ESTIMATION OF HARMONIC ACTIVITY FROM CITY STREET LIGHTING DEPENDING ON SUPPLY VOLTAGE

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Key words: Street lighting, harmonic activity, nonlinear model, MATLAB® Simulink

ABSTRACT

In recent years an increasing power harmonic distortion is measured in electrical power systems. One of the main harmonic sources is a ballasted lighting fixture. Especially, mercury and sodium type luminaires apply harmonic distortions to their power supply systems. In this study, the harmonics created by the street lighting fixtures are studied with respect to supply transformers and operation conditions. A MATLAB® simulation is developed for street lighting system.

I. INTRODUCTION

In low voltage (LV) system lighting fixtures with ballast (mercury, sodium, and fluorescent luminaires) are mentioned as main harmonic sources [1, 2]. Generally, sodium and mercury lamps are main illumination sources for street lighting [3]. Galvanized luminaires masts with specific span, depending on the standard lighting level calculations, are put along the street accordingly. The luminance (cd/m^2) of the illuminated street is selected with respect of its width's. The ratio should be 1.4 to 2.4 cd/m^2. The project values usually are confirmed after implementation [4].

The luminaires should be suitable for their intended working conditions (the ballasts and igniters used in lighting fixtures must comply with the IEC 922, 923, 925, 927 standards) [5]. As a result of laboratory measurements, terminal equation of the mercury lamp luminaire can not be written in form of **v=Ri** or **i=Gv**. Thus,

$$f(i,v) = 0 \quad (1)$$

function has a nonlinear characteristic.

Typical properties of nonlinear load characteristics are also valid for lighting fixtures:

- Instant current is not proportional to instant voltage,
- Load impedance is not constant and changes with terminal voltage,
- On each maximum value of voltage pulse currents occur,
- Even if terminal voltage waveform is sinusoidal the current waveform is nonsinusoidal,
- The $\sqrt{2}$ ratio between maximum value and rms value of the current differs,
- Load equation is represented by a nonlinear function [6].

The harmonic activity of nonlinear lighting fixtures in a street lighting installation depends on:

- Number of luminaires,
- Supply voltage variations,
- Equation of the luminaires.

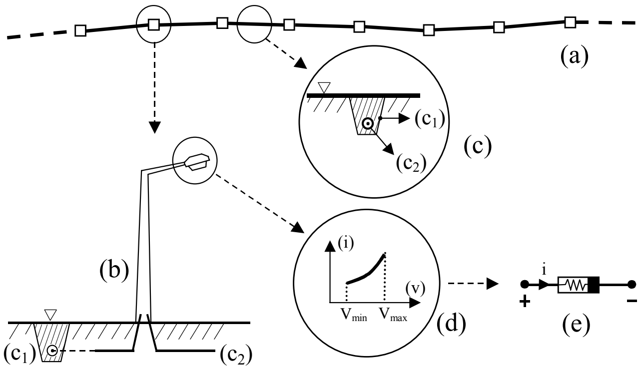

Figure 1. Schematic drawing of a street lighting installation: alignment (a), mast (b), cable trench (c$_1$), supply cable (c$_2$), luminaire's voltage-current variation (d), luminaire's electrical equivalent model (nonlinear resistance) (e).

The number of lighting fixtures in the installation (n) depends on project design. (n) is a function of various parameters:

$$n = f(A,B,C,D,E,F,G,H,I,J,K) \quad (2)$$

where

A : Width of the street,
B : Traffic intensity,
C : Mounting height,
D : Mast spacing,
E : Number of fixture per mast,

F : Street surface,
G : Mounting angle of fixtures,
H : Lamp power,
I : Number of intersection,
J : Environmental conditions (number of trees, buildings etc.),
K : Number of tunnels, viaducts, and bridges.

The power and type of luminaires might vary depending on intersections, tunnels, viaducts, and bridges. Therefore, harmonic activities may change on street segments.

$$THA = f\,[(HA)_i \times n_i\,]; \quad i = 1, \ldots ,k \tag{3}$$

where
THA : Total Harmonic Activity,
HA : Harmonic Activity,
n_i : Number of fixtures in the i^{th} segment of the street.

$$L = \sum_{i=1}^{k} \ell_i \tag{4}$$

where
L : Total length of illuminated street in meters,
k : Number of different segments on the street,
ℓ_i : Length of i^{th} segment of the street in meters.

Total Harmonic Activity is used to define the nonlinearity of the luminaires. THA can be defined in terms of Harmonic Ratio (HR), Distortion Factor (DF) or Total Harmonic Distortion (THD).

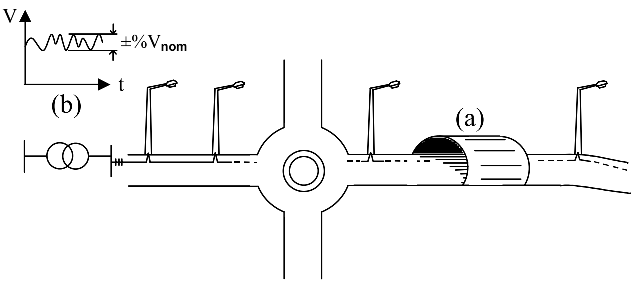

Figure 2. Street lighting's harmonic activities depend on structural components (a), voltage variation of supply transformer (±%V from nominal supply voltage) (b).

II. THE NATURE OF HARMONIC ACTIVITIES

Harmonic Activity occurs along the lighting installation and the nature of this activity can be summarized as follows:

- Harmonic losses of supply transformer (P_{CU}),
- Phase and neutral conductor harmonic losses (I^2R),
- THD transferred to primary side of the supply transformer.

The mathematical expressions of definitions mentioned above are

$$\left.\begin{array}{l} \hat{P}_{CU} / \sum P_{CU_{(TR)}} \\ \sum_{i=2}^{v} \left[I^2 R_{(Ph)} + I^2 R_{(N)} \right]_v \\ T\hat{H}D / THD_{(TR)} \end{array}\right\} \tag{5}$$

The (^) marked terms are related to lighting installation. Harmonic Activity can be written in respect to the following indexes as a nonlinear function,

- K_1 : Street lighting structure index,
- K_2 : Street lighting supply transformer terminal voltage index.

$$\text{Harmonic Activity} = f\,(K_1)\cdot f(K_2) \tag{6}$$

K_1 is not time-dependent; since, in Equation (6) functions are in multiplication form, this shows that this equation is nonlinear. K_1, K_2 can be calculated as follows:

- K_1 can be derived from the lighting project specification through Equation (2).
- K_2 can be derived from the supply transformer terminal voltage daily characteristic.

Other loads connected to the supply transformer affect the secondary windings terminal voltage. Transformers supply voltage (V_{TR}) can be written as

$$V_{TR}^{(t)}=f\,(x_1, x_2, x_3) \tag{7}$$

where
x_1 : Capacity usage ratio of other loads connected to the transformer,
x_2 : Diversity index of the above mentioned loads,
x_3 : Load characteristics (office, residence, etc.).

x_1, x_2, x_3 parameters are determined with the help of ;

- Monthly data from The Institute of Statistics,
- Statistical data for billing from utility companies.

III. NUMERICAL APPLICATION

For numerical application in this study, a main street lighting installation is selected. The mast height is twelve meters and the angle of lighting fixture is 15 degree. The span between the masts is 30 meters and the power of luminaires is 250 W. Mercury lamps are used. The supply voltage is 220 V and the fundamental frequency is 50 Hz, cable type is 4x16 mm^2. The lighting masts are put on center strip. Lamp current and the harmonic spectrum for fundamental frequency are shown in Figure 3 (a), (b) respectively. For harmonic measurements, Fluke® ScopeMeter 190 type analyzer is used [7].

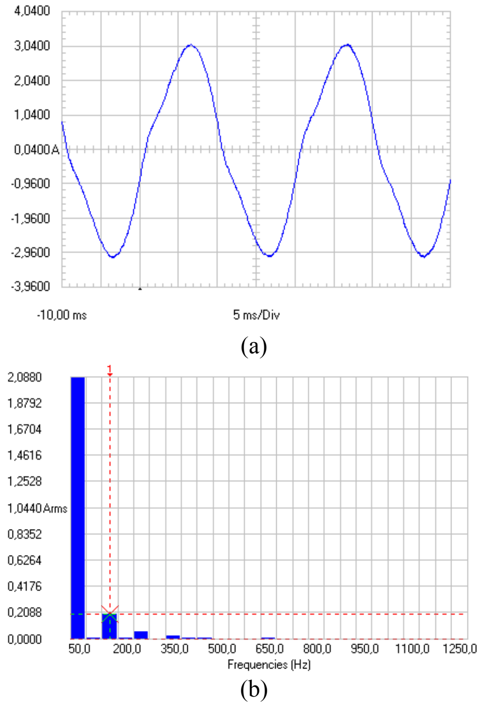

Figure 3. Nonsinusoidal current variation (a) and harmonic spectrum (b) of a luminaire with a 250 W mercury lamp.

The equivalent nonlinear circuit diagram of the street lighting system is given in Figure 4. In order to solve the nonlinear circuit in MATLAB a proper nonlinear equation (Figure 5) of luminaire with mercury lamp is used.

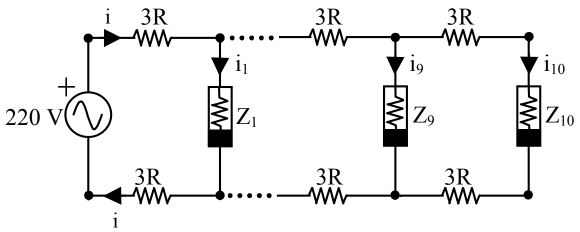

Figure 4. Single-phase equivalent circuit scheme of street lighting.

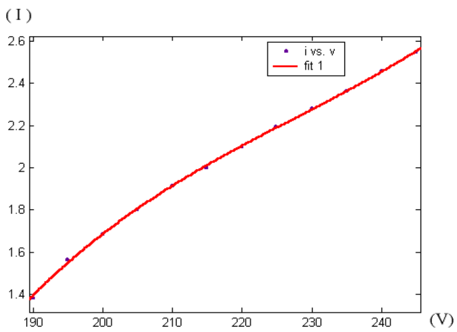

Figure 5. Graphical representation of mercury lamp fixture's nonlinear equation (i = f(v)).

According to the circuit solution the voltage and current distribution is obtained. With respect to the node voltage distribution, harmonic currents are injected [8] to the nodes in Simulink three-phase model shown in Figure 6. Voltage range of the currents spectrum used in Simulink model varies 180-225 volt with ΔV=5 volt increment.

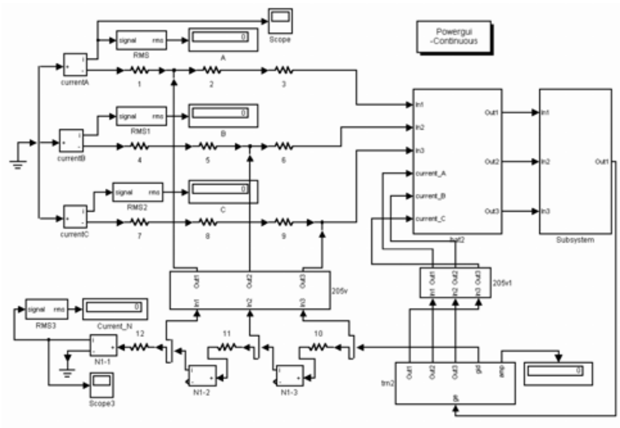

Figure 6. Proposed MATLAB® Simulink three-phase model.

Harmonic activities (THD_i, harmonic voltage drops) on phase and neutral conductors are calculated from the MATLAB® Simulink results and summarized on Table 1.

Table 1. Calculated Harmonic activity of sample street lighting for various supply voltage and mast span.

Supply voltage (Volt)	THD_i (%)				Harmonic voltage drop (Volt)			
	Phase A		Neutral		Phase A		Neutral	
	30 m	40 m	30 m	40 m	30 m	40 m	30 m	40 m
210	7,32	8,53	21,85	25,69	1,15	1,42	2,37	3,60
215	6,06	5,55	17,63	16,35	1,12	1,32	2,23	2,62
220	4,85	5,36	13,07	16,23	1,02	1,31	1,84	2,42
225	3,31	4,09	7,61	10,54	0,95	1,09	1,39	2,26

Thus, the graphical representations of neutral conductor harmonic losses (I^2R) with respect to mast span (30 and 40 meter) and voltage are given in Figure 7 and 8 respectively.

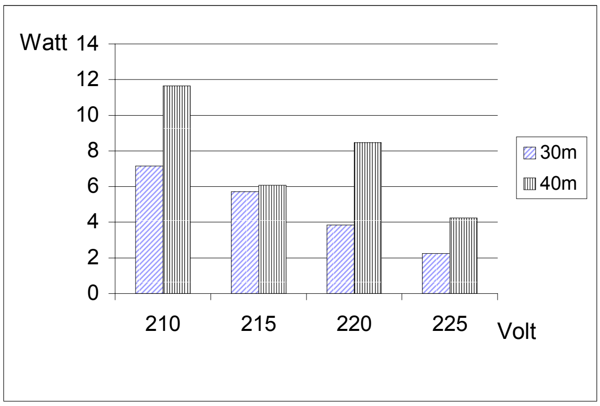

Figure 7. Harmonic losses on neutral conductor as a function of voltage for 30 m and 40 m mast span.

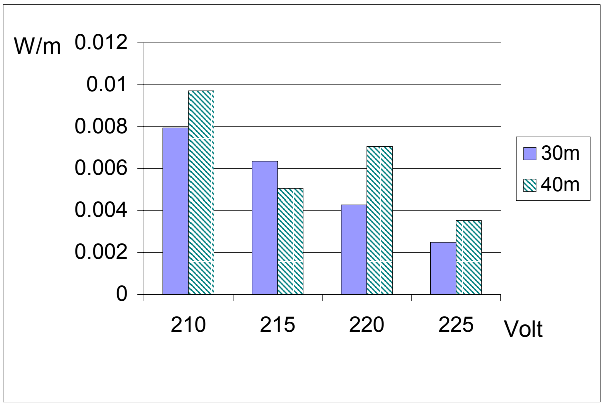

Figure 8. Unit length harmonic losses on neutral conductor as a function of voltage for 30 m and 40 m mast span.

IV. CONCLUSIONS

In this study the harmonic activity of a street lighting is estimated using measured real harmonic current spectrums of luminaires and proposed MATLAB® Simulink three-phase model. The numerical application has shown that harmonic activity is affected from the following parameters:

- Physical structure of the lighting system,
- Supply transformers daily terminal voltage variations.

This conclusion can be reached from calculated results given in the Table 1. According to the values on the table,

- An increment of 10 meters on mast span has increased the harmonic activity,
- An increment of 5 volt on minimum supply voltage has reduced the harmonic activity.

Minimum harmonic activity is observed at 225 volt supply voltage and 30-meter mast span; and maximum harmonic activity is observed at 210 volt supply voltage and 40-meter mast span, for both phase and neutral conductors.

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