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Modeling of specific harmonics source in EMTP/ATP – case study of Compact Fluorescent Lamp

***Abstract**. The paper deals with Compact Fluorescent Lamps (CFL), which are widely used by electricity consumers and with problems related to harmonics generation by CFLs in electric power networks. Additionally, typical electric diagram of CFL, registered current waveform and its analysis for single CFL, as well as numerical model of CFL in EMTP/ATP program are presented in the article. Model of CFL developed for EMTP/ATP simulation software may be useful for simulations related to influence of collective impact of CFLs installed into power network on power quality.*

***Streszczenie.** Artykuł dotyczy problematyki generacji zaburzeń harmonicznych przez świetlówki kompaktowe (CFLs) przyłączone do sieci niskiego napięcia. W artykule przedstawiono budowę świetlówki kompaktowej oraz dokonano opisu przebiegów pobieranego przez nią prądu, jak również przedstawiono model tego źródła światła jako odbiornika energii elektrycznej, opracowany w programie EMTP/ATP. Model może być wykorzystany do symulacji wpływu dużej liczby świetlówek na jakość energii elektrycznej w pewnej przykładowej sieci dystrybucyjnej.*
*(**Modelowanie specyficznego źródła harmonicznych w EMTP/ATP na przykładzie świetlówki kompaktowej**).*

Słowa kluczowe: jakość energii elektrycznej, modelowanie świetlówki kompaktowej, program EMTP/ATP, składowe harmoniczne
Keywords: electric power quality, compact flash lamp modeling, EMTP/ATP program, harmonic components

Introduction

Since September 1st 2009 legal status of classic incandescent lamps in European Union countries has been changed to "special purpose lamps", according to Commission Regulation of European Commission [14] (regulation related to ecodesign requirements for non-directional household lamps). In this connection, the information contains following phrase: "lamp is not suitable for household room illumination" should be clearly and prominently indicated on packaging of each incandescent lamp. This modification has been agreed for energy consumption reduction in order to environment protection. Therefore, it has been decided, that in the commercial market energy-efficient substitutes of incandescent light bulbs – mainly Compact Fluorescent Lamps (CLFs) [10], halogen lamps, and LED light sources [11] should replace energy-intensive incandescent bulbs. According to information contained in Commission Regulation [14], classic incandescent lamps by energy-efficient substitutes replacement leads to estimated energy savings c.a. 39 TWh in the 2020 year, in comparison to assumed energy consumption in that year if no ecodesign measure would be implemented. In turn, The International Energy Agency estimates, that using energy-substitutes of incandescent lamps will cut worldwide electricity consumption by 18% and simultaneously significantly reduce greenhouse emissions [15]. On the other hand, it should be noticed that each CFL comprises a small amount of mercury and for this reason recycling of each CFL is necessary in order to environmental protection, which is not necessary in contrast to the classic incandescent lamp.

Thus, CFLs are increasingly being used by electricity customers [4, 10, 11]. These light sources are able to reduce electricity usage, but simultaneously CFLs show negative incremental impedance over the normal operating range, therefore need ballasts for stable operation [1]. There are two types of ballast for CFLs: magnetic and electronic ballasts used in practice (e.g. figure 1). These circuit types are applied in CFLs because of the following advantages: capability to dim the lamp and reductions in flicker, audible noise and weight [2]. On the other hand, application of CFLs with electronic ballasts in practice causes harmonic currents generation in the distribution system and results in significant deterioration of power quality. It is affected by application in CFLs of high frequency (10÷50 kHz) converters with non-linear load characteristics. Thus, this factor is identified as major source of harmonics generation in CFL [3, 9, 13]. The main effect of this process could cause of unacceptable voltage distortion in analyzed electrical networks.

Harmonics are sinusoidal waveforms with frequencies that are whole number multiples of power system fundamental frequency [7, 8]. Level of distortion from ideal sinusoid is expressed by Total Harmonic Distortion (THD) factor, defined for electric current as [6]:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_{RMS,n}^2}}{I_1} \tag{1}$$

where: I_1 – RMS value of fundamental frequency current component, $I_{RMS,n}$ – RMS value of *n* harmonic component.

THD factor is usually used as the one of the power quality parameters in electrical networks. According to IEEE standards, the average value of THD_I coefficient should be around 120% for current of single CFL [7]. In analogous way Total Harmonic Distortion coefficient is calculated for voltage waveform [6] as voltage quality parameter:

$$THD_U = \frac{\sqrt{\sum_{n=2}^{\infty} U_{RMS,n}^2}}{U_1} \tag{2}$$

where: U_1 – RMS value of fundamental frequency voltage component, $U_{RMS,n}$ – RMS value of *n*-harmonic component.

High harmonics content in voltage and current of distribution system has negative influence for electrical devices installed into electrical network. Occurrence of harmonics in distribution systems can cause both additional power losses in electrical devices, transmission lines as well as may lead to other problems electrical devices.

Current harmonics at electricity receiver can be limited by filters application and power factor correction system in the electrical device with high value of THD for current. Implementation of systems to correct of power quality of electrical device with high value of THD is compromise between the price, weight, size of device and lower value of THD. Therefore, in case of widespread cheap CFLs, value of THD in current of CFL is kept relatively on high level.

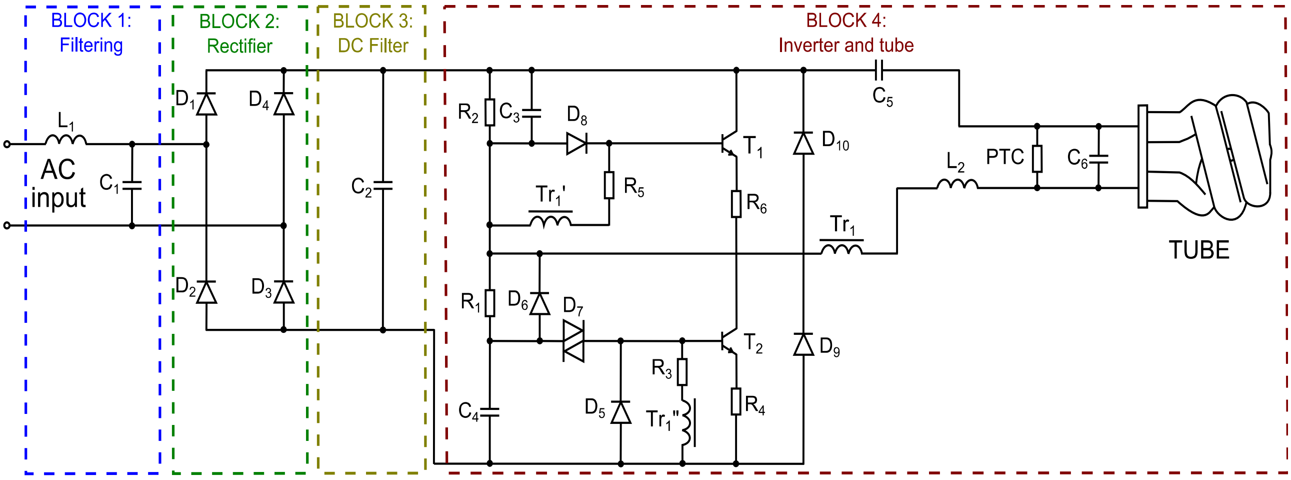

Fig. 1. Typical Compact Flash Lamp Ballast Circuit [10,15]

Compact Fluorescent Lamp ballast circuit

The typical electronic ballast of CFL comprises couple of elements: harmonic filter, power factor correction stage followed by rectification and high frequency inversion stages. In consequence typical CFL ballast matches resonant circuit [7]. Exemplary block diagram of typical CFL ballast circuit has been presented in figure 1.

Block 1 contains passive components (inductance L_1, capacitance C_1) for harmonic filtering of CFL load current. This block has been applied in order to improvement of THD factor in CFL current. Depends on CFL fabrication costs requirements, complexity of this block can be designed in various versions. In case of sophisticated circuits, complexity of *Block 1* can cause incensement of weight and CFL dimensions. Typical systems for improvement of THD factor in CFL have been described in following part of this paper.

Block 2 is typical full diodes ($D_1 \div D_4$) Graetz bridge applied to convert AC into DC stage.

Block 3 comprises the voltage smoothing capacitor and provides the DC input voltage of the resonant inverter for the tube located in *Block 4*. Increase of capacitance C_2 in filter block limits the ripple on the DC voltage, but simultaneously causes increase the peakiness of the AC current waveform. This unfavorable phenomenon is related to harmonics generation. Lighting tube lifespan depends on magnitude of ripple on DC voltage stage. The magnitude of ripple in voltage waveform can be determined by crest factor (it is defined as voltage peak value divided by RMS value).

The resonant inverter has been applied in *Block 4*. Signal frequency at the output of this converter is usually in the range between 10 kHz and 50 kHz. The diac D_7 has been used for starting the resonant inverter. In order to prolong tube life, in *Block 4* Positive Temperature Coefficient (PTC) thermistor has been applied. This component has a low value of impedance during cold ensuring voltage across the tube, and it does not try to strike causing a large current to flow through the electrode, thereby heating them up. After heated the tube up to required for strike level, impedance of PTC increases what allows the tube to strike (normally after a second) [4, 9]. The HF converter can be constructed also by using adaptive ballast controller IC. Exemplary construction has been presented in figure 2.

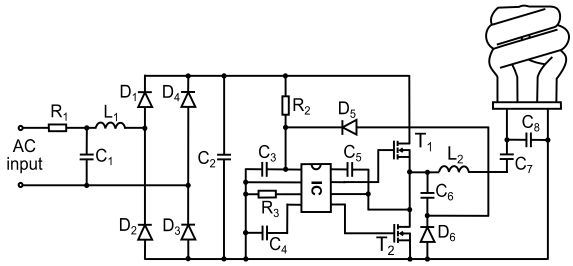

Fig. 2. Electronic ballast for CFL with custom control chip IC IRD2520D [5, 7, 10, 12]

In contrast to circuit diagram presented in figure 1, ballast circuit in figure 2 comprises control chip (International Rectifier's 2520D). That provides the following advantages: high current crest factor, non-zero voltage switching, protection against open filaments, and failure to strike. This ballast circuit is designed to operate at 42 kHz frequency and has been applied in currently produced CFLs [7]. Additional difference between diagrams in figure 1 and figure 2 is different type of applied transistors – in case of electronic ballast with IC chip, MOSFET transistors have been used. View of ballast circuit in CFL has been showed in figure 3.

Fig. 3. Compact fluorescent lamp circuit exemplary practical implementation

Input systems for improving the power factor in CFLs

There are five categories the CFLs can be categorized. Referring type of input system they are equipped for power factor and power quality improvement. Figure 4 presents basic input system for CFL, with no filtering circuit and not improved power factor. The resistor R_1 has been used to limit current peak value. CFLs with this input system generate high harmonic current levels – it depends on value of resistor R_1 and capacitor C_1 was utilized.

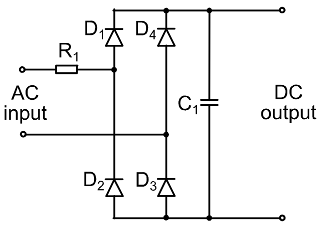

Fig. 4. Basic input system for CFL without harmonic filtering [9]

Exemplary input system for CFL with passive filtering circuit has been presented in figure 5. Many types of arrangements to harmonic filtering is used in commercial use, therefore the most typical system has been presented below.

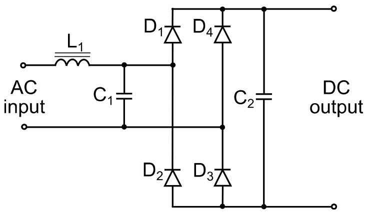

Fig. 5. Input system for CFL with passive filtering circuit [9]

Main advantage of systems with passive components applied is ease of implementation and simplicity of construction, what result in production cost significant reduction. In the other hand, filters with passive components applied in CFLs generate inherent power losses, and can be unattractive because of physical size and weight.

Different construction of input system in CFLs to filter harmonics is valley-fill (figure 6). In this solution, two capacitors C_1 and C_2 are alternately charged and discharged by using the three diodes (D_5÷D_7). Main drawback of this circuit is large voltage ripple on DC side, what may cause luminous flux fluctuation. In this connection, it can lead to lifespan lamp reduction.

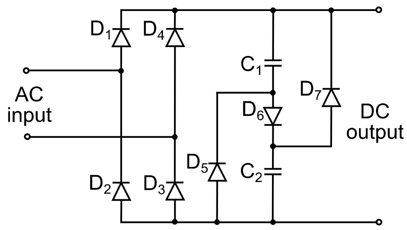

Fig. 6. Valley-fill filtering circuit [9]

Developed valley-fill filtering circuit is presented in figure 7. In contrast to previous circuit, this schematic diagram contains additional two identical small capacitors C_1 and C_2. These capacitors are used for enhance the current waveform near cross-over point. The resistor R_1 is connected between capacitor C_4 and DC line for purpose limit the charging current spikes at the voltage peak. This solution is relatively cheap and allows reduction of CFL current harmonics.

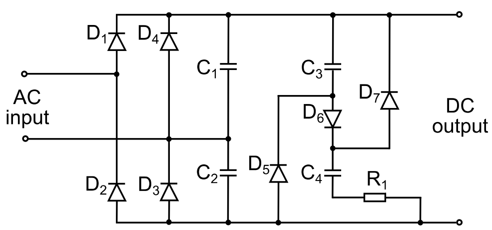

Fig. 7. Developed valley-fill filtering circuit [9]

Active Power Factor Control (PFC) is more complicated and expensive solution used in electronic ballasts of CLFs in order to harmonics filter. In this method, power factor is controlled by high frequency switch operated by means of IC chip. The concept of exemplary PFC circuit used in CFLs has been presented in figure 8.

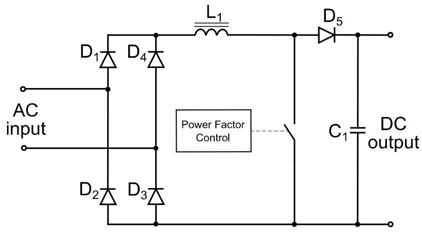

Fig. 8. Input system of CFL with active filtering circuit [9]

Though there are possibilities of application of advanced input system for harmonics filtering in CLFs, because of cost efficiency as well as minimize of size and weight of CFL, passive filter is widespread used as system for improve power quality for CFL.

Waveforms measurements for real CFL

In order to investigate of CFL influence on power quality in electrical network waveforms for real CFLs have been measured in laboratory conditions. Eleven CFL types from different vendors (table 1) have been analyzed in terms of harmonics contain in waveform of current. Main criterion for CFLs selection for tests was theirs price (from \$3 to \$15), what makes that it can be widely used by end users, and similar power consumption (≈20 W).

Table 1. Basic parameters of tested CFLs

CFL No.	Power	Luminous flux	Color
	[W]	[lm]	[K]
CFL_01	18	1010	827/2700
CFL_02	24	1600	827/2700
CFL_03	21	1230	2500
CFL_04	20	1211	827/2700
CFL_05	24	1445	2500
CFL_06	15	760-780	2700
CFL_07	18	1145	2700
CFL_08	23	1500	827/2700
CFL_09	20	960	2700
CFL_10	20	1100	827/2700
CFL_11	24	1600	827/2700

Waveforms recorded during tests were compared each other. It was stated they were very similar in shape and their harmonics spectrum was very comparable as well. Therefore, in this paper, waveforms for only one CFL have been presented. Measurements results in the form of view from oscilloscope have been presented in figure 9.

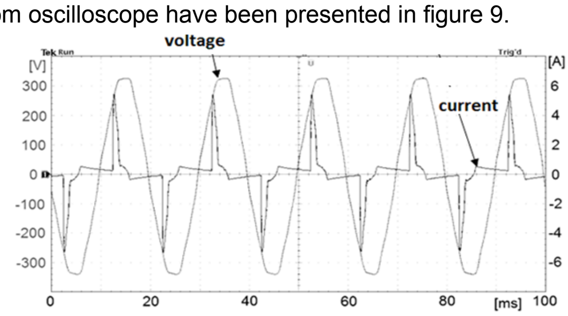

Fig. 9. Measured waveforms for single CFL (CFL_05)

CFL current measured waveform is strongly deformed what is caused by simply ballast circuit applied in analyzed CFL. The harmonic voltage magnitudes for power supply have been listed in table 2.

Table 2. Harmonic components for power supply

Harmonic order	1	3	5	7	9	11	13	15
Magnitude [V]	235	3.04	2.29	2.17	1.39	2.63	1.11	0.47
Angle [deg]	0.0	82.9	122.5	-76.1	47.2	-93.7	-81.9	-41.7

THD coefficient for measured voltage supply is 2.44%.

Whereas, harmonic current magnitudes and phase angles for measured CFL_05 have been listed in table 3 and graphically presented in figure 10.

Table 3. Harmonic components for measured CFL current

Harmonic order	1	3	5	7	9	11	13	15
Current [A]	1.12	0.97	0.69	0.60	0.56	0.43	0.30	0.23
Angle [deg]	-134.5	87.7	-25.6	-128.3	118.9	4.2	-99.1	163.2

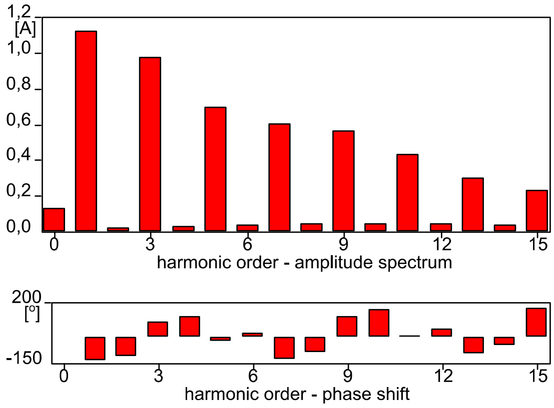

Fig. 10. Spectrum for measured current of CFL

As showed in figure 9, harmonic content in current of tested CFL is significantly deformed. Value of THD coefficient calculated according to formula (1), in this case equals 139.29%. Measurement results including harmonic order have been listed in table 4. Measurement results listed in table 4 have been calculated as percentage base frequency relation.

Table 4. Harmonic components for measured currents of CFLs in relation to fundamental frequency

			CFL No.										
			01	02	03	04	05	06	07	08	09	10	11
			[%]										
Harmonic No.	3	min	81	75	76	85	21	80	51	81	80	72	83
		max	83	78	78	89	86	81	73	83	84	81	85
	5	min	62	52	54	66	2	56	18	60	53	54	55
		max	64	57	55	67	67	57	27	62	64	65	59
	7	min	52	47	46	56	5	41	11	51	43	45	47
		max	56	52	48	57	58	50	31	52	52	51	55
	9	min	48	38	38	53	6	32	3	44	34	35	37
		max	53	42	40	54	56	44	12	45	46	41	43
	11	min	38	22	12	44	6	20	6	32	16	25	18
		max	45	26	23	46	48	31	7	33	34	30	32
	13	min	24	13	7	33	4	9	8	18	2	5	11
		max	31	17	10	34	37	17	11	20	20	19	18
	15	min	16	9	3	24	2	3	15	10	6	11	5
		max	24	18	4	25	28	10	16	11	10	20	15

Only for CLF_05 and CLF_07 measurements results are most varied, what can be caused e.g. by low quality of circuit diagram applied in CFL.

Model of CFL in EMTP/ATP program

Mathematical model of CFL has been developed basing on the real schematic diagram of CFL from figure 1. For this purpose, equivalent circuit diagram of CFL has been performed in EMTP/ATP program and presented in figure 11.

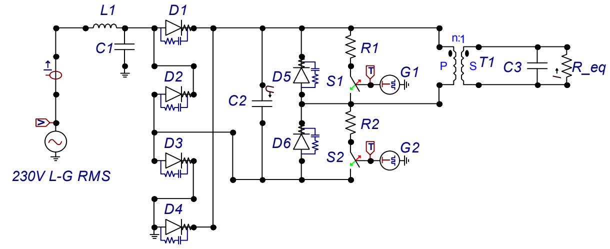

Fig. 11. Circuit diagram of CFL prepared in EMTP/ATP program

Similarly to schematic diagram presented in figure 1, circuit diagram developed in EMTP/ATP program also contains harmonic filter (inductance *L1* and capacitance *C1*), diodes bridge (diodes: *D1*, *D2*, *D3*, *D4*), smoothing capacitor (*C2*), DC/AC converter (diodes: *D5*, *D6*, resistors: *R1*, *R2*, switches *S1*, *S2*, generators: *G1*, *G2*, HF transformer *T1*) and equivalent resistance *R_eq* represented tube. In DC/AC stage, diodes *D5* and *D6* are gated by switches *S1* and *S2*, which are controlled by generators *G1* and *G2* at frequency 35 kHz. Both generators give square wave for controlling switches *S1* and *S2*. Due to constant load on DC busbars, only filter block, rectifier and DC Filter *C2* must be represented in details to investigate the harmonics currents on AC input. Thus, the resonant inverter and tube can be represented by a resistor in mathematical model [9].

Calculated waveforms for developed CFL in EMTP/ATP program have been showed in figure 12.

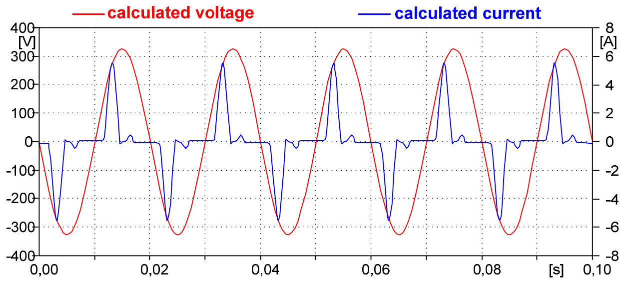

Fig. 12. Calculated current and voltage waveform in EMTP/ATP program for single CFL

The harmonic content in calculated current of CFL modeled in EMTP/ATP program has been listed in table 5.

Table 5. Harmonic components for modeled CFL current

Harmonic order	1	3	5	7	9	11	13	15
Current [A]	1.80	1.45	1.16	0.77	0.32	0.09	0.05	0.09
Angle [deg]	-146.1	97.8	-14.8	-135.9	104.2	-2.8	-116.3	-48.3

As presented in table 5, harmonic content in current of modeled CFL is significantly deformed, very similarly to current of measured CFL (according to table 3 and figure 10). In this case, value of THD coefficient calculated according to formula (1) equals 113.48%. Data from table 5 have been presented in figure 13.

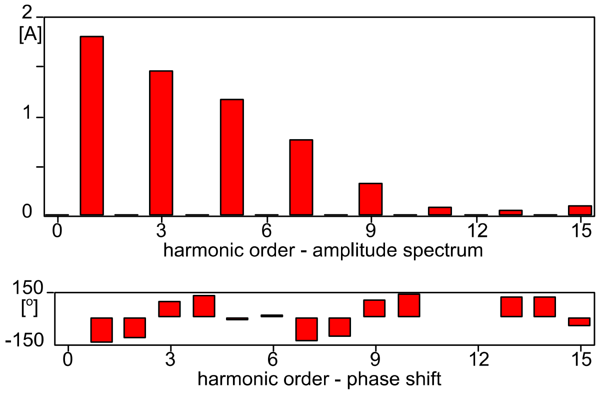

Fig. 13. Spectrum for calculated current of CFL

As showed in figure 13, harmonic content in current of tested CFL is very significant deformed. Value of THD coefficient calculated according to formula (1), in this case is equal 113.48%.

Verification of CFL model

In order to investigate developed model of CFL in EMTP/ATP program, measured and calculated waveforms of CFLs have been presented in one figure. It has been illustrated in figure 14.

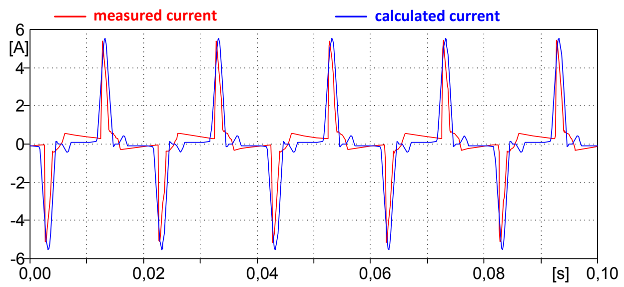

Fig. 14. Comparison of measured and calculated waveforms

As showed in figure 14, both waveforms are very similar in shape. The absolute difference between THD coefficients for measured and calculated waveforms equals 25.81%. Both waveforms have almost the same peak value, and very like character. Thus, model of CFL developed in EMTP/ATP program quite well reflect operation of real CFL.

Conclusions

Modern non-linear low-power loads can in many cases produce relatively high level harmonic distortions because of synergic effect action [16]. Example of such type loads are Compact Fluorescent Lamps used last years as popular replacement for removed from European light-sources market classic incandescent lamps. Described in the paper EMTP/ATP numeric model can be used for complex analysis of influence of large number of CFLs on power quality factors in low-voltage electrical distribution networks.

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