HARMONIC MODEL FOR THE FLUORESCENT LAMP.

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Abstract— This paper describes a method for modelling harmonic currents injected by fluorescent lamps. A model was developed using experimental results from commercially available lamps and takes into account the tube and ballast non linearities and their dependence on source voltage variations. A simulation method with the ability to analyse non linear networks is needed for this model. We proposed an extension to the Iterative Harmonic Analysis (IHA) to calculate the harmonic currents injected by fluorescent lamps. The IHA algorithm is currently used to analyse the interaction between non-linear converters and linear networks.

I. INTRODUCTION

The wide use of the fluorescent lamps for illumination makes necessary the study of their influence in the network harmonic spectrum. The fluorescent tube operation is based on the setting up of an arc into the tube. This arc has a clear non-linear behaviour.

In order to get a study based on simulation, first it is necessary to achieve a model that represents the more important lamp non-linearities. We proposed a model that takes into account the tube and ballast non-linearities [1] and their dependence on source voltage variations.

A simulation method with the ability to analyse non linear networks is needed for this model. We proposed an extension on the Iterative Harmonic Analysis (IHA) to calculate the harmonic currents injected by fluorescent lamps. The IHA algorithm is widely used to analyse the interaction between non-linear converters and linear networks[2][3][4]. It involves a hybrid technique which formulates the non linear component in the time domain and the linear system in the frequency domain, using the common voltage to interface between the two systems at every iteration.

In order to achieve the greatest rate of convergence, the current across the tube is used as the interface because its waveshape has a distortion lower than the voltage of the tube.

II. DERIVATION OF THE LAMP MODEL.

Figure 1 is represents the lamp circuit. The model will represent the normal tube operation with the starter opened. Thus, the starter has not been modelled.

The source voltage e(t) has a sinusoidal waveshape with the expression:

$$e(t) = \sqrt{2} E_{RMS} sin(2\pi Fr\, t) \qquad (1)$$

where Fr is the frequency (50Hz) and E_{RMS} is the RMS source voltage.

The voltage and current waveforms of a typical 36W tube operation at different source voltage levels, E_{RMS}={200V,220V,240V}, are illustrated in Figure 2 and Figure 3.

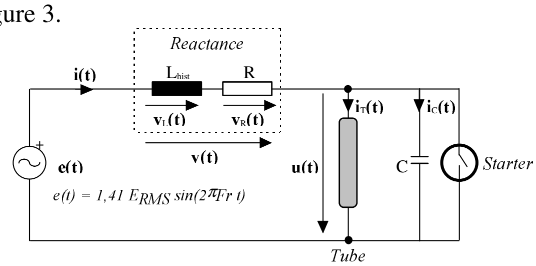

Figure 1. Fluorescent lamp equivalent circuit.

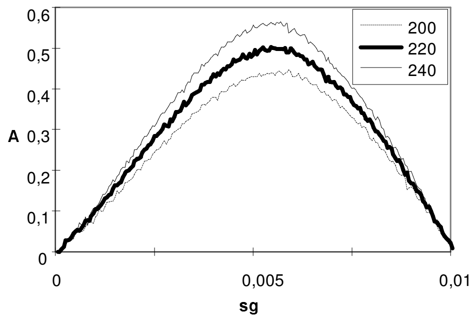

Figure 2: Half-period of the current across the tube with different source voltage levels (E_{RMS} =200-240 V).

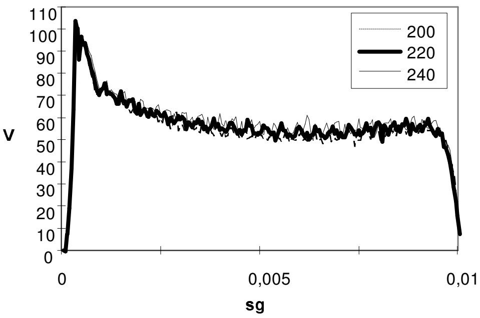

Figure 3: Half-period of the voltage of the tube with different source voltage levels (E_{RMS} =200-240 V).

The steady state characteristic of the tube with E_{RMS} = 220V is shown in Figure 4. As can be seen, the curves obtained have an important level of noise. The first step to get an approximate characteristic, which allows a model to be achieved, is a filtering of the voltage and current to focus the main points of the characteristic.

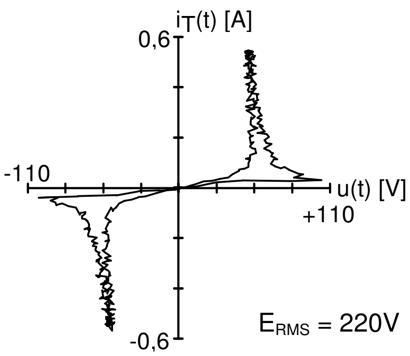

Figure 4. u-i characteristic of the fluorescent tube.

The current across the tube $i_T(t)$ can be easily filtered using a low-pass filter with a cut-off frequency of 1kHz. The result is shown in Figure 5.

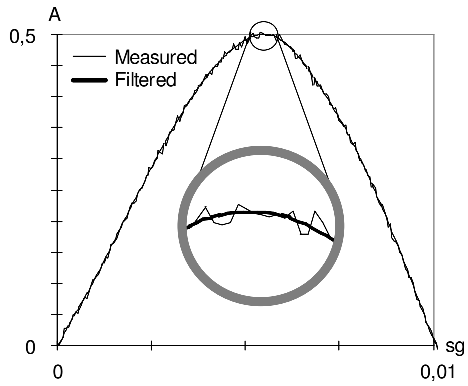

Figure 5: Current across the tube after and before the filtering.

The voltage has more difficulties because it has a harmonic spectrum with high frequencies due to its waveshape. Then, a Least Square Method (LSQ) is the way to eliminate the noise. A 5th grade polynomial is used to approximate the part of voltage with more level of noise. As can be seen in Figure 6 this area is the wave between W_1 and W_2. The position of these two points has no dependence on the source voltage level. So the width of *Filtered Area* is constant even thought E_{RMS} takes different values between 200 and 240V. Moreover, the portions of waveforms between W_A and W_1 and between W_2 and W_B are independent on E_{RMS} level. Thess conditions make the implementation of LSQ easy.

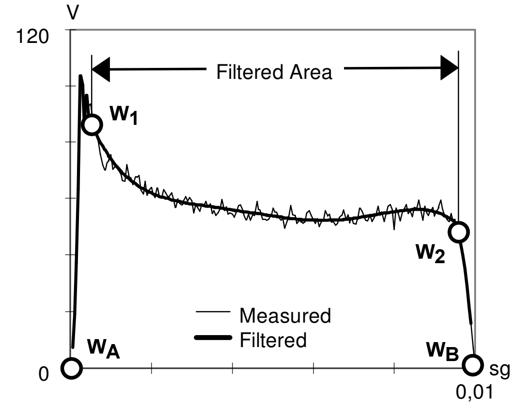

Figure 6: Voltage of the tube after and before the filtering.

A point by point ratio of the magnitudes of the voltage and current waveforms of Figure 5 and Figure 6 yields the steady state non-linear characteristic of the tube shown in Figure 7. As can be seen in this figure, the characteristic is affected by the RMS voltage of the supply voltage (E_{RMS}).

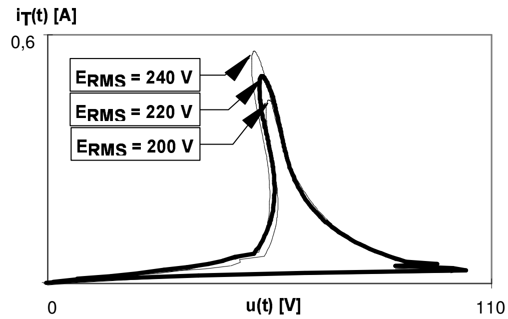

Figure 7: Filtered characteristic of the tube.

To model this characteristic an approximation by straight traces is used (see Figure 8). Small variations in the supply voltage (E_{RMS}) only affect substantially the position of point E = {U_E, I_E} that follows the straight line (E_1-E_2) :

$$U_E = 26{,}9 \cdot I_E + 66{,}5 \qquad (2)$$

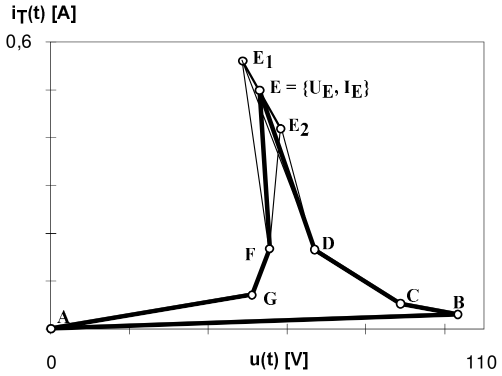

Figure 8: Approximate u-i characteristic.

The behaviour of the u-i characteristic obtained above remains valid for small variations (from 40Hz to 50Hz) in the frequency of power source voltage , Fr, as shown in Figure 9. In order to compare the characteristic behaviour under the two situations, the point E position and its approximation via LSQ (see Figure 8) are represented in Figure 10.

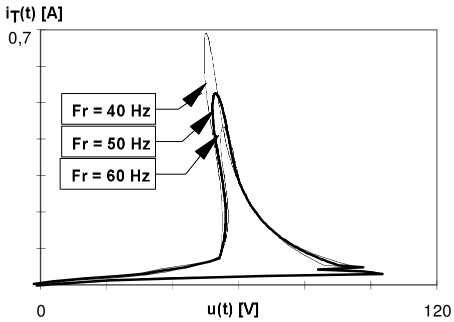

Figure 9: Filtered characteristic of the tube at different frequencies.

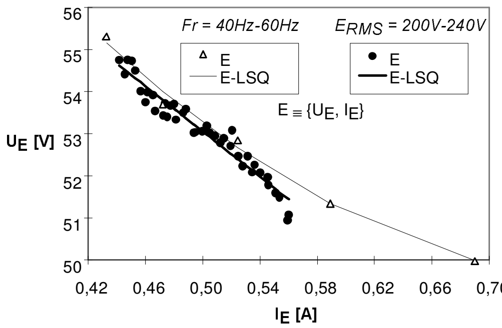

Figure 10: Variation of point E position and LSQ approximation.

At this point the most important non-linearity of the tube is modelled. The other important non-linearity is the ballast due to the presence of some saturation and hysteresis in the iron-core ballast. These effects are modelled with a parallel inductance/resistance equivalent The inductance has the expression[5]:

$$i(t) = a\phi(t) + b\phi^2(t) \qquad (3)$$

where $\phi(t)$ is the flux and a and b are constants,. The parallel resistance is derived from the hysteresis curve by the expression:

$$R = 2\pi\phi_{max} fr / d_i \qquad (4)$$

where ϕ_{max} is the maximum flux, fr the fundamental frequency and d_i one half of the hysteresis width at $\phi=0$.

III. ITERATIVE HARMONIC ANALYSIS.

Having obtained accurate models for the different elements of the lamp, it is necessary to use an iterative algorithm to derive the tube voltage and the current harmonic spectra. The IHA algorithm shown in Figure 13 is used for this purpose.

In a first approximation a tube equivalent resistance is used for the calculation of initial currents. This resistance is derived from the values of fundamental frequency voltage and current obtained from tests, with small current in the starting capacitor ($i_c(t)$) ignored.

The main blocks in the algorithm are the Calculation of Tube's Voltage and the Correction of the Characteristic. In order to do this correction, the maximum of the current across the tube $i_T(t)$ is obtained, so:

$$I_E = max\{i_T(t)\} \qquad (5)$$

and then the value of U_E is calculated from Equation 2.

With the corrected characteristic, the tube voltage is derived from the approximate characteristic as shown in Figure 14.

Another important block is the calculation of the current through the reactor that is derived as shown in Figure 15; it is first necessary to calculate the flux from:

$$\phi(t) = \frac{dv_L(t)}{dt} \qquad (6)$$

which is solved via a double FFT transformation. The flux is then used to obtain the i(t) waveform.

In the final block a comparison is made with the current obtained in the previous iteration to quantify the error (ε), ie

$$\varepsilon = \sum_{n=1}^{N} \left| i_k(nT) - i_{k-1}(nT) \right| \qquad (7)$$

In Figure 11 and Figure 12 a comparison between measured and simulated waveforms is shown.

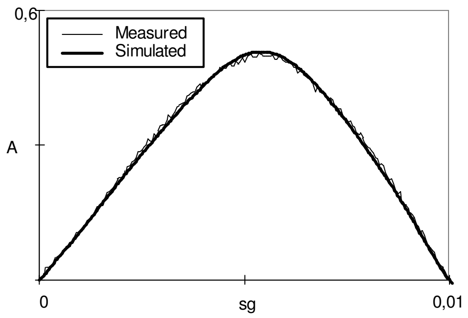

Figure 11: Comparison between the simulated and measured current across the tube (E_{RMS} = 220V).

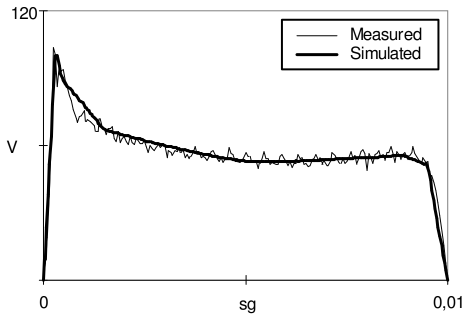

Figure 12: Comparison between the simulated and measured voltage of the tube (E_{RMS} = 220V).

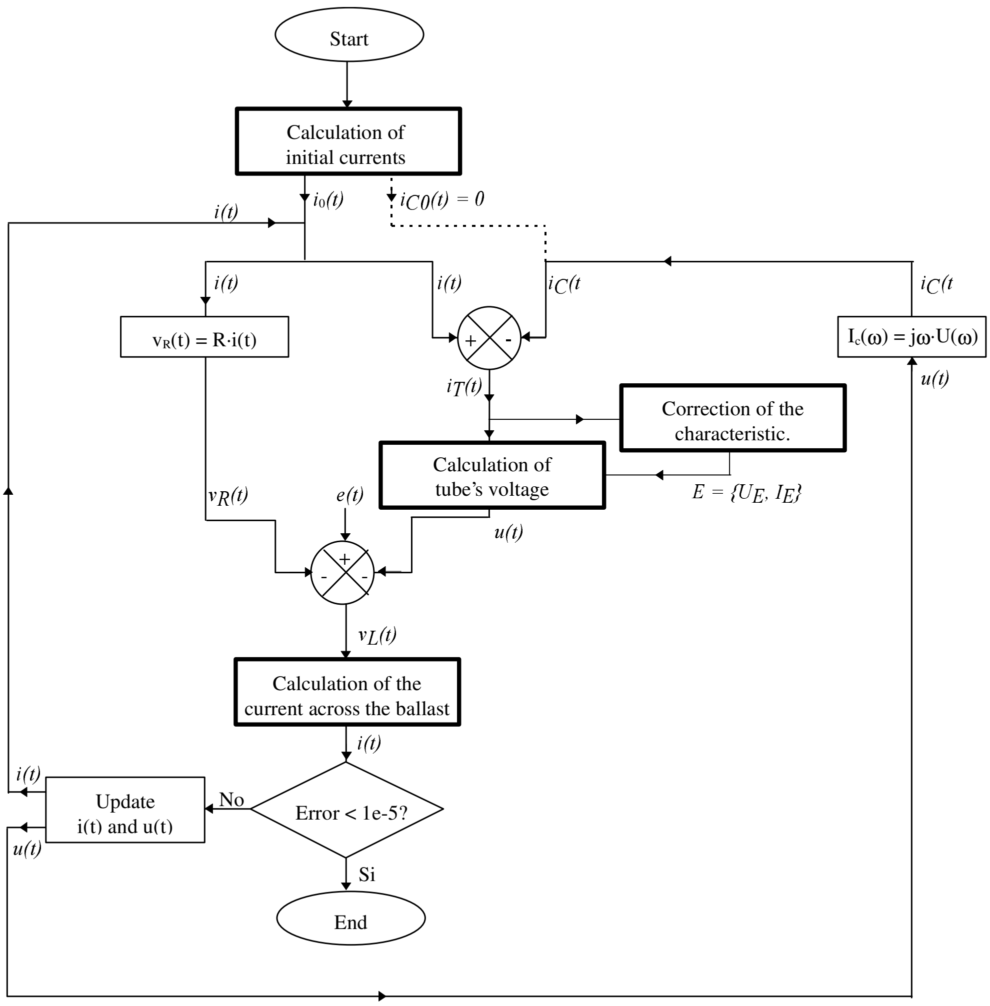

Figure 13: Simulation of flow diagram.

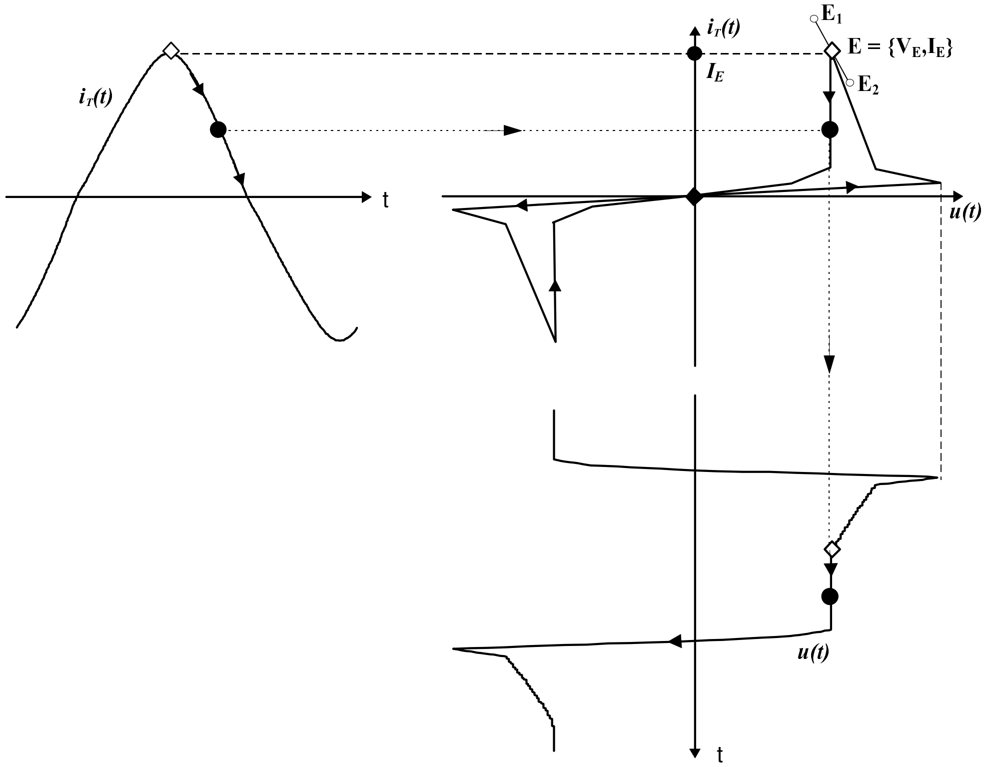

Figure 14: Derivation of voltage in the tube.

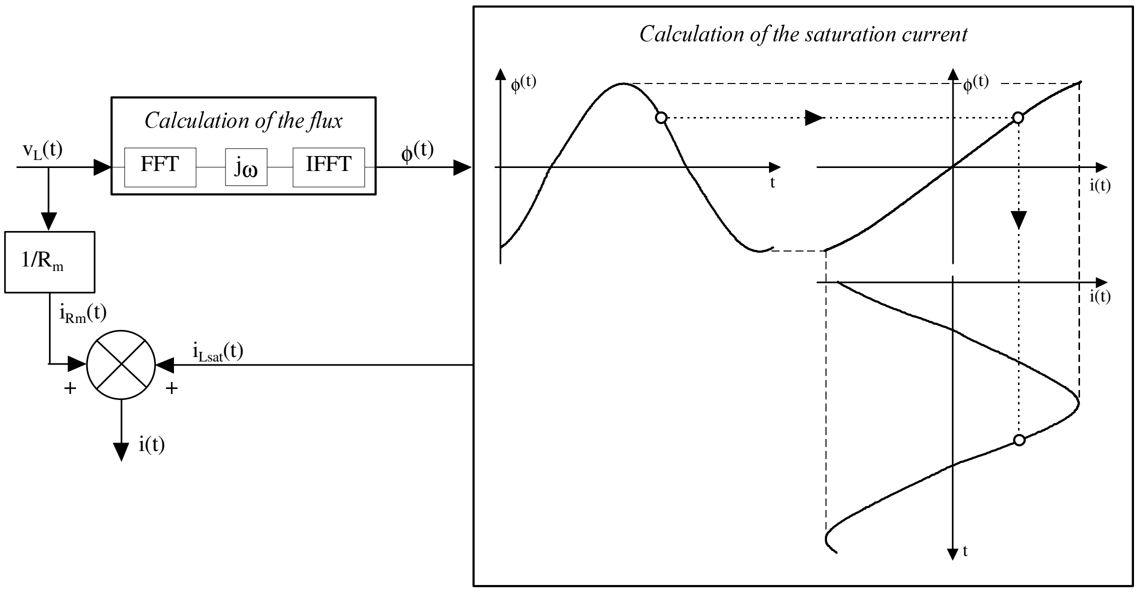

Figure 15: Derivation of the current in the reactance.

IV. TEST SYSTEM AND RESULTS.

When the fluorescent lamp includes a power factor correction capacitor at the input the equivalent circuit will also include a Thevenin equivalent source as shown in Figure 17. The test system illustrated in this figure consists of the lamp components of the previous section, a $220V_{RMS}$ voltage source in series with a resistive (R=0,37Ω) inductive (L=42μH) impedance and a power factor correction capacitor of Cc = 5μF.

In the example, the equivalent circuit is assumed to be feeding 100 lamps.

A second iterative loop[7], shown in Figure 16, is needed to represent the effect of the power factor correction capacitor and the source impedance. The iteration results can be seen in Figure 18 and Figure 19.

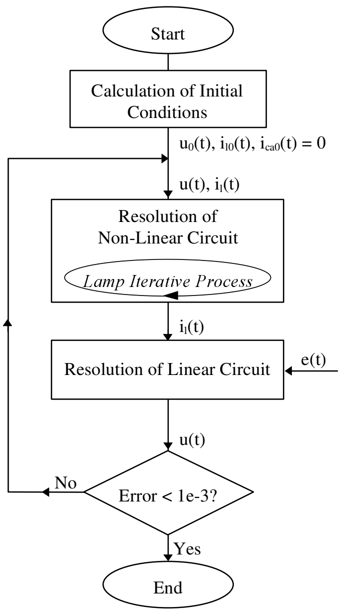

Figure 16: Simulation of lamp and network.

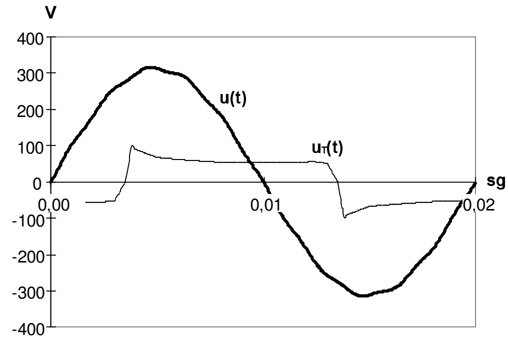

Figure 18: Voltage of compensation capacitor and tube obtained during the simulation.

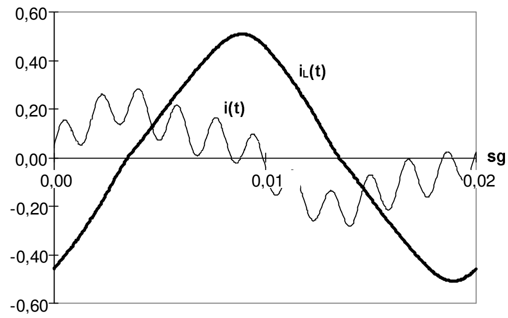

Figure 19: Network and lamp currents obtained during the simulation.

V. CONCLUSIONS

The influence of source voltage level on the characteristic of the tube must be taken into account during the fluorescent lamp simulation. With this consideration, very little error between the measured and simulated waveforms is achieved.

The model obtained is valid when small variations in voltage frequency are present. This could be used for a flicker simulation.

The presence of noise in the voltage and current waveforms makes necessary a filtering process to analyse the behaviour of the u-i characteristic of the tube. Paying special attention to the filtering process of the voltage in the tube because of its sharpness waveform. So, an LSQ method is needed to filter this voltage.

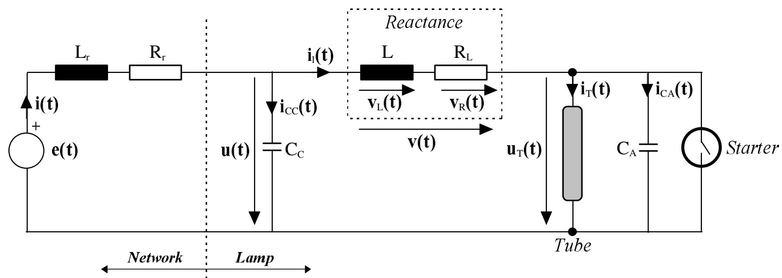

Figure 17: Complete equivalent circuit of the test system.

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VII. ACKNOWLEDGEMENT

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VIII. BIOGRAPHY.

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