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A MEASUREMENT METHOD FOR RESIDUAL LIFE ESTIMATION OF HPS ROAD LAMPS

A. Bernieri [1], *L. D'Alessandro* [2], *M. Laracca* [1], *C. Liguori* [3]

[1] DAEIMI University of Cassino, Cassino (FR), Italy, Email: {bernieri, m.laracca@unicas.it}
[2] Lenze Gerit S.r.l., Italy, Email: l.dalessandro@gerit.it
[3] DIIIE, University of Salerno, Fisciano (SA), Italy, Email: tliguori@unisa.it

Abstract: Replacing a lamp in an outdoor installation, like roadway lighting, requires a lot of time and money. The proper maintenance strategy of installed lighting-system components is an essential element in ensuring that systems perform as designed and consequently ensure the safety. The paper presents a method for evaluating the residual life of High Pressure Sodium road lamps and for detecting incoming fault. The proposed method is based on the frequency domain analysis of the lamp current that changes its harmonic content in consequence of the aging.

Keywords: lamp, maintenance rate, life estimation.

1. INTRODUCTION

The quality and efficiency of outdoor lighting systems play an important role in traffic security and in crime prevention, improve the nighttime environment and provide increased sense of safety in parking garages, roadways and other public areas. For instance, recent research shows that road accidents occur mostly at night because of the insufficient nighttime visibility [1].
As consequence of this consideration, lighting technology continues to improve the quality and efficiency of lighting systems increasing the efficacy, color quality and lifetime of lamps as well as the ballast quality. High-intensity discharge (HID) lighting are widely used for outdoor applications thanking to their better efficiency and longer life than fluorescent lighting, with color quality approaching that of incandescent lighting (see figure 1).
Among the lamps that fall in HID category, high pressure sodium (HPS) lamps have taken an important role in outdoor lighting; their efficacy vary more widely than the others.

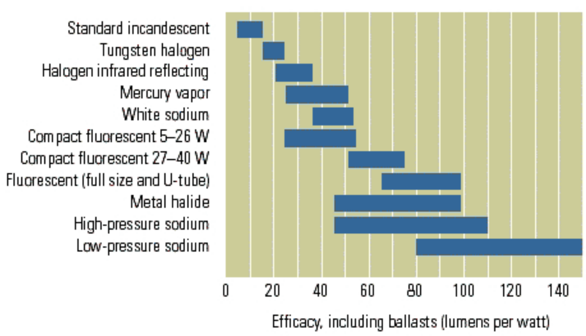

Fig. 1. Efficacy comparison among lamps on the market (efficacy is calculated as light output divided by power input).

It is important to say that components quality is just a first step in order to have an efficient lighting system. In fact, the proper maintenance of installed lighting system components remains an essential element in ensuring that systems perform as designed and consequently ensure the safety. For example, it is easy to understand that some broken lamps, if not replaced in the due time, involves in a loss of lighting system performance.
Even if HID (and in particular HPS) lamps generally have long lifetimes, maintenance costs can significantly affect system economics. This is particularly true in the roadway lighting for the wide area of installation. Therefore, the maintenance strategy has a great importance since it allows a reduction of costs both in term of time and money as well as lamps replacing time [1].
Two different maintenance strategies are usually employed.

i) Maintenance based on spot replacement where, each night, trained technicians drive around roadway and record each pole position where a lamp is burned-out. This solution has high mobilization costs and is characterized by long mean time between replacements.
ii) Planned maintenance usually based on the planned mass replacement of lamps before they fail. The relamping interval is calculated by average lamp-life and burn-hours data. The recommended point for relamping is usually at 70% rated lamp life. This method calls for the purchase of more lamps than required to completely re-lamp an area. In addition the average lamp-life can change depending on environmental conditions, power quality, lamp/ballast compatibility and so on [2]-[4]. Finally it is not taken into account the possibility that lamps can broke for different reasons that natural lifetime (for instance, vandalism actions). As a consequence, it is easy to fall in wrong replacing time that can be too early or after lamp failure.

Since all the above mentioned consideration it is clear that neither i) nor ii) maintenance strategy is the best, even if mass-replacement of lamps is a good option and proves to be less expensive than spot replacement.
Maintenance costs reduction and assuring a good maintenance are two opposite requirement and the best maintenance solution have to be a compromise between them. From technical and safety point of view, the on-line monitoring of the life status of lamps should be the best maintenance solution.

The authors experienced different measurement stations able to on-line detect and isolate faults on electrical and mechanical component and systems [5]-[8]. The proposed approaches were mainly based on on-line signal processing coupled with the use of either artificial intelligence techniques [5]-[6] or FFT analysis [7]-[8].
In this paper, the authors propose a method for the residual life estimation of lamps, based on the frequency domain analysis of the absorbed current of a group of lamps and taking into account the previously experienced pattern matching techniques. The difficulties due to very long-life component will discussed in this paper together with the preliminary experimental results.

2. THE PROBLEM STATEMENT

The simplest method for lamp life monitoring could be the measurement of the current absorbed by each lamp: when a lamp breaks down, it becomes an open circuit and then it doesn't drain current. Obviously, this solution does not meet low cost requirement because the high number of lamps to be monitored.
Roadway lighting is usually organized in group of lamps connected in series or parallel, depending on the design choice. As an example the most used solution in Italy is 20 lamps connected in parallel. As a consequence, a cheaper solution could be to monitor the amplitude of the current absorbed by the group of lamps instead of the one absorbed by each lamp. Unfortunately the amplitude of the current absorbed by a group of lamps is not useful to highlight the failure of a limited number of lamps. As an example, Fig. 2 reports the current absorbed by a group of 20 lamps and the one absorbed by a group of 19 lamps, acquired by using the measurement station described in section 4. In particular, the RMS values of the absorbed currents in 24 hours, under normal operating condition, together with a 1% accuracy band are shown. It is evident that it is not possible to discriminate between current changing due to burned-out of a lamp and current changing due to other factors like measurement uncertainty, voltage supply variations, and so on.
Moreover, the value of the absorbed current can not be used for evidencing the lamp aging, since the variation of the absorbed current is comparable with the normally daily variability. As an example, in Fig. 3, the current absorbed by a new lamp and the one absorbed by an old one (about 8000 hours of continuous operation) are reported. Their behaviors are practically coincident.

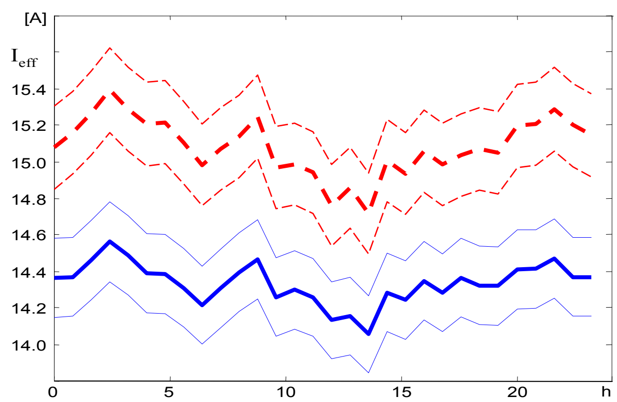

Fig. 2 Evolution of the current absorbed, together with a 1% accuracy band, by a group of 19 (solid lines) and 20 (dashed lines) lamps.

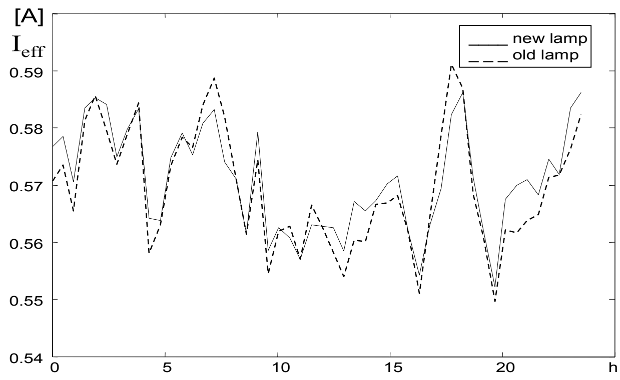

Fig. 3 Evolution of the current absorbed by a new and by an old lamp.

3. THE PROPOSED FREQUENCY DOMAIN PARAMETER ANALYSIS

The proposed approach for the estimation of the residual life of lamps is based on the analysis of some characteristics of the absorbed current waveform. In particular, some synthetic parameters are defined and the study of these parameters in different life lamp phases will lead to the identification of those one more sensible to the lamp aging. As a matter of fact the very long life of this kind of lamps and the very slow modification of their parameters render this analysis very troublesome. In this preliminary phase (the oldest lamp under analysis has about 8000 hours of continuous operation) all the potentially meaningful parameters have been monitoring. Intermediate evaluations will allow some selection and/or modifications to be carried out looking for single or suitably combined parameters [8] more sensitive to lamp aging and on-line estimable.
Parameters currently under control are:

Y^{1st} Lamp admittance at the supply frequency which is defined as the ratio between the spectral components at the supply fundamental frequency, f_0, of the current and of the voltage, respectively:

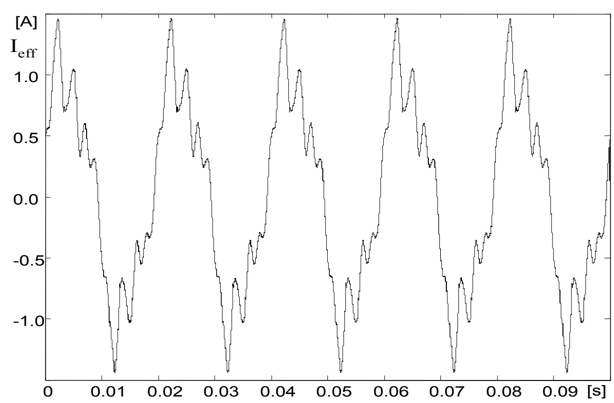

Fig. 4 Example of current evolution of a new lamp under sinusoidal supply.

$Y^{1st} = I(f_0)/V(f_0)$. (1)

It is in fact very reasonable that the lamp admittance changes with the aging.

HDEven HDOdd Since lamps are nonlinear devices, they will adsorb a distorted current even under ideal sinusoidal supply (in Fig. 4 for example the evolution of an absorbed current is reported). The measurement of the current signal distortion can give an indication of the lamp aging [9] and, in particular, to the hours before lamp fail. Two parameters have been defined in order to share the contribution due to even and odd harmonics. Additional information comes from a comparison between these two parameters. They are defined as follows:

$$HDEven = \frac{\sum_{k=1}^{M} I^2(2 \cdot k \cdot f_0)}{I(f_0)}; \quad HDOdd = \frac{\sum_{k=1}^{M} I^2((2 \cdot k + 1) \cdot f_0)}{I(f_0)} \quad (2)$$

where the number M is fixed on the basis of the new lamp spectral content: M= int $(B/f_0)+1$ where B is the maximum spectral component in the current absorbed by a new lamp.

LFHFr, FmaxL, FmaxH With the aging the distribution of the current spectral content will change. Several parameters are introduced for estimating in a quantitative way this phenomenon. In particular, the low frequency components (less than B/2) can vary differently than the high frequency ones (greater than B/2); The parameter "LFHF ratio" (LFHFr) takes into account this behavior. It is defined as the ratio between the sum of the powers of all low-frequency components above the fundamental and the sum of the powers of the high frequency components:

$$\mathbf{LF}HF\mathbf{r} = \frac{\sum_{\ell=f_0}^{B/2} I^2(\ell)}{\sum_{\ell=B/2}^{B} I^2(\ell)}; \quad (3)$$

FmaxL, FmaxH represent the frequencies characterized by the maximum amplitude at low and high frequency, respectively.

$$\begin{aligned} &FmaxL \ni' \ I(FmaxL) = \max_{\ell \in]f_0, B/2[} (I(\ell)) \\ &FmaxH \ni' \ I(FmaxH) = \max_{\ell \in [B/2, B]} (I(\ell)) \end{aligned} \quad . \quad (4).$$

The previously described parameters give extensive indication of the current spectrum. To take into account also local behaviors, several Boolean parameters have been considered. These logical parameters point out the presence of noticeable spectral component amplitude I(f) at a specific frequency, f_{xi}:

if $I(f_{xi}) / I(f_0) > th_i$ **then** P_i=*true* **else** P_i=*false*. (5)

In all the tests, the measured spectral components are normalized to the amplitude of the fundamental in order to take into account eventual fluctuation of the supply voltage.

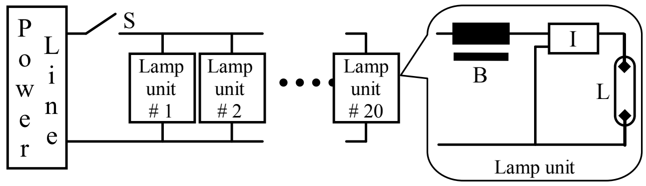

Fig. 5. The test station for the controlled aging of lamps (S automatic power switch, B ballast, I igniter, L lamp).

4. MEASUREMENT STATIONS FOR AGING MONITORING

In order to set up and tune the previously described methodology, a test station for the controlled aging of lamps and a measurement stations for monitoring the absorbed current during lamp lifecycle have been set up.

For the aging of a group lamps, a suitable test station was developed (see Fig.5). It is composed by:

- twenty lamps OSRAM NAV4Y 150W with a lamp luminous efficacy of 93 lm/W, a reliability of 16000 hours and a failure level after 16000 hours of 5%;
- twenty ballasts, one for each lamp, OSRAM NV 150-01, 230V operating voltage, 1.8A maximum current, 50Hz operating frequency;
- twenty igniters OSRAM I150-01 P, 220÷240V operating voltage, 50/60Hz operating frequency, 1.8A maximum current, 3.5÷4.5kV pulse voltage;
- twenty capacitors, one for each lamp (for the power factor correction), OSRAM MF1 20-250, 20μF ±5% capacitance, 250Vac operating voltage, 50/60Hz operating frequency;
- an automatic power switch controlled by a suitable software to make possible switch on and off the lamps, in order to reduces their lifetime.

Fig. 6 shows the first developed measurement station. With the aim of assuring a stable controlled supply, a California Instruments™ Programmable AC Power Source (SIMULBUS) is used. It is able to furnish a stable supply with the following main characteristics: three phase 15 kVA (5kVA per phase), 270 V maximum voltage per phase, 37 A maximum current and 16 - 66 Hz fundamental frequency range.

In this case the voltage and the fundamental frequency were fixed to 220 V and 50 Hz, respectively, as in the Italian mains. The SIMULBUS supplies each HPS lamp with its ballast, igniter and capacitor.

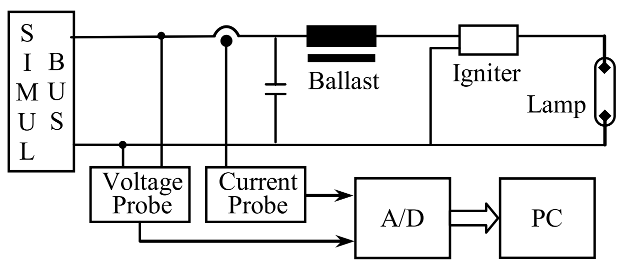

Fig. 6. The measurement station used for the lamp aging monitoring in a controlled environment.

The data acquisition system is composed by:

- a Tektronix P5205 high-voltage differential probe, with 1.3 kV maximum voltage, DC-100 MHz frequency bandwidth, and a gain accuracy of ±3%;
- Tektronix A621 current probes, with 2 kA (at 1mV/A gain and 2% accuracy) or 20 A (at 100mV/A gain and 3% accuracy) maximum current and 5Hz-50kHz frequency bandwidth;
- a LECROY™ waverunner-2 LT264 digital oscilloscope, four channels, 1 GS/s maximum sampling rate, 350MHz bandwidth, 100 kpoints per channel memory depth, 8 bit vertical resolution;
- a PC for the measurement station control and for data processing.

This measurement station allows the parameters introduced in section 3 to be analyzed in a controlled environment, and, consequently, allows the modifications in the lamp spectrum due to the aging to be evidenced in an easier way.

Once the optimal parameter selection has been carried out, another measurement station has been used in order to evaluate the variation of the selected parameters under real supply conditions (e.g. characterized by power supply fluctuation, voltage harmonics). In particular, the same instruments reported in Fig. 6 (current and voltage probes, the oscilloscope) are applied to the test station reported in Fig. 5.

This measurement configuration also allows a sensitivity analysis to be carried out in terms of system capability of detecting aging or damaging of only one lamp in a group.

Using the measurement stations described above, twenty lamps have been monitoring for 12 months. Every two weeks, a one day total monitoring is carried out. This in-depth control will be intensified when approaching the lamp death. In each monitoring time, two buffers (current and voltage) of 100kpts, sampled at 100kHz, were stored. In particular, the applied voltage and the current absorbed by all the twenty lamps, the applied voltage and the current absorbed by some single lamps (two lamps) were monitored.

5. PRELIMINARY EXPERIMENTAL RESULTS

In figures 7-9, the first results of the parameter monitoring are reported. First of all, it is important to stress that the following are very preliminary data, since the actual aging (8000 hours) is still far from the nominal one (about 50% of lifecycle). The figures show the measured parameters in the controlled environment obtained using SIMULBUS. Results refer to two different lamps at different aging (0 months and 12 months), in several repeated acquisitions. Fig. 7 reports Y^{1st} parameter evolution. A little reduction, comparable with the measurement uncertainty is measured (less than 1%), but probably the lamps are still too young. Figs. 8a and 8b report HDEven and HDOdd, respectively. As you can see the parameter HDEven does not present an identifiable trend at this age status of the lamps. Vice versa, the parameter HDOdd decreases with the aging. Also the LFHFr parameter (see Fig. 9) does not present any identifiable trend. Only a very little decreasing is measured, but the high frequency components are supposed to increase with aging, giving a significant diminution to the LFHFr parameter.

Fig. 10 reports the Y^{1st} parameter measured during one day

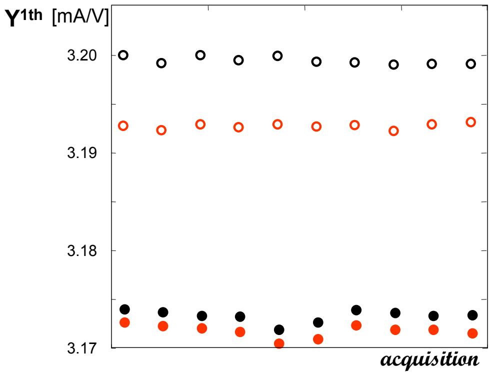

Fig. 7 The measured Y^{1st} parameter for two different lamps, red and black, at different lifetime (○ marker 0 months, ● marker 12 months).

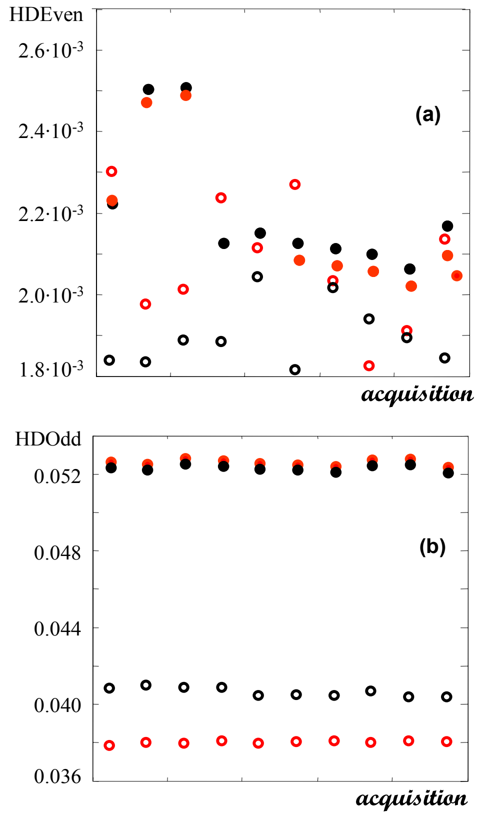

Fig. 8 The measured HDEven (a) and HDEven (b) for two different lamps, red and black, at different lifetime (○ marker 0 months, ● marker 12 months).

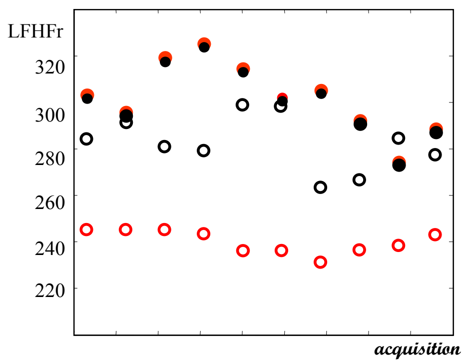

Fig. 9 The measured LFHFr for two different lamps, red and black, at different lifetime (○ marker 0 months, ● marker 12 months).

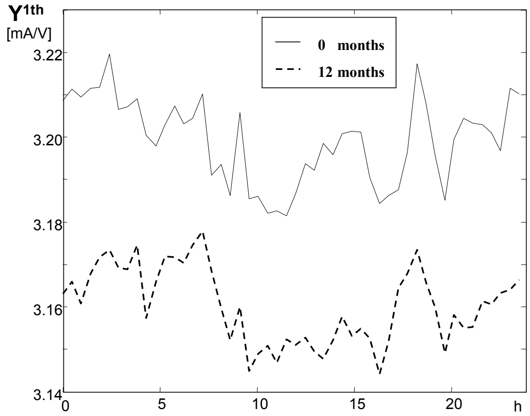

Fig. 10 The measured Y^{1st} parameter for the same lamp at different lifetime in real supply condition.

acquisition with the station of fig. 5 for the same lamp at different lifetime. As you can see, data acquired in real operating conditions confirm the result obtained in the controlled environment, even if the measured daily variability is comparable with the reduction due to aging.

6. CONCLUSION

In this paper a methodology for the estimation of residual life of HPS road lamps is presented. The estimation is based on the evaluation of some synthetic parameters based on the frequency domain analysis. Only preliminary results were presented because of the very long-life of HPS lamps that are, at the moment, at about 50% lifecycle. The developed test station reproduces, inside the laboratory, a line of road illumination and it is able to monitor the lamps aging. The results obtained after 12 months lamps lifetime, shown the goodness of the selected synthetic parameters, in order to estimate the residual life of HPS road lamps, even if additional experimental results, on older lamps, need to be carried out.

The final idea of the proposed study is the development of a smart maintenance strategy based on the residual life knowledge of the lamps. This strategy will allow both economic and safety aspects improvements. The measurement and control system for implementing the proposed strategy will then be designed and realized.

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