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Development of Light Sources Fulfilling EMC Requirements

Thesis Booklet

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1 Introduction and goals of the work

One important demand of the development of modern discharge lamps is to satisfy the ever increasing electromagnetic environmental regulations. Fulfilling the **EMC** (**E**lectro**M**agnetic **C**ompatibility) conditions is an essential criterion of producing marketable products. A light source which meets EMC considerations on the one hand does not emit more electromagnetic disturbances than the permissible level, while on the other hand it operates reliably under a well-defined disturbance level.

Electric, magnetic and electromagnetic disturbances spread in a conducted or radiated way. Discharge lamps produce and radiate high-frequency disturbances to their surroundings continuously. The reason of disturbing the surroundings can be explained by the help of the physical processes of the operation of the lamps. Electronic ballasts that operate discharge lamps, feed conducted disturbances back to the power supply network and disturb the operation of the sensitive equipment that is placed near the luminaire with radiated signals. The unstable operation of our considerably sensitive infocommunication systems, due to electromagnetic interference, cannot be permitted.

In my thesis I have analyzed the operation of CFLs from EMC point of view - not only at the system level, but also the system broken down into components. Thus the arc - including the electrodes and the discharge itself -, the electronic ballast that feeds the lamp and I have also examined the role of the wires that connect them. The reduction of the noise emitted by the lighting systems becomes possible only after understanding these phenomena.

Besides incandescent lamps, CFLs are recently being used in lighting applications where it is a requirement being able to regulate the light output of the tubes (dimming). However this process is much more complicated than in case of incandescent lamps.

The cathode must be heated by an additional heating current during dimming, so that its temperature remains constant despite the decreasing arc current. The optimal value of heating current ensures a low cathode fall (no light, but only heat is generated in the cathode fall region) while the cathode is not overheated (too high heating current, thus excessive cathode temperature causes an excessive evaporation of the emissive material).

As the dimming of compact fluorescent lamp systems is much more complicated than in case of incandescent lamps, it raises EMC issues which are also analyzed in details in my thesis.

2 Methods

I have set up a newly developed EMC measuring system at the Department of Electric Power Engineering in close co-operation with the Department of Broadband Infocommunications and the Lighting division of General Electric. The system is intended for making standard high frequency and low frequency emission and immunity measurements. On the other hand, it serves as a platform of scientific research.

The main part of the system is the GTEM (Gigahertz Transversal Electromagnetic) cell The GTEM cell is a pyramid-shaped, doubly-terminated 50 Ω transmission line. At the input, a normal 50 Ω coaxial line is physically transformed to a rectangular cross section. The cross sectional dimensions are in a ratio of 3:2 horizontal to vertical dimensions. The centre conductor, known as the septum, is a flat, wide conductor that when driven by a signal generator through a microwave amplifier will produce a reasonably sized region of a nominally uniform electric field distribution. This region of nominally uniform field is the test volume for radiated immunity (susceptibility) testing. By the theory of reciprocity, radiated emissions testing is also conducted in the test volume. The septum is physically terminated in a resistive array having a total value of 50 Ω for matching the current distribution of the septum. The volume fields, either applied to an immunity test item or produced by the equipment under test (EUT) during emissions testing, are terminated in free-space foam RF absorber. The fields generated by application of an RF voltage to the input of the GTEM propagate with a spherical wave front from the apex of the GTEM to the termination [73-74].

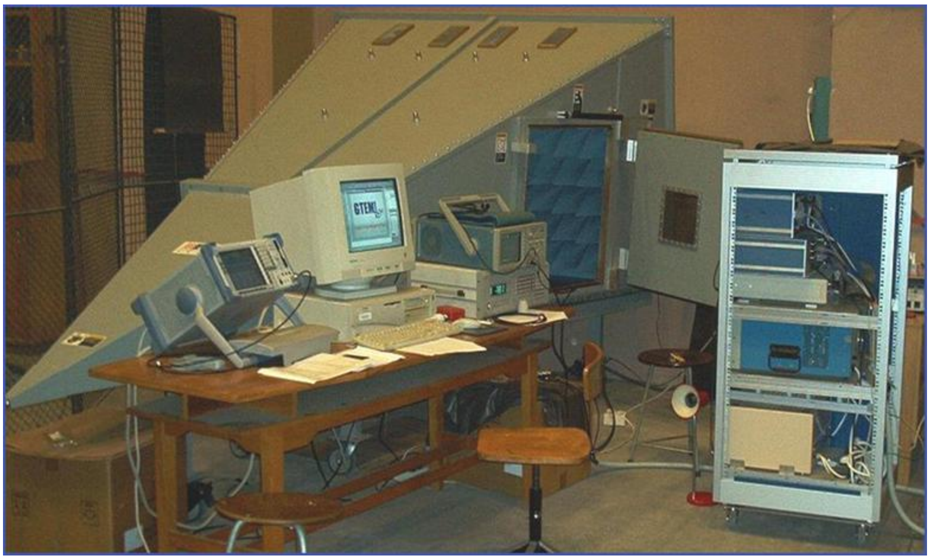

Fig 1 The measurement system based on the GTEM cell

During the radiated RF emission testing the noise signal emitted by the light sources or luminaires is detected by an EMC receiver that is connected to the front of the cell through an N-type connector and a 50-ohm coaxial cable. The software-controlled pneumatic system allows the rotation of the test device in any direction compared to the longitudinal axis of the cell, so that the device can be examined in any orientation. There are 3 or 9-input correlation algorithms [75-80], which allow the calculation of the detectable signal strength of an antenna at a distance of 3 or 6 m from the measured field strengths. In case of near-field measurements (approximately up to 30 MHz) it is necessary to have nine measuring points due to the complexity of the radiation pattern; while in case of far-field measurements it is sufficient to measure in three orientations. The GTEM cell is suitable for radiated emission testing up to an upper frequency limit of 20 GHz [81]. In all cases however, attention must be paid that the light source, the ballast, the luminaire and the cables are firmly fixed relative to each other, since any movement during the rotations affect the measurement results, and thus the correlation algorithm cannot provide a reliable result. This movement, of course, is mostly related to the wiring, thus special attention needs to be taken to avoid this.

Due to the complexity and the time need of the measurements I have not used the 9 orientation test method, since the exact measurement results would be of utmost importance only in case of the standard compliance test and that requires the usage of the above-described loop antenna test method providing an induced current quantity. On the other hand, even the standard test is carried out in three planes, and each of the results has to meet the same limit curve. Thus, it is not the goal of the standard to detect the full distribution of the radiation.

On the other hand, the GTEM cell-based test setup allows for the achievement of a higher sensitivity, enabling the individual examination of the system's components (arc tube, electrodes, electronic ballast, wires).

The measurement system I have developed and implemented is fully automated; each measuring instrument is controlled by a PC via the GPIB (IEEE-488) bus. The measurement results are collected and processed by the software I have developed.

3 Theses

3.1 First thesis

Although EMC problems caused by compact fluorescent lamps are known, only the electric, magnetic and electromagnetic disturbances they produce are being measured according to the relevant standards. The physical background of the noise emission has not been investigated. Decreasing the effect of the radio-frequency emission is only possible after understanding and analyzing their sources, namely the causing the physical processes. This is not the goal of the relevant standards. The test methods defined by them are not suitable for development aims. Because of this, I have developed and built a new test system, which can be used for the analysis of the above mentioned physical processes, and as a result, it is optimal for development aims (12, 13).

The EMC standards related to the low and high frequency emission and immunity of light sources and luminaires are widely known. Related tests are carried out even during the CFL development. However, these tests are in accordance with the provisions of the standard which treats the light source in each case as a system, and basically seeks the answer for the question whether the entire system complies with the limits set by the standard or not. It is not their purpose to analyse the system by breaking it down into its components, in order to identify the exact source of emissions within the system. Thus, they do not offer solutions to reduce radio frequency emissions [60, 61, 65, 82, and 83]. In my thesis I have analyzed the compact fluorescent lamps from EMC point of view operating in both normal and dimmed operation, and presented the potential sources of emission within the system. In order to reach this goal, I have developed and implemented a new EMC measurement system, which is based on a GTEM-cell capable of radiated emission testing with improved sensitivity, and a generator system which provides driving the CFL and cathode heating in an adjustable form, together with the software that controls this equipment and processes the test results.

3.2 Second thesis

Based on the laboratory experiments carried out on the newly developed measurement system, I have concluded that the discharge tube (the discharge itself) operated in optimal circumstances, acts as an antenna, whose generated far (electromagnetic) field is negligible compared to its near field (electric and magnetic field strength), in the frequency range of 9 kHz – 30 MHz at frequencies defined by the ballast. The discharge tube itself does not generate disturbance in this case (12, 13).

The compact fluorescent lamp as a light source, under certain conditions, can be operated at optimal circumstances. In this case, the lamp is operated at its intended working point, at nominal arc current. Furthermore, the cathode type fits the nominal arc current of the lamp, so that the arc current heats up the cathode during operation to a temperature which is optimal for the thermal emission, there is no need for additional cathode heating current. According to this, the lamp is not operated in dimmed mode, so it is not (in terms of the number of emitted electrons) overheated or underheated (unstable operation and lack of hot spot due to the low cathode temperature). The arc tube (including the arc), operated under the above described conditions acts as an antenna, whose electrical parameters (frequency, arc current and the corresponding arc voltage defined by the impedance of the arc or arc voltage and the corresponding arc current defined by the impedance of the arc) are determined by the electronic ballast, and whose far field is negligible compared to the generated near-field being tested in the frequency range of 9 kHz - 30 MHz. However, this effect can be eliminated through shielding.

3.3 Third thesis

I have analysed the operation of the discharge tube of compact fluorescent lamps in normal and dimmed mode. I have concluded that during the operation of fluorescent and compact fluorescent lamps, mainly in dimmed operation mode the emitted radio-frequency radiation is strongly affected by the connection between the number of electrons emitted as an effect of the additional cathode heating and the arc current which flows through the cathode and the number of electrons taking part in the arc current flow. The difference of the above may cause a radio-frequency oscillation in the cathode region (cathode oscillation), resulting in wideband noise emission (5, 6, 8, 12, 13).

Today, there is an increased demand for the controllability of the amount of emitted light from fluorescent lamps and compact fluorescent lamps (dimming). The dimming process (which practically means a reduction compared to the nominal value) is executed by changing the arc current. This however, in contrast with the incandescent lamps, poses problems, it is not sufficient to simply reduce the arc current, because in this case, the current flowing through the cathode (with a lower value) does not heat the spiral with the same power as the nominal (higher) current. The fluorescent lamp cathode is designed to be operated at the nominal arc current. Lower current flowing through the cathode results in a temperature, which is less than the required for the thermionic emission.

Due to the above, during dimming an additional heating current is passed through the electrodes. This additional heating does not feed the electric arc; it flows only through the cathode and the anode, galvanically isolated from each other, of course. Although the dimming of discharge lamps is widespread today, it is difficult to define what values of heating current shall be applied to each lamp current values. The heating current, which is optimally selected, ensures that the various operating points with lower-than-nominal arc current values do not reduce the life of the lamp, while the lower arc current despite the applied additional heating current saves energy. In case of too low cathode heating the cathode fall voltage is increased, and this increased field strength in front of the cathode accelerates the positively charged ions flowing in the direction of the cathode to a higher speed, which, due to their relatively high kinetic energy, hit the emissive material (e-mix) and may break off macroscopic material pieces. This results in an extremely fast loss of the material weight, and the blackening of the arc tube. In case too high additional heating current is applied, the filament (and the e-mix) heats up over the temperature that is optimal for the thermionic emission, and these results in an excessive evaporation of the emissive material. Both phenomena decrease the lamp life dramatically.

Applying improper heating current also leads to electromagnetic compatibility (EMC) problems. During the lamp operation, the cathode emits electrons into its pre-sheet volume by thermionic emission. If a higher-than-optimal heating current is applied during dimming, the number of thermionically emitted electrons will be much higher than what is necessary for supplying the arc current. Those electrons, which are not being fed into the arc current, form a cloud of negative charge in front of the electrode, which means a potential well for the positive ions advancing to the electrode. After the charge cloud is formed, there is no need for further ionization for the operation of the cathode, the ions are slowed down, and encounter the electrons that form the charge cloud. A recombination takes place when the electrons and positive ions encounter; and the corresponding energy is released in form of an electromagnetic, radio frequency radiation (oscillation). Knowing the arc voltage and longitudinal temperature distribution of the cathode, the intensity and the frequency of the emitted radiation can be estimated. Soules [38] has set up the thermal model for the temperature distribution of the cathode during operation (dimming), although his goal was to determine the number of electrons emitted from the cathode.

3.4 Fourth thesis

Having analysed the physical processes related to the anode and its pre-sheet volume and their influencing factors, I have concluded that the anode oscillation, which takes place in the pre-sheet volume of the electrode, causes radiated and conducted radio-frequency emission. Further emission can be caused by the instability of the arc (the continuous, stochastic, rapid change of the location of the hot spot) (5, 6, 8, and 12).

Arriving to the anode, the electrons may have significant kinetic energy. This energy can reach the levels where the electrons can cause additional ionization in the anode fall region or in the lower plasma density range in front of it. If this additional ionization happens, the plasma density increases suddenly, so that the anode can collect the electron current even without positive anode fall. Then the anode fall suddenly drops to 0, causing additional ionization to end. The increased number of ions flow in the direction of the arc tube during the ambipolar diffusion, and then they slow down and recombine with the electrons that are present in that region. So the original plasma density is reset, and the additional ionization stops. As the plasma density is decreased, the anode fall starts to increase, until it reaches the value required for the ionization, and the process starts again. This phenomenon also causes an oscillation, namely in the arc voltage, thereby also in the arc current of course, which can be detected by an oscilloscope. The critical anode fall voltage corresponds to the ionization potential of Hg. When the anode fall reaches this level, the ionization starts suddenly, and accordingly the anode fall voltage instantaneously drops to 0. The anode oscillation causes electromagnetic radiation similarly to the oscillation taking place in the pre-sheet volume of the cathode, the anode fall can be adjusted with potential controlling aids, and thus the oscillation and the resulting electromagnetic radiation can be avoided.

If the cathode temperature / the temperature of the hot spot is not sufficiently high, the arc becomes unstable and the hot spot rapidly changes its position (this is the point where the arc begins and the electrons exit from the cathode). This stochastic process causes a random, broadband radio frequency emission. This phenomenon can occur in case of inadequate cathode construction; during dimming, if insufficient additional heating is applied; or at the end of lamp life (EOL), when the total amount of emission mix is consumed from the cathode. No previous source is known, which would describe the effect of an unstable arc / unstable hot spot on the radio frequency emission behaviour. Waymouth [16] presents the anode oscillation phenomenon, however he does not associates it with radio-frequency emission behaviour.

3.5 Fifth thesis

I have investigated the operation of dimmed compact fluorescent lamp systems. The IEC61000-3-2 standard does not require the testing of these systems (they contain requirements for the individual components of the system), while the CISPR15 standard does not require the testing of the full spectrum in dimmed operation, but checking at several pre-defined discrete frequencies only. In fact, the elements of the system interact with each other from emission behaviour point of view, both in case of harmonic currents, both in case of radio-frequency conducted-radiated emission. As a result of this, the behaviour of the system might be less favourable than the behaviour of the individual components. As the phase-cut dimmer and the dimmable compact fluorescent lamp necessarily build up the lighting system together, interacting with each other, there is a need for taking this fact into account in the requirements of the above mentioned standards (13).

The IEC61000-3-2 standard requires the phase-cut dimmers (otherwise recommended for incandescent lamps) to be tested using the Class A current harmonic limits, but only above a rated load of 1000W and in case of resistive loads. Also dimmable CFLs are to be examined, but not in dimmed state, using the Class C limit values. In real applications, these dimmers are operated together with dimmable compact fluorescent lamps. The actual load of compact fluorescent lamps is less than 1000 watts (also typically less than 100 W) in almost all cases due to a higher efficiency. Thus, the analysis of these systems is reasonable, however, with eased criteria. Because of the cut sine-shaped voltage from the dimmer, the CFL, in principle, cannot meet the standard's requirements on the angle of current flow and the position of the current peak. The above support the opinion about this gap in the standard [65]. In [60], although the standard prescribes requirements for a dimmable system, however, does not require the testing of the full spectrum, but some pre-defined discrete frequency lines. However, due to the interaction between the phase-cut dimmer and the dimmable CFL, this is not sufficient (as we have seen, the operating frequency varies during dimming).

Examination of the entire system is desirable in each case because the behaviour of the overall system may be different from the behaviour, which could be deduced from the behaviour of the individual components.

4 Practical application

I have built a new, full EMC measurement system at the Department of Electric Power Engineering of the Budapest University of Technology, in close cooperation with the Department of Broadband Infocommunications and the Lighting division of General Electric (GE). I have developed an own control and evaluation software for the system, which has solved the automation of testing. The measuring system on one hand is capable of standard, high-frequency and low-frequency EMC measurements. On the other hand, it can serve as a platform for scientific experiments.

In my thesis I have analyzed the operation of CFLs from EMC point of view - not only at the system level, but also the system broken down into components. Understanding the physical processes that are responsible for the radiated emission allows us to design light sources, which may disturb their environment at a significantly lower level. I have identified the plasma of the lamp as the main source of emission. However, the spectrum is determined by the electronic ballast (inverter and resonant circuit) through the lamp voltage and lamp current, as the arc behaves as an antenna. If we ensure the optimal operation of the discharge, the discharge tube itself and the discharge does not produce any noise.

I have analyzed the dimming of compact fluorescent lamps from EMC point of view. According to this, the role of the most commonly used phase-cut dimmers is critical in terms of the emission. The cathode heating being used in the lamp has an additional effect of broadband noise emission in the pre-sheet area of the cathode during the cathode oscillation phenomenon. The electronic ballast changes the operating frequency during operation. We have to consider the ever-present harmonics in the design phase, as the third harmonic may get to the CISPR B band, where the permitted emitted disturbance voltage level is 14 dB lower than in the CISPR A band (below 150 kHz).

The power cord had earlier been considered as a significant contributor to the radiated emissions. I have shown that its impact is negligible with a 1 m cable length in the 9 kHz - 30 MHz frequency range. This can be explained by the high wavelengths at these frequencies. The dimming of compact fluorescent lamps affects their radiated noise emission characteristics through the shift of their working point and the additional cathode heating. The latter influences the number of electrons that are present in the discharge and it can cause oscillations. Unstable operation of the discharge lamp is to be avoided since such operation is stochastic from EMC point of view.

5 Next steps

As the further development of the topic and the finished work, the examination of LED-based light sources (incandescent replacement lamps) follows. The investigation of these - retrofit - light sources will appear in the near future in the relevant IEC standards. The dimming is also an existing requirement for these types, which causes partly similar problems, as we have seen in case of compact fluorescent lamps, but also differs from them partly due to the differences in physical operation, partly due to the different drive circuit.

Another main field of potential future experiments is transient testing – investigating the emission behavior of discharge lamps during the ignition phase. There is a highly intense emission during this period due to ignition voltages might range even up to several times ten kilovolts.

6 Publications of the author

This list contains those own, or shared publications, which were referenced by the author in the thesis. I have marked the number of the publication in the bibliography with [x]. The numbering corresponds to the order of appearance.

(1) **Schmidt G.**, Tasi Miklós, Orbán János: A kompakt fénycső, mint az izzólámpa környezetbarát helyettesítője, Elektrotechnika, No. 4, 2008 [7]

(2) Medvedev M., Siti A., **Schmidt G.**: Operating Principles of Induction Fluorescent Lamps, Svetotechnika, Moscow, Russia, 2006 [9]

(3) **Schmidt G.**: Energy Smart – új kompakt fénycső család a GE-től, Elektrotechnika, No. 2, 2010 [13]

(4) **Schmidt G.**: Katódhőmérséklet közvetett mérése kompakt fénycsövekben optimális dimmelési karakterisztika meghatározása céljából, Diplomaterv, Budapesti Műszaki és Gazdaságtudományi Egyetem, 2001 [30]

(5) **Schmidt G.**: EMC Problems of Fluorescent and Compact Fluorescent Lamps, IEEE Postgraduate Power Conference, Budapest, Hungary, 2002 [54]

(6) **Schmidt G.**, Novák B., Istók R.: Electromagnetic Interference In Office and Household Appliances Caused by Fluorescent Lighting Systems, 3rd International Conference on Electrical and Power Engineering, Iasi, Romania, 2004 [55]

(7) Novák B., **Schmidt G.**, Istók R.: Electromagnetic Interference on Instabus EIB Systems Caused by Continuous Noise Sources such as Fluorescent Lighting Systems, 3rd International Conference on Electrical and Power Engineering, Iasi, Romania, 2004 [56]

(8) **Schmidt G.**, Istók R.: Fluorescent Lighting Systems Causing Electromagnetic Interference in Office and Household Appliances, City of Tomorrow and the Electricity Conference, Prague, Czech Republic, 2003 [57]

(9) Istók R., **Schmidt G.**: Fénycsövek nagyfrekvenciás zavaremisszió-vizsgálatának eszközei és rendszere, Elektrotechnika, No. 4, 2006 [59]

(10) Istók R., Bagoly Zs., **Schmidt G.**: A modern autólámpa EMC-vizsgálata, ELEKTROnet, No. 8, 2006 [63]

(11) Istók R., **Schmidt G.**: Imbunatatirea metodei de masurare a perturbatiilor emise prin conductie de catre lampile auto HID, Electricianul, No. 2., Romania, 2006 [64]

(12) **Schmidt G.**, Berta I.: Radiated radiofrequency emission from compact fluorescent lamps, International Journal of Plasma Environmental Science & Technology, Japan, 2011 [84]

(13) **Schmidt G.**: Dimming of Compact Fluorescent Lamps and One of Its Related Aspects – Electromagnetic Compatibility, Acta Electrotechnica et Informatica, Slovakia, 2010 [104]