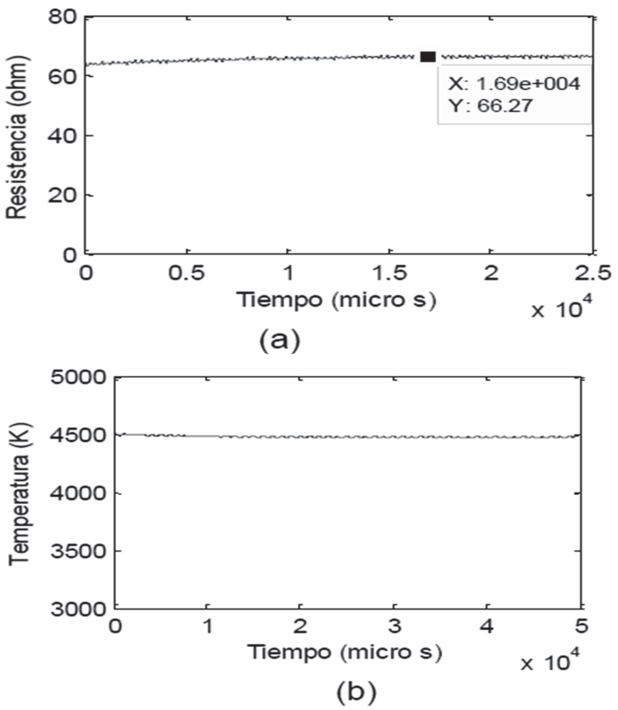

Figure 4. Graphs of Resistance (a) and temperature of the lamp (b), obtained by the model at 9 kHz.
Source: The Authors

To validate the results, the various criteria mentioned in [14] were used. First is the comparison of curves, to assess the similarity between the actual current and voltage curves with those obtained by the model. The measured data set at 9 kHz, was divided into three for use in the steps of parameterization, and validation of the model's resolution respectively. Fig. 5 shows the waveforms of voltage and current, both real and obtained for the model in the interval corresponding to the observed data validation, a little convergence and mismatch between the actual and modeled forms of waves can be appreciated. The voltage model shows slightly higher amplitude compared to the actual values, but overall there is a good fit.

Another validation method used is the operational validation, by which it is determined if the model responds with sufficient approximation to the real system for the intended purpose and in the domain of intended use. Therefore the simulation proceeds in other frequency ranges, real data is then compared with the model output. The results for the frequency of 15 kHz are shown in Fig. 6

As it can be seen, for this new frequency, the response of the model is also quite good, the curve fitting is appropriate, the amplitudes and waveforms of current and voltage generated by the model are consistent with the power of the HPS lamp (70 W). The voltage waveform pattern, as in the real system, does not shown reignition peaks in the lamp because it is operating at high frequency.

Another interesting result on the operational validation of the model at high frequency is in the resistance curve lamp's arc generated by the model for a frequency near to the resonance frequency of the lamp study (3.95 kHz). Fig. 7 shows that, as expected, the resistance of the lamp should be increased to values above 100 Ω, with a tendency to decrease, consistent with that shown in Fig. 3 at the same frequency for the real system, as result of which the operating frequency goes away from the acoustic resonance frequency.

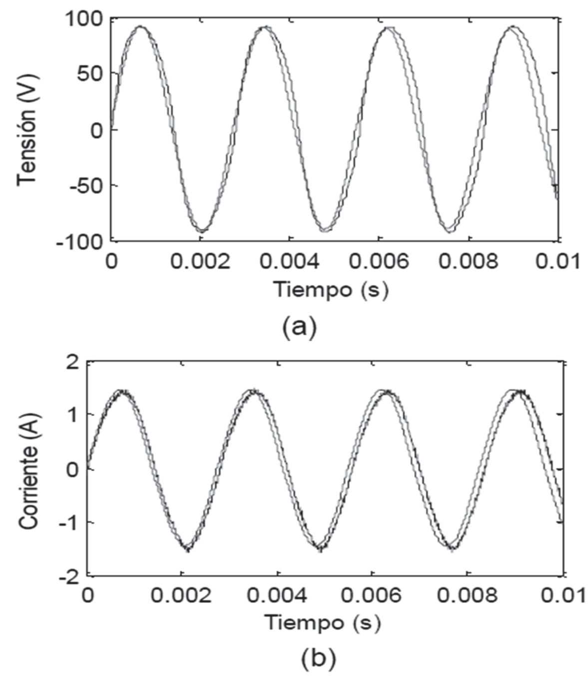

Figure 5. Comparison between actual wave forms and modeled, (a) tension and (b) current of a HPS lamp, for a frequency of 9 kHz.
Source: The Authors

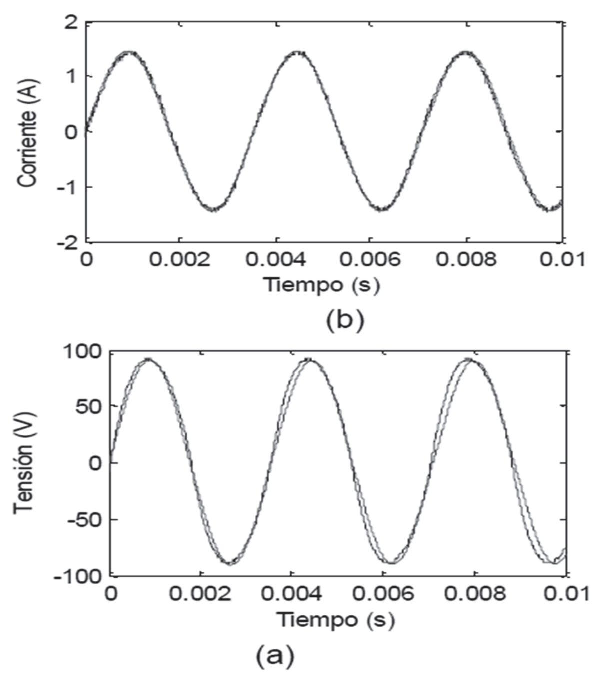

Figure 6. Comparison between actual wave forms and modeled, (a) tension and (b) current of a HPS lamp, during the validation of the model for a frequency of 15 kHz.
Source: The Authors

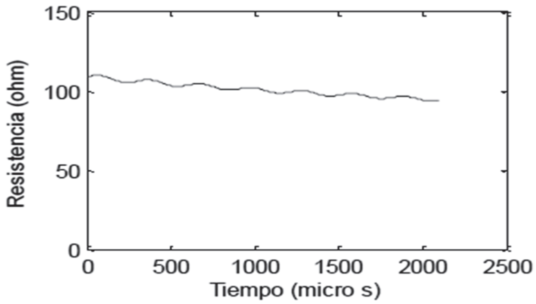

Figure 7. Lamp resistance graph obtained by the model at high frequency, specifically at 4 kHz.
Source: The Authors

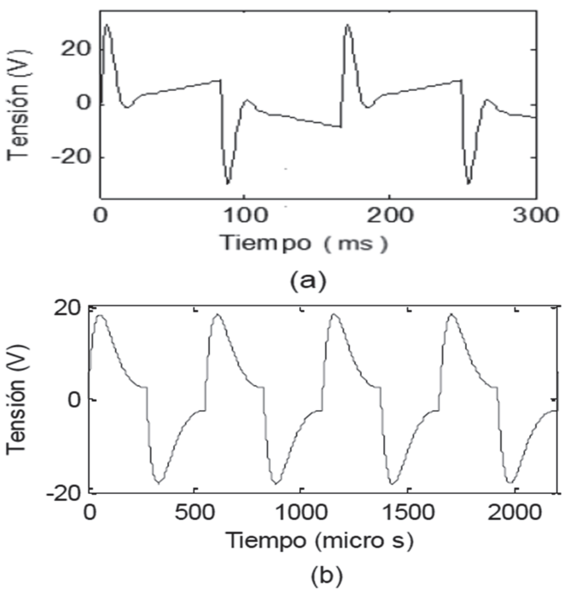

Figure 8. $\mathbf{V_{ele}}$ waveform. a) low frequency (60Hz), b) high frequency (9 kHz).
Source: The Authors

The behavior of $\mathbf{V_{ele}}$ waveform to high frequency also validates the model. According to [4], as the frequency of operation of the lamp increases, the second maximum in each half cycle of the waveform $\mathbf{V_{ele}}$ is reduced, as shown in Fig. 8b, where contrary to the $\mathbf{V_{ele}}$ waveform for a lamp operating at 60 Hz (Fig. 8a), the second peak of each cycle almost no appears [4].

All simulations were performed in the frequency range in which the voltage and lamp current data were collected, yielded similar results convergence.

The third method of validation implemented was statistical, using criteria related to the mean square error [15]. In this way the percentage of fit was calculated according to eq. (9) and the last 30% of the data set was used for this method.

$$FIT = \left(1 - \frac{\sqrt{\frac{\sum_{i=1}^{n}(y-y_{mod})^2}{N}}}{\sigma}\right) * 100 \qquad (9)$$

Table 3.
Statistical analysis of the model for different frequencies. Calculation of FIT.

Frequency (kHz)	Fit voltage waveform (FIT_V)	Fit current waveform (FIT_I)
7	85.67	89.46
9	79.44	74.68
11	82.65	84.89
12	80.65	83.12
13	84.50	85.01
15	83.50	83.53
16	77.19	79.49

Source: The Authors

Where:
σ is the standard deviation.
y is the actual output
ymod is the model output
N is the number of samples

The FIT rate reflects a good model when its value is close to 100% [15]. Table 3 shows the result of calculating the percentage of model fit for various frequencies for the 70 W HPS lamp during the validation stage. In all cases, the results exceed 70% of adjustment, which indicates a good fit for the model.

The average value of the adjustment rate calculated for the model was 85.6086%, since the mean values of the fitting percentages for the modeled voltage and current curves are 84.4709% and 86.7464%, respectively. Considering the results obtained from the model validation, it can conclude that the model is perfectly suitable for use in the development of the power stages control systems for high frequency ballasts.

5. Conclusions

The implementation of a model for discharge high intensity lamps capable of working in a high frequency range, that also take in to consideration the influence of the acoustic resonance phenomenon and other characteristics of the lamps was made. This model can be used in future design studies of high-frequency ballasts for HID lamps. It was possible to optimize the parameter of the model by using the optimization techniques based on Genetic Algorithms with Matlab and the results were verified for high pressure sodium (HPS) lamps .

Obtaining the parameters of the proposed model to predict the behavior of the HID lamp, which in turn facilitates the design of a controller for acoustic resonance free operation.

The simulations and statistical calculations showed great graphical convergence and agreements between the results obtained by the model developed and the real system (HPS lamp 70 W) and high levels of fit, which on average were around 85%.

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