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Faculty of Mechatronics and Interdisciplinary Engineering Studies
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Selfreport of the Ph.D. thesis

ELECTRIC CONDUCTIVITY MODEL OF DISCHARGE LAMPS

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Electric Conductivity Model of Discharge Lamps

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Anotace

Tato dizertační práce se zabývá modelováním světelných výbojů pro popis elektrických obvodů. Nejedná se o modelování plazmatu, ve smyslu modelování jeho vnitřních dějů, ale o využití rovnice elektrické vodivosti světelného výboje, která však vychází z jeho fyzikálního rozboru.

Parametry vodivostního modelu jsou určeny z naměřených napěťových a proudových charakteristik v praxi běžně používaných výbojek bez znalosti technologických dat od výrobce. Zpracování naměřených dat $u(t), i(t)$, aplikace idetifikačního algoritmu a simulace elektrických obvodů je provedena v prostředí Matlab, resp. Matlab Simulink.

Výsledky simulace jsou porovnány s naměřenými údaji. Model je ověřen v simulacích nízkotlakých i vysokotlakých výbojek v zapojení s elektromagnetickými předřadníky.

Klíčová slova: dynamický vodivostní model, identifikace parametrů, numerický model, nelineární zátěž, simulace elektrických obvodů, světelené zdroje, výbojky.

Annotation

This Ph.D. thesis deals with light discharges modelling for description of electric circuits. It is not modelling of internal behaviour of a plasma, but its equivalent conductivity.

The parameters of conductivity model are determined by measured voltage and current characteristics of discharge lamps. This model does not require any technological data from lamp producers. The Matlab/Matlab Simulink is used for data processing of $u(t)$, $i(t)$, application of identification algorithms and electric circuits simulation.

The simulated results are compared to measurements. The model is tested in simulations of low and high pressure discharge lamps in circuits with magnetic ballasts.

Key words: discharge lamps, dynamic conductivity model, light sources, numerical model, nonlinear load, parameter estimation, simulation of electric circuits.

Annotation

Cette thèse de doctorat est consacrée à la modélisation de décharges luminescentes pour la description de circuits électriques. L'objet n'est pas la modélisation du comportement interne d'un plasma, mais de sa conductivité équivalente.

Les paramètres de la conductivité sont déterminés à partir des caractéristiques de tension et de courant de lampes à décharges. Ce modèle ne requiert aucune donnée technologiques de la part des fabricants de lampe. L'environnement Matlab/Matlab Simulink est utilisé pour le traitement de $u(t), i(t)$, l'exécution des algorithmes d'identification et la simulation en termes de circuits électriques équivalents.

Les résultats des simulations sont comparés avec les données mesurées. Le modèle de conductance est testé dans des simulations de lampes à décharge à basse et haute pression, alimentées par ballast magnétique.

Mots Clés: lampes à décharges, modèle de conductance dynamique, sources d'éclairage, modèle numérique, charge nonlinéaire, estimation de paramètres, simulation de circuits électriques.

Contents

1 Introduction

Without the artificial light life would be hardly imaginable nowadays. It has been a long time ago since we stayed in dark and waited for the sunlight to come. The artificial light has become practically omnipresent all across the developed world. It is mainly a product of the electric energy which is transformed into the light by various electrical light sources. Approximately 25 % of the worldwide electricity production is consumed by these light sources [21]. There are numerous types of electric light sources and they could be classified *e.g.* according to the way of the light emission [15, 26, 41]:

- In solid states
  - incandescent
    - vacuum light bulbs,
    - light bulbs filled by gas – conventional, and halogen;
  - luminescence
    - light-emitting diodes,
    - organic light-emitting diodes.
- In gases and in metal vapours
  - arc discharge
    - low pressure – fluorescent, sodium, sulphur lamps, *etc.*,
    - high pressure – mercury, sodium, xenon lamps, metal halide lamps, *etc.*
  - glow discharge

* low pressure – glow-lamps.

It has been estimated that 80 % of electric light sources which are used for indoor commercial, industrial, institutional, and retail applications, is fluorescent. The discharge lamps significantly prevail compared to the other types, mainly due to their efficiency of electrical energy conversion into light [37].

Discharge lamps are based on plasma emitting light in visible or invisible luminous spectrum. The principle is very complex and due to it can exist many types of arc discharge tubes. These light sources do not work directly from the mains electricity as the light bulbs do, but rather over special circuits called *ballasts*. They are required for the lamp starting, arc-current limiting in the steady-state operation and relighting each half cycle (for alternate current operation). The ballast must provide these functions with minimum consumption of electric power, no adverse effect on lamp life and with no negative influence to the mains supply.

To solve such problem is a multidisciplinary task. The luminary system lamp-ballast is a product of many scientific/technical disciplines: plasma physics, chemistry, materials, optics, electrical engineering, electronics, *etc.* [1, 39].

The electrical point of view is the main interest of this work. The problem confines then to the field of electrical engineering, especially to the electric circuit design, where the most interesting characteristic for the ballast designer is lamp terminal characteristic as an electrical load. This highly nonlinear part of the circuit should be described by a simplified model usable in various CAD systems.

1.1 State of the art

Specialists who focus on discharge lamps are aware of a strong link between the source and the lamps characteristics, such as color temperature, operating power or luminous flux. However, there are hardly any analytic models linking the lamps characteristics with their electrical properties.

Numerical simulations must therefore take into account a number of coupled phenomenons: fluid motion and convection, heat dissipation, chemical reactions, electric and magnetic field computation, *etc.* Fundamental data like the species cross section (*e.g.* [19]) or the chemical reactions occurring at this range of temperatures and pressures are not well known and are a subject of a discussion among specialists.

Lister *et al.* [21] wrote a review of the physics of discharge lamps recently and discussed the modelling of gas discharge. Schematically, this topic can be subdivided into two main branches:

- models based on the plasma equations,
- semiphysical or black box models.

The first one is about solving numerically the plasma equations. So far, numerous groups are working on various aspects of the discharge lamp simulations, like the influence of an electrode on the discharge column [7, 9], or the plasma properties inside the lamp [20]. This approach is based upon Finite Elements discretization and delivers results as local variables like ions and electrons densities, temperatures, velocities, *etc.*

Due to its complexity and computational heftiness, such approach is not suitable for simpler tasks like electric circuits modelling, ballast design, influence of discharge lamps (electric load) evaluation, *etc.* In this case, semiphysical or black box models are applied, with parameters identified from real lamp data. This approach is called *global*, as the result is directly expressed in terms of the global electrical properties like voltage and current.

Those models are useful in specialised environments, like *e.g.* SPICE or Matlab [42]. They are mainly based on approximation of:

1. non-linear voltage-current characteristics (see fig. 1.1),

2. equivalent conductivity/resistance.

The first approach enables using of a fixed *negative* resistance describing the negative slope of the voltage-current curve [5, 6, 10, 28, 36]. Such approach is better suited for high frequency operating mode, as the lamp starts behaving as a linear, constant load. But at mains frequencies, the time scale permits a significant variation of the plasma properties, leading thus to a time-varying formulation as a function of various easily measurable lamp parameters.

For low pressure fluorescent lamps such conductance variation can readily be obtained from the Francis equation [14] complemented by various relationships between electrons density, temper-

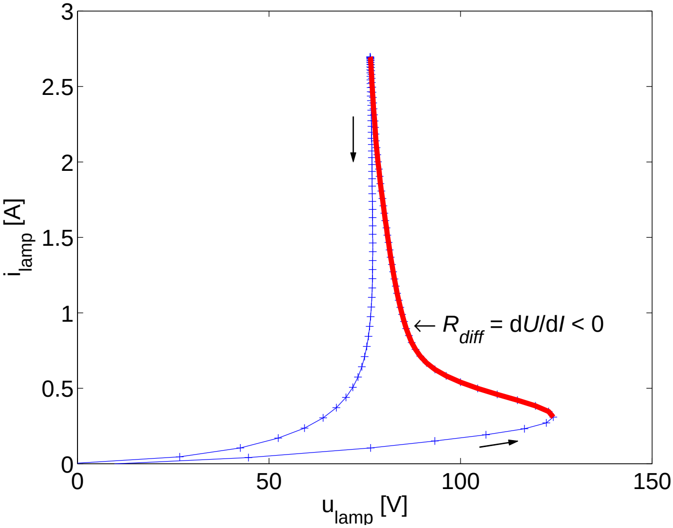


Figure 1.1: Part of the dynamic voltage-current characteristic of HID lamp powered by 50 Hz voltage with magnetic ballast. The part with negative differential resistance ($R_{diff} < 0$) is red lined. Two arrows show the counterclockwise direction of the characteristic evolution.

ature, mobility and discharge parameters like current, gas properties, thermal emissivity, *etc.* [22, 23, 24].This leads to analytical and often nonlinear models suitable for circuit simulators.

Herrick [16] extrapolated the Francis model to High Intensity Discharge (HID) lamp, applied on data obtained from Hg and Na lamps. Based upon a black box approach, he expressed a Taylor developement of the time derivative of the conductance as a polynomial of the lamp current and conductance.

Other authors [2, 3, 4, 33, 34, 35] followed the same path with various adjustments to the basic structure.

The model used for our study specified below by (1.1) belongs to this family, and it can be recognised that certain function of the conductivity was approximated by a polynomial in the conductivity.

1.2 Aims of the thesis

The aim of the work is to describe a discharge lamp (different types) as an electric load for the electric circuits simulation. Such model can be used in light net model to observe the behavior and influence onto mains supply of electricity and for design of new electronic ballasts.

The lamp will be described by the G-model based on the electric conductivity $G(t)$ of the plasma proposed by Zissis *et al.* [42]:

$$\frac{\mathrm{d}G}{\mathrm{d}t} = a_2 i^2 + \sum_{k=1}^{N} b_k G^k, \tag{1.1}$$

and other lamp models based on description of equivalent conductivity *eg.* from works [3, 4], too.

The optimal structure of lamp models with its parameters will be determined. Such model will be used as the block in Matlab Simulink and verified against experimental results.

1.3 Outline of the thesis

The theory of the electric discharge is briefly explained in the first part of the thesis and the light production principles of different types of discharge lamps are introduced. The summary of widely used discharge lamps is given. Then the presentation of a necessary electric circuit for their operation – *ballast* follows.

Second part deals with mathematical modelling of discharge lamps for lighting. It focuses on electrical description modelling of discharge lamps, on their simulation in electric circuits especially. The calculation and modification of the G-model is noted.

The part with the presentation of experiments deals with measurements on different discharge lamps and their circuits. This step represents the data acquisition (oscillograms of lamp voltage and current $u_{lamp}(t), i_{lamp}(t)$) for model verification.

The next chapter describes the process of lamp model identification which is followed by simulation part where the applications of models in the luminary system models are shown.

In the conclusion, the advantages and disadvantages of used methods are discussed and perspectives of electrical modelling approaches are summarized.

2 Problem analysis

The structure of the thesis as well as problem solution was described in previous section.

This report shows briefly how the work was solved.

2.1 Characteristics of discharge lamps

The construction of different types of measured discharge lamps and sample of their electrical characteristics is presented.

2.1.1 Low pressure discharge lamps

The following text is focused on low pressure (LP) mercury vapour discharge lamps – *fluorescent lamps* (FL), because measurements were taken on them. That is why LP sodium lamps mentioned in summary of light sources are not discussed.

There are various of FLs in the market. They are produced in wide range of powers (6 up to 80 W), shapes, dimensions, colours, *etc.* FLs can be divided into five groups [31]:

- tubular;
- bent;
- integrated;
- non-integrated;
- electrodeless (induction) lamps.

Tubular (linear) FLs are widely used. Their common construction with potential characteristic in direct-current (DC) operation mode describes figure 2.1.

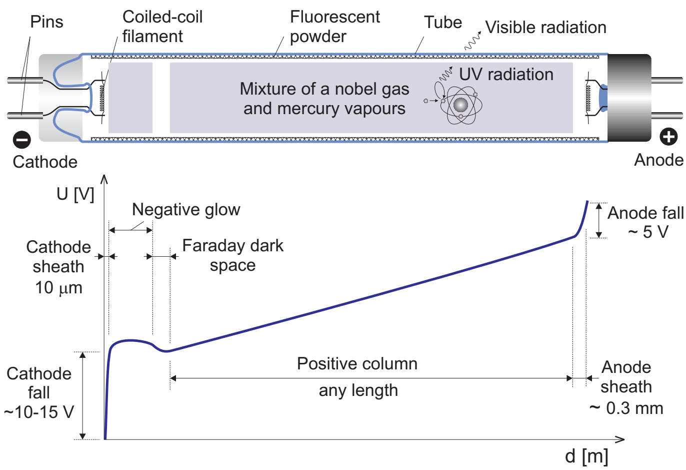


Figure 2.1: Structure of a LP rare-gas discharge lamp in DC mode [37, 38].

A standard commercial luminary set with 58 W fluorescent lamp in circuit with magnetic ballast is used for demonstration of characteristics of this group of discharge lamps. The specification of used components as well as electrical characteristics are summarized in table 2.1. The measured oscilograms of the lamp in circuit with magnetic ballast (MB) are shown in figure 2.2.

The majority of all measurements was realized by multichannel recorder EMU-2 of TU of Liberec [29]. All captured data were processed then and visualized in Matlab environment.

2.1.2 High pressure discharge lamps

There are three general types of HID lamps distinguished by their plasma forming species:

- high pressure mercury lamps;
- high pressure sodium lamps;

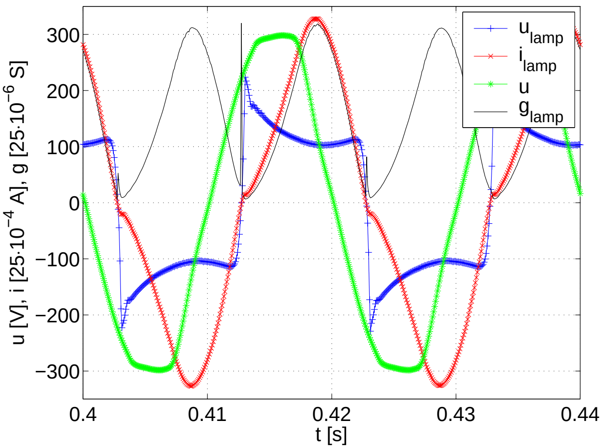


Figure 2.2: Measured electric characteristics of 58 W linear fluorescent lamp and waveform of computed conductivity.

Table 2.1: Parameters of the circuit with 58 W FL

FL	Sylvania standard F 58 W/154				
MB	Layrton ARC 65/23, 65 W, 230 V, 50 Hz, 0.67 A				
U_{net}	=	221 V	U_{lamp}	=	126 V
I_{lamp}	=	0.52 A	G_{lamp}	=	5 mS
P_{net}	=	61 W	P_{lamp}	=	51 W
Q_{net}	=	98 VAr	Q_{lamp}	=	41 VAr
S_{net}	=	115 VA	S_{lamp}	=	65 VA
R_{ball}	=	37 Ω	L_{ball}	=	970 mH
THD_{lamp} V	=	57.43 %	THD_{net} V	=	7.74 %
THD_{lamp} A	=	15.32 %	λ_{lamp}	=	0.778

- metal halide lamps.

Typical high pressure discharge lamp (see fig. 2.3) is assembled of *inner discharge tube (arc tube)*. An arc tube can have different

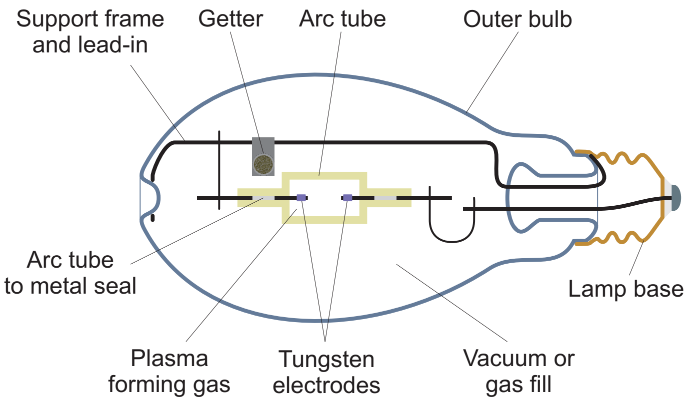


Figure 2.3: The general construction of a high pressure discharge lamp.

shapes (cylinder or sphere) and can be made of different materials (glass or ceramic). The arc tube with electrodes contains plasma forming gas and is fixed by *support frame* and hermetically sealed in *outer bulb*. The outer bulb protects the inner tube and inner tube seals from oxidation, stabilizes the work conditions around the arc tube, absorbs emitted UV radiation and it can be covered by fluorescent powder for the same reason as in fluorescent lamps. On the frame inside the outer bulb can be mounted a *getter* [8] which absorbs impurities (oxides, water vapour *etc.*) remained after the fabrication processes.

The metal halide lamp (MHL) with ceramic discharge tube is used as an example of the light source of this group.

The lamp was standard type Osram Powestar HCI-T 150 W NDL that can work in any position, and operate with magnetic or electronic ballast. More information about this lamp is in the company catalogue [30].

Values of the components and electric characteristics are presented in table 2.2. The waveforms of electric characteristics of vertically operated lamp are shown in figure 2.4.

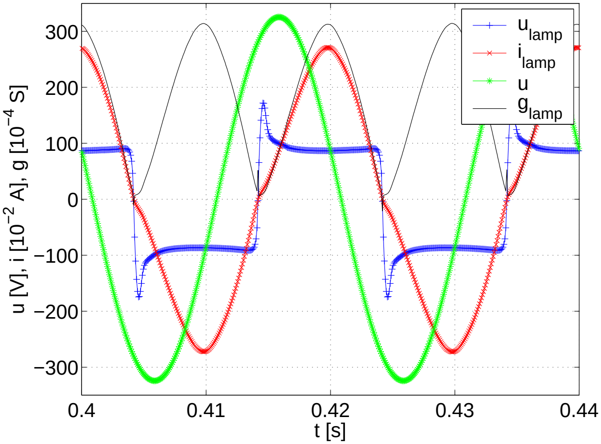


Figure 2.4: Measured voltages, current and computed conductivity of 150 W MH lamp in circuit with MB.

Table 2.2: Parameters of the circuit with 150 W MH lamp and MB

HID	Osram Powerstar HCI-T 150 W/NDL				
MB	OMBIS 150 A604W 220 – 240 V 50 Hz – connection to the tap 230 V				
Starter	ZRM 2,5 – WS/B				
U_{net}	=	230 V	U_{lamp}	=	95 V
I_{lamp}	=	1.81 A	G_{lamp}	=	21 mS
P_{net}	=	164 W	P_{lamp}	=	142 W
Q_{net}	=	382 VAr	Q_{lamp}	=	97 VAr
S_{net}	=	416 VA	S_{lamp}	=	172 VA
R_{ball}	=	7 Ω	L_{ball}	=	350 mH
THD_{lamp} V	=	59.35 %	THD_{net} V	=	0 %
THD_{lamp} A	=	8.17 %	λ_{lamp}	=	0.825

Another figure 2.5 displays two samples of voltage-current characteristics for two frequencies (50 Hz and 1 kHz) of supply voltage.

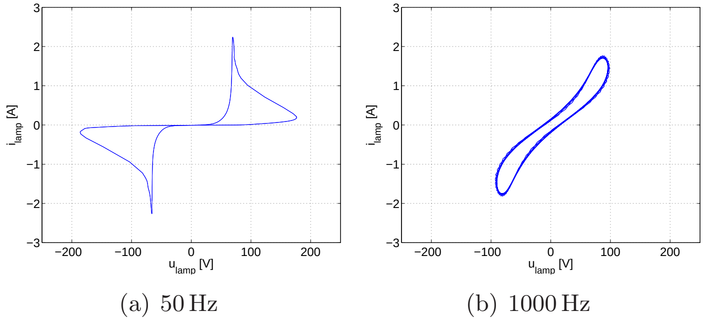


Figure 2.5: Voltage-current characteristics for two frequencies of power supply.

The linearization of the lamp characteristic with increasing voltage frequency is obvious.

2.1.3 Electric circuits for electric discharge lamps

Electric discharge lamps need some electric circuits for their correct operation. It is realized through *ballasts*, which can be constructed from classical passive components only (resistive/reactive ballasts) or from semiconductors and passive components R, L, C (electronic ballasts).

Majority of discharge lamps are powered by *alternate-current (AC) voltage*. The circuits in AC regime have to ensure three general functions:

- start of a discharge lamp;
- a lamp relighting each half cycle;
- control of current through a discharge lamp.

In figure 2.6 is a typical electric circuit with discharge lamp. The mains voltage $u(t)$ is connected in parallel to the capacitor. In series are inductive (magnetic) ballast and parallel combination

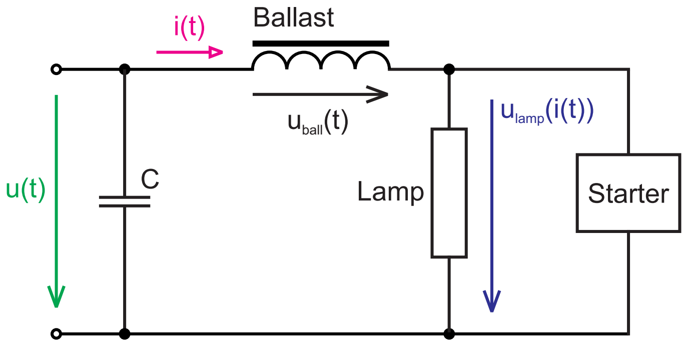


Figure 2.6: Typical electric circuit for discharge lamp with inductive ballast, starter and compensating capacitor.

of lamp and starter. During the steady operation state the current $i(t)$ induces fall voltage on ballast $u_{ball}(t)$ and lamp $u_{lamp}(i(t))$. Through the opened starter does not flow any current. Under this condition is possible to write the equation 2.1, where ballast is represented by ideal resistance R and inductance L.

$$
\begin{aligned}
u_{lamp} &= u - u_{ball}, \\
u_{ball} &= i\,R + L\frac{\mathrm{d}i}{\mathrm{d}t}
\end{aligned}
\tag{2.1}
$$

The term $u_{lamp}(i(t))$ describes the lamp behaviour as an electrical load. Just the model of such load is the object of analysis of this work.

2.2 Identification

An approach of offline experimental identification (fig. 2.7) of parameters of lamp models (see equations (2.2), (2.3) and (2.4)) is described in this chapter.

The optimal lamp model structure for high and low pressure lamps is proposed, the behaviour of the model under frequency, voltage value and shape change is also studied.

The data processing and computation routines were programmed in Matlab language (*note*: Optimized for Matlab version 6.5 Release 13.) [25]. Some of them are compatible with a free alternative programming language – Octave [13].

2.2.1 Computation structure

The identification procedure is a part of the computation structure. Some steps (*f.i.* data preprocessing) have to be done before the identification. The whole technique can be summarized as follows:

1. data loading;

2. data preprocessing:

    - data filtration (removing of bad samples of EMU-2, data allocation);
    - data analysis (signal period, values, *etc.*);
    - creating of whole periods of signals;
    - conductivity computation from $\mathbf{u}_{lamp}, \mathbf{i}_{lamp}$ vectors;
    - displaying of analyzed waveforms of voltage, current and conductivity;
    - data adjustment for identification:
        - removing of DC component from measured signals of u_{lamp}, i_{lamp},
        - removing of critical samples near zero,
        - conductivity limitation in specific range,
        - reformulating the conductivity computation process;
    - data visualisation after correction;

3. identification:

- optimum criterion;
- identification methods:
  - iterative method [32, 17, 18],
  - non-iterative method [11, 12];

4. simulation.

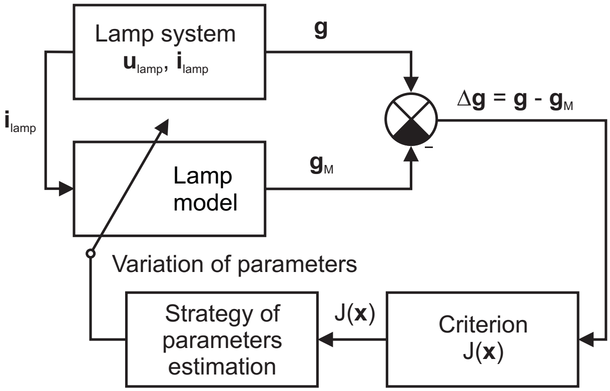


Figure 2.7: Structure of experimental offline identification of a lamp model.

2.2.2 Lamp model

For the purpose of this thesis a number of lamp models was used. They came out of different hypothesis of Zissis *et al.* [42] and Antón *et al.* [3, 4], but they describe the equivalent lamp conductivity and are basically the same. Their modified structure follows:

$$\frac{\mathrm{d}G(t)}{\mathrm{d}t} = a_2(i(t) + a_1)^2 - [b_3\ G^3(t) + b_2\ G^2(t) + b_1\ G(t) + b_0]; \quad (2.2)$$

$$\frac{\mathrm{d}G(t)}{\mathrm{d}t} = \frac{a_2}{G(t)}(i(t) + a_1)^2 - [b_2\ e^{b_3 G(t)} + b_1\ G(t) + b_0]; \quad (2.3)$$

$$\frac{\mathrm{d}G(t)}{\mathrm{d}t} = \frac{a_2}{G(t)}(i(t) + a_1)^2 - [b_3\ G^3(t) + b_2\ G^2(t) + b_1\ G(t) + b_0]. \quad (2.4)$$

In following text are these equation named as *polynomial* (2.2), *exponential* (2.3) and *quadratic* (2.4).

2.2.3 Iterative computation method

For the strategy of parameters estimation the `fminsearch` function of Matlab Optimization Toolbox [25] was used. The function `fminsearch` finds a minimum of a scalar function of several variables

$$\min_x f(\mathbf{x}), \quad (2.5)$$

starting at an initial estimate. This is generally referred to as *unconstrained nonlinear optimization*. This function uses *simplex search method* [27].

In program is used this call of `fminsearch`:

```
x = fminsearch(fun, x0, OPTIONS)
```

As the function was written `gk_minprezg` which realizes computation of conductance with new parameters

$$G(t) = \int \left[a_2\left(i\ + a_1\right)^2 - \sum_{i=1}^{3} b_i\ G^i(t)\right]\mathrm{d}t, \quad (2.6)$$

where the integration is performed numerically as explicit one-step Euler method; and realizes criterion (2.7)

$$J(\mathbf{x}) = \sum_{i=1}^{N} [g_i - g_{Mi}]^2. \quad (2.7)$$

2.2.4 Graphical user interface for the lamp model identification

For friendly application and visualisation of proposed identification algorithm (see page 20) a graphical user interface was designed. The application window developed in Matlab GUIDE environment [25] is shown in figure 2.8. A simple manual for this application was written also.

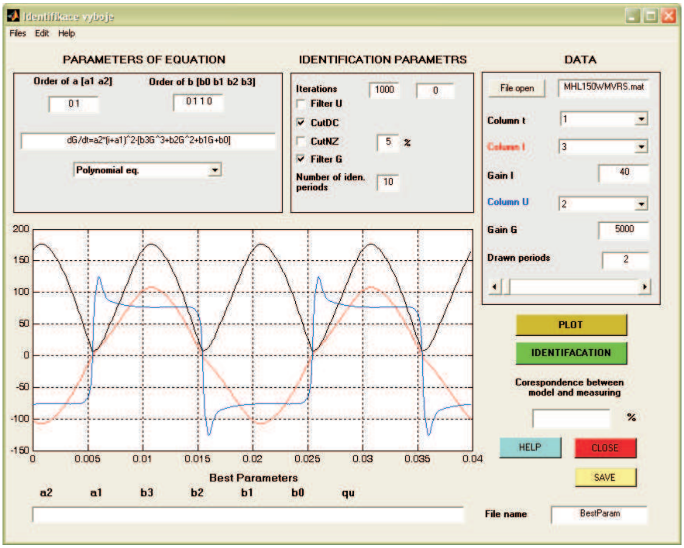


Figure 2.8: The application window of the graphical user interface for the lamp model identification.

2.3 Simulation

All simulations of lamp models and electric circuits were implemented in MATLAB Simulink (*note*: Optimized for Simulink version 5.0 Release 13).

2.3.1 Simulation model of a discharge lamp with a ballast

The simulation diagram in figure 2.9 represents an electric circuit with a discharge lamp in connection with magnetic ballast (*cf.* figure 2.6). This circuit describes following equation

$$u(t) = R_{ball}\ i(t) + L_{ball}\frac{\mathrm{d}i(t)}{\mathrm{d}t} + u_{lamp}(t). \tag{2.8}$$

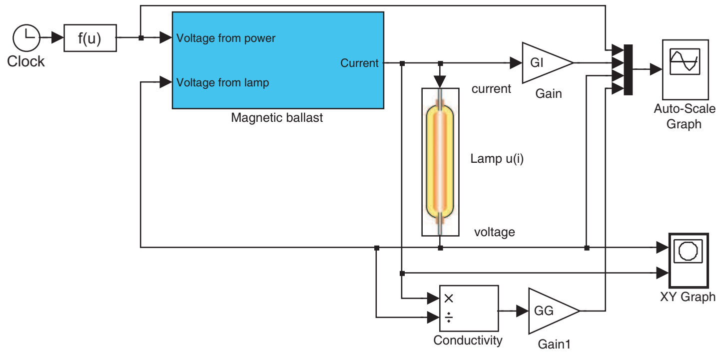


Figure 2.9: Simulation model of an electric circuit with a lamp load.

2.3.2 Simulation model of a discharge lamp

The simulation diagram in figure 2.10 is a universal lamp model. It simulates this equation

$$u_{lamp}(t) = \frac{i_{lamp}(t)}{G(t)}. \tag{2.9}$$

The time dependant conductivity is given by differential equation (2.10). It includes three types of models already mentioned

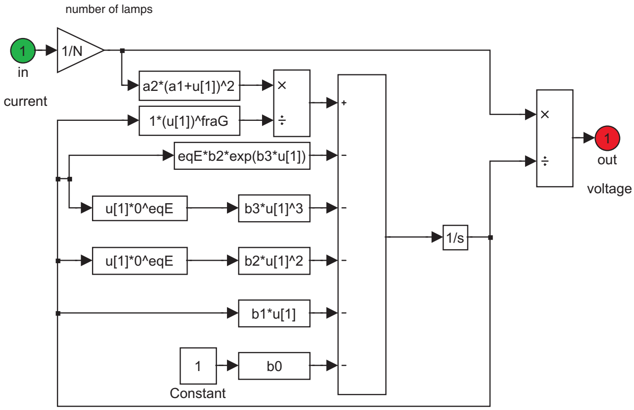


Figure 2.10: Universal simulation scheme of a discharge lamp.

in section 2.2.2.

$$\frac{\mathrm{d}G(t)}{\mathrm{d}t} = \frac{a_2}{G(t)^{\mathtt{fraG}}}\,(i(t)+a_1)^2 - \Big[\big(b_2\ e^{b_3 G(t)}\mathtt{eqE}\big) + \big(b_3\ G^3(t) + b_2\ G^2(t)\big)\mathtt{eqE} + b_1\ G(t) + b_0\Big], \quad (2.10)$$

where

- N is a number of lamps (default is 1);
- $a_2, a_1, b_3, b_2, b_1, b_0$ are model parameters;
- `fraG` is the first universal constant:
  - if `fraG` is 0 then the polynomial model is chosen,
  - if `fraG` is 1 then the conductivity is in fraction (quadratic and exponential model);
- `eqE` is the second universal constant:

– if `eqE` is 0 then the polynomial or quadratic model are chosen,
– if `eqE` is 1 then the exponential model is chosen.

3 Results

3.1 Results of identifications

A number of discharge lamps was measured and data for the identification were acquired. The results for certain settings of identification processes are summarized.

3.1.1 Model parameters of low pressure discharge lamps

The parameters of quadratic model (2.4) in table 3.1 were obtained. Settings of identification are in table 3.2.

Table 3.1: Parameters of quadratic model (2.4) of fluorescent lamps.

	a_2	a_1	b_3	b_2	b_1	b_0	qu
FL18W	1.12	0	0	1074	3778	0	0.00402
FL36W	0.30	0	0	-208009	3727	0	0.00004
FL58W	0.20	0	0	-169190	3525	0	0.00026

The qu value gives the information about quantitative difference between simulated and experimental curves of conductivity.

3.1.2 Model parameters of high pressure discharge lamps

In table 3.3 are parameters of lamp models of two types of high pressure discharge lamps. The similar settings of identification

Table 3.2: Identification settings for models of fluorescent lamps.

Analyzed data	LPFLxxW.mat
Used model	quadratic model (2.4)
Number of iterations	1000
Filter U	no
CutDC	yes
CutNZ	no
Filter G	yes
Number of iden. periods	10

process as in table 3.1 were applied. The different *analyzed data* HPxL400W.mat and *model type* polynomial model (2.2) were used instead.

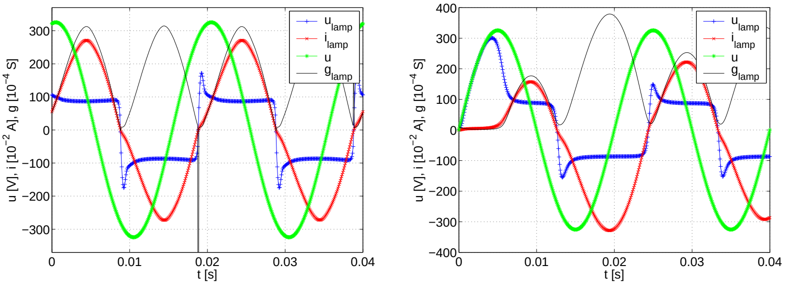
Table 3.3: Parameters of polynomial model (2.2) with conductivity polynome of second order.

	a_2	a_1	b_3	b_2	b_1	b_0	qu
HPML400W	5.4	0	0	104230	85	0	0.00227
HPSL400W	21	0	0	100171	299	0	0.01049

3.2 Experimental verification

The verification of experimental and simulated curves of lamp conductivity, lamp current, and lamp voltage was accomplished.

The simulation models of the whole electric circuit with the discharge lamp or parts of it were partially verified. The simulation of the whole electric system is problematic due to *starting phase* (*cf.* figure 3.1(b)) that in some cases can cause divergence of the



(a) experiment

(b) simulation of polynomial model fig. 2.9

Figure 3.1: Comparison of experiment and simulation characteristics with the complete electric circuit model with 150 W metal halide lamp.

simulation. Therefore the lamp model powered by current source for experimental verification was used.

3.2.1 Metal halide lamp verification

The metal halide lamp is used as an example again. Electrical characteristics measured in vertical operation position, in circuit with magnetic ballast, powered by ideal sine supply voltage, under different conditions were verified.

Variance of lamp models at frequency 50 Hz

Three types of characteristics of lamp models shown in figure 3.2 are compared. Parameters for all models are summarized in table 3.4.

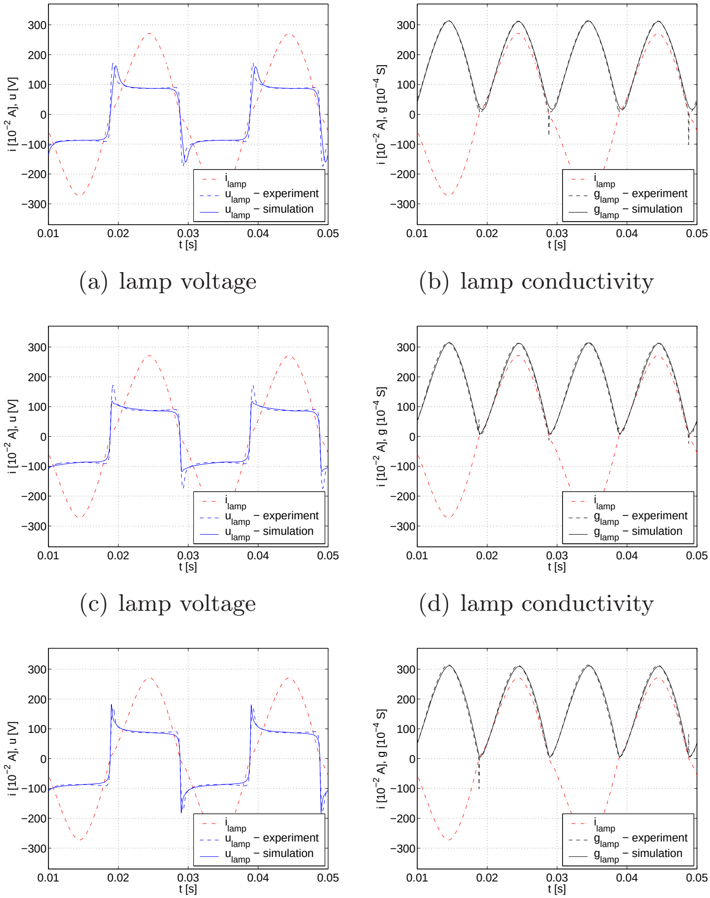
Table 3.4: Settings of simulations with three types of lamp models of 150 W metal halide lamp.

model	xp						
type	a_2	a_1	b_3	b_2	b_1	b_0	qu
poly	54	0	0	$3.87\,10^5$	710	0	$1.8\,10^{-3}$
quad	0.53	0	0	$-2.4\,10^4$	$4.8\,10^3$	0	$2.3\,10^{-3}$
expon	0.52	0	0.037	4.3	$3.9\,10^3$	0	$2.5\,10^{-3}$

Variance of frequency of supply current with polynomial lamp model

In another study data of 150 W MHL with resistive ballast were used. The simulated characteristics in figures 3.3 are obtained with polynomial lamp model. Settings are the same as in table 3.4 and were obtained from identification of the lamp at 50 Hz with the magnetic ballast.

The results of simulations show differences between experimental and simulated curves. It is expectable taking to account that variation of parameters values of identification is present.

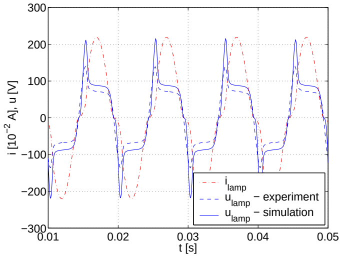


(a) lamp voltage (b) lamp conductivity

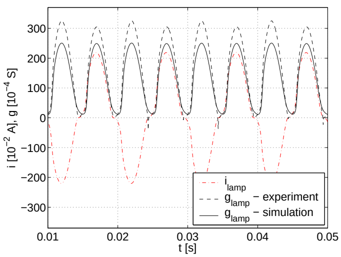
(c) lamp voltage (d) lamp conductivity

(e) lamp voltage (f) lamp conductivity

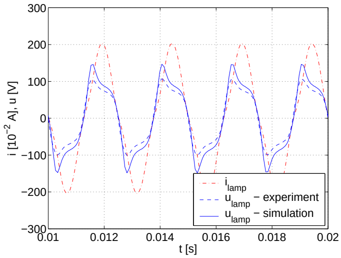
Figure 3.2: Experimental and simulated lamp voltage and conductivity of 150 W MHL with polynomial (a)–(b); quadratic (c)–(d); exponential (e)–(f) lamp model application.



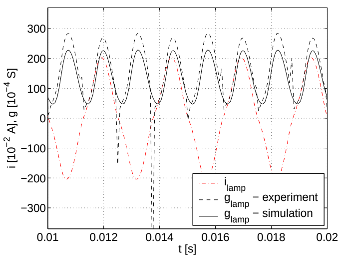
(a) lamp voltage



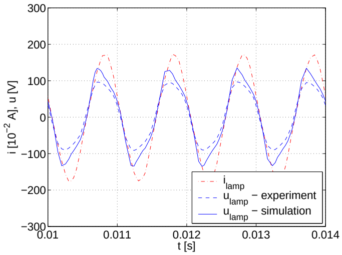
(b) lamp conductivity



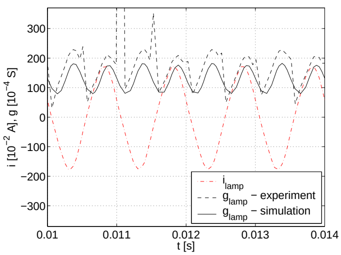
(c) lamp voltage



(d) lamp conductivity



(e) lamp voltage



(f) lamp conductivity

Figure 3.3: Experimental and simulated lamp voltage and conductivity of 150 W MHL with polynomial model at frequency 100 Hz (a)–(b); 400 Hz (c)–(d); and 999 Hz (e)–(f).

4 Conclusion

The modelling of discharge lamps is not a simple task mainly due to the fact that the discharge is a complex phenomenon which involves electrical, chemical, thermal and optical characteristics.

This thesis studies low and high pressure discharge lamps from the electrical point of view. It is focused on stable operation behaviour of such highly nonlinear electric loads.

It presents briefly the vast field of the theory of electric discharges used partially in lighting applications. Approaches to modelling and simulation of discharge lamp in electric circuit are mentioned also.

Two optimal structures of lamp models for low and high pressure discharge lamps based on the equivalent conductivity function of the lamp current and several parameters were proposed.

The methodology of parameters searching was established on the offline identification where the iterative or non-iterative approaches were applied. Problems with conductivity computation from measured lamp voltage u_{lamp} and current i_{lamp} were solved. So the parameters are determined from measurements only and data from lamp manufactures are not required. A graphical user interface for the iterative method was designed in the Matlab graphical user interface development environment.

The simulation of models with identified parameters was verified with measured data in Matlab Simulink. The models approximate measurements for certain operation very well, but applicability in wide range of frequency or powers is discutable. Because model parameters are semi-constants and depend on input signals, the identification for other operation state is needed. The parameters' dependence can be explored in further research work.

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