Using Incandescent Lamp Failure Levels for Assessment of the Surge Environment

Hubert Bachl
Cooperative Testing Institute
Vienna, Austria

François Martzloff
National Institute of Standards and Technology
Gaithersburg MD 20899 USA
f.martzloff@ieee.org

Doni Nastasi
Power Electronics Applications Center
Knoxville TN 37932 USA
DNastasi@epri-peac.com

Reprinted, with permission, from
Proceedings, 12th International Zürich Symposium on Electromagnetic Compatibility, 1997

Significance:
Part 2 Development of standards – Reality checks

Investigations were conducted in the US as well as in Austria, on 120-v and 240-V incandescent lamps to determine the levels of surges that can trigger an internal flashover of the hot filament, resulting in filament burnout. Repetitive surge application below the threshold do not result in premature failure of the lamp, but above the threshold, a single application can trigger a fatal flashover. By combining measurement of currents and voltage during the event with high-speed video recording, the mechanism has been clearly determined.

Depending on the characteristics of the surge (waveform, amplitude, and timing with respect with the power-frequency sinewave), thresholds of failure range between 800 V and 2000 V. Very few bulbs survive surges above 2200 V. Therefore, the conclusion is inescapable: if such surges were occurring frequently – according to some SPD advertizing claims – lamps would fail very promptly. We know they do not, ergo the alleged frequency of occurrence is incorrect.

USING INCANDESCENT LAMP FAILURE LEVELS FOR ASSESSMENT OF THE SURGE ENVIRONMENT

Hubert Bachl
Cooperative Testing Institute
Vienna, Austria

François Martzloff
National Institute of Standards and Technology
Gaithersburg MD USA

Doni Nastasi
Power Electronics Applications Center
Knoxville TN USA

Abstract The paper reports a joint investigation of the failure modes and levels of incandescent lamps ("light bulbs") exposed to surges occurring in low-voltage AC power systems. Tests were performed in one European laboratory and in one U.S. laboratory on typical 100-W bulbs used in the two environments, the North American 120-V systems, and the 230-V European systems. Through complementary tests and high-speed video observation of the flashes, more detailed understanding of the parameters has been obtained. Having determined what it takes to fail a light bulb by a surge, this information can be used to assess the surge environment by noting that frequent bulb failures do not occur, therefore surges above the failure threshold must be infrequent.

1. Introduction

Some proposals for standards on equipment surge immunity or on performance of surge-protective devices are driven by the commendable quest for conservative ratings. However, when this quest produces compounded safety factors, the result might not be cost-effective. The purpose of our paper is to present information on the failure mechanisms and levels of incandescent lamps ("light bulbs" or "bulbs" for short) under surge conditions, in support of the development of realistic standards on the surge environment in low-voltage ac power systems. Since we do not hear reports of endemic failure of light bulbs beyond what can be expected from their known service life [1], we must conclude that the reality is that there is not a high rate of occurrence of line-to-neutral surges at levels in excess of the threshold voltage at which bulb failure occurs.

The concept of applying reality checks to standards on the surge environment has been presented in earlier papers [2], [3], producing discussions on what the mechanism of bulb failure might be and how repeatable test results might be to define a representative threshold. This interest motivated further research into the subject at a U.S. laboratory where the initial measurements were made and at an Austrian laboratory for possible replication.

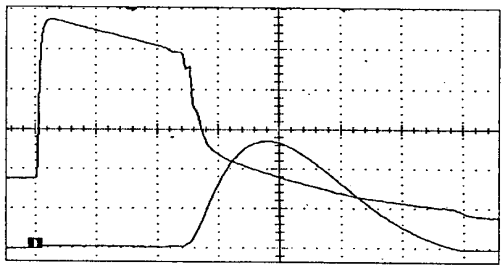
Therefore, we embarked on a systematic comparison where bulb specimens and test methods would be identical in the two laboratories. The test bulbs were taken from two shared batches, a 120-V type manufactured in Canada, and a 230-V type manufactured in Europe. Each laboratory planned to use a "Combination Wave" surge generator to apply the surges to the bulbs under similar conditions.

As it turned out, the test equipment available in the two laboratories were not identical, so that some unavoidable differences crept into the initial plan of exact replication. However, as the tests progressed in the two laboratories, enough other significant parameters affecting the outcome were found for a given generator, so that the generator variations became less significant, and the final conclusions cover a range of parameters rather than a single threshold value. This finding does not affect the conclusion that a pragmatic range of surge levels can be identified, beyond which high bulb failure rates would become noticeable (which historically they have not been), thus providing a reality check on possible occurrence of frequent line-to-neutral surges.

2. Preliminary tests on 120-V bulbs

In these preliminary tests, first reported in [3] and summarized here, the test circuit used in the U.S. laboratory consisted of a Combination Wave surge generator capable of applying surges to the light bulb which was powered through the back-filter typically included in commercial surge generators. The phase angle of surge application with respect to the power frequency sine wave could be set at any value within 360 degrees. Monitoring the event was performed by a multi-channel digital oscilloscope with differential voltage probes.

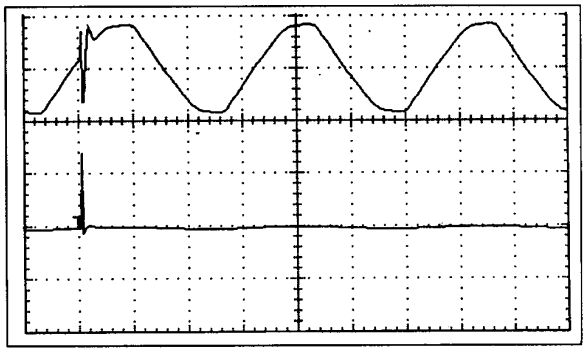
Figures 1, 2, 3, and 4 present oscillograms of the voltage across an energized 120-V bulb and of the current flowing in the bulb. Figure 1 shows a narrow window, commensurate with the duration of the surge delivered by a 1.2/50 - 8/20 µs surge generator. We observe the chopping of the voltage wave, typical of a gap sparkover, and the rise of the surge current after the sparkover. The scale of the current trace selected to record the surge (hundreds of amperes) does not show the normal current (1 A) in the bulb.[1] Observations during this test include hearing a pinging noise and seeing a bright flash of light, followed by darkness. After the test, the filament can be seen broken at one or both its points of attachment to the supporting connecting stems.



Top trace: Voltage across bulb terminals, 200 V/div
Bottom trace: Current in bulb, 100 A/div
Sweep: 10 µs/div

Figure 1: Voltage and current in bulb during application of a 1.2/50 µs - 8/20 µs surge, resulting in surge sparkover

1 The measurements reported in this paper have been made with instrumentation for which the combined uncertainty should not exceed ±5% to ±6%. Given the process of applying the measurement results to the failure levels of light bulbs exposed to environments with characteristics that are at best known within an order of magnitude, this level of uncertainty does not affect the practical conclusions.

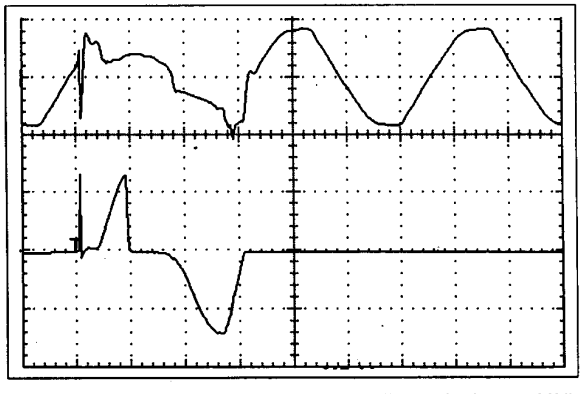


Top trace: Voltage across bulb terminals, 200 V/div
Bottom trace: Current in bulb, 100 A/div
Sweep: 5 ms/div

Figure 2: Voltage and current in bulb during application of a 1.2/50 - 8/20 µs surge at 30°, with surge sparkover but no power-frequency flashover

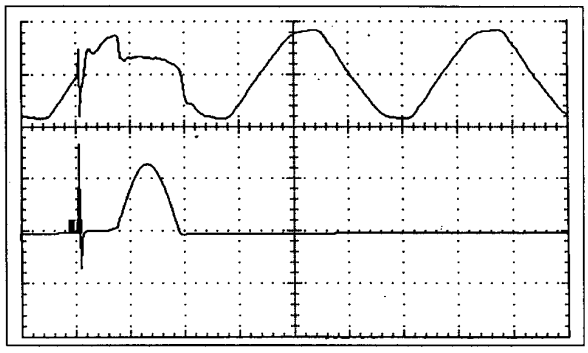
Figure 2 was recorded (with a new bulb) with a longer window than Figure 1, so as to display three full cycles of the power frequency. At that sweep rate, the surge is no longer resolved, and its apparent peak shown on the trace may be lower than the actual peak because not enough data samples are collected around the peak. However, the timing of the surge, not its amplitude is what is important in this figure. The surge event appears as a voltage spike and a current spike, followed by return to practically normal voltage and no visible large power-frequency current.

Figure 3 shows for the same bulb as that of Figure 2 the events during a subsequent shot under the same conditions. At first, after the surge, the pattern is identical to Figure 2. Then, suddenly, a pulse of power-frequency current appears, with a large amplitude -- the source of the observed flash. We believe that it is this current that causes the burn-out of the filament, not the "trigger" surge. The randomness of the process of igniting the power arc is such that in the case of Figure 2, the power arc was not ignited, while in the subsequent surge application on the same bulb (Figure 3) and in the same conditions, the power arc was ignited, resulting in burn-out of the filament -- a threshold situation.



Top trace: Voltage across bulb terminals, 200 V/div
Bottom trace: Current in bulb, 100 A/div
Sweep: 5 ms/div

Figure 3: Voltage and current in bulb during application of a 1.2/50 - 8/20 µs surge at 30°, resulting in surge sparkover, with delayed two-pulse power-frequency flashover



Top trace: Voltage across bulb terminals, 200 V/div
Bottom trace: Current in bulb, 100 A/div
Sweep: 5 ms/div

Figure 4: Voltage and current in bulb during application of a 1.2/50 - 8/20 µs surge at 0°, with surge sparkover and delayed single-pulse power-frequency flashover

As further evidence, Figure 4 shows the process (in a new bulb) when the surge was applied at 0°, requiring more energy for ultimately igniting the power-frequency flashover. At zero degrees, there is the least power-frequency voltage to ignite a power arc. Figure 4 shows the last of a seven-shot sequence in which the first applied surge had an amplitude of 1200 V. The applied surge was then raised in 100-V steps to 1500 V, still with pinging heard but no fatal power-frequency arc. To explore the hypothesis that the filament might be burned out by the surge energy, we held the surge at 1500 V for the next three shots. Only the last of the three triggered the fatal flashover, recorded in Figure 4. At that level of energy deposited by the surge, enough plasma was generated in the path of the surge current to eventually ignite the power-frequency arc, but for that shot it had to wait until the power-frequency voltage had reached its peak, again indicating a threshold situation.

To conclude this summary of preliminary findings, Table 1 shows the relationship between the timing of the surge with respect to the sine wave and the minimum peak amplitude of the surge sufficient to trigger ignition of the power-frequency arc. When the surge is applied at 90 degrees (the peak of the sine wave, making immediate ignition of the power arc easiest), a surge of 800 V is sufficient to trigger the power arc. At zero degrees, the surge must be raised to 1500 V to produce sufficient plasma to result in a subsequent power-frequency arc. The phenomena are of course subject to the statistical variations of sparkover.

The values shown in Table 1 are the lowest of several tests performed on a total of 20 bulbs of the same manufacturer, rated 100 W, replicating the test at several timing angles. At and near 90 degrees, the values were identical, at and near zero degres, there was up to 200 V difference among tests. There is not enough space in this paper for reporting in detail our series of experiments (involving several hundred bulbs) on other manufacturers and other watt ratings. These produced similar results, so that our inferences are not based on just the 20 bulbs tested under the conditions of Table 1.

Table 1: Relationship between timing angle of the Combination Wave surge and theshold amplitude necessary to produce fatal power-frequency flashover

Angle of surge application	0	15	30	45	90	135	150	165
Open-circuit voltage setting of generator (V)	1400	1100	900	800	800	800	850	1100

3. Comparative tests at two laboratories

One of the motivations for comparing the tests at two laboratories was that preliminary data indicated some possible behavior differences between 120-V bulbs and 230-V bulbs, as well as some differences in the laboratory facilities and procedures. To alleviate this uncertainty, researchers on both sides of the Atlantic joined forces, hence the multinational authorship of this paper. As mentioned in the introduction, we started out with the goal of exact replication in the two laboratories: lamps from the same manufacturing batches, generators with similar characteristics, and power-frequency supplies with comparable available fault current.

However, practical limitations of available equipment and resources made that goal elusive. Instead, we then focused on identifying similarities in general behavior rather than identical numerical results. We also recognized that many independent parameters would affect the numerical results. Since our goal was to find the range of threshold values where failures begin to occur, our main concern became one of confirming the initial hypothesis that the failure was triggered by a surge and thus provide insights on the surge characteristics at the threshold of bulb failures. With that narrower goal, we made some side experiments by changing the parameters to develop a set of anecdotes, allowing us to identify the most significant parameters of the surges, and thus make inferences on their (limited) occurrence in the real world, given the absence of endemic bulb failures.

3.1 Influencing parameters

The influencing parameters that we considered involve lamp characteristics, surge characteristics, and power-frequency supply characteristics. The list below is given as an indication of the possible complexity of a comprehensive experiment -- which was not our goal -- as well as an invitation to other researchers who might be interested in lamp behavior. Clearly that level of detail is not in the scope of an EMC concern, and we will not give it much space, save for a few intriguing observations.

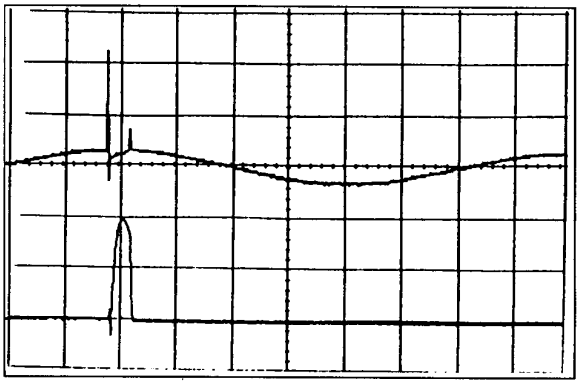
Lamp characteristics
Geometry (axial or longitudinal, straight or c-shaped filament);
Base position (up, down, horizontal);
Nature of the gas fill (breakdown tendency);
Temperature gradient near the filament;
Characteristics of the fuse contained in the stem.
Surge characteristics
Waveform (peak, duration, Combination or Ring Wave);
Source impedance (ability to deposit energy in the arc);
Timing with respect to power-frequency sinewave.
Power-frequency supply
Voltage;
Available fault current (ability to establish stable arc).

3.2 Typical test results

Figures 5, 6, and 7 show typical recordings obtained at the Austrian laboratory during application of a 1.2/50 µs - 8/20 µs surge with a peak amplitude sufficient to produce a sparkover, either immediately or after a short delay. (In the figures, the surge peaks are not resolved at the millisecond sweep rate.)

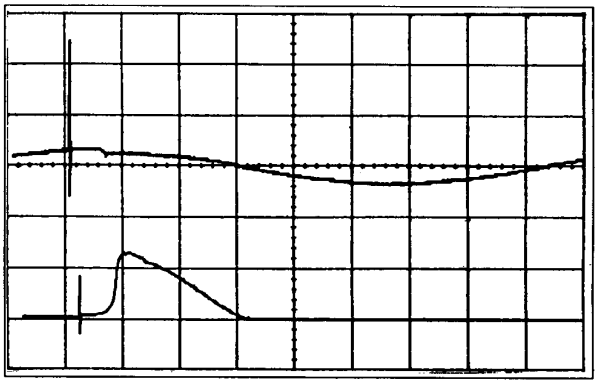
In Figure 5, a 230-V bulb shows the occurrence of a single-pulse of power-frequency flashover occurring immediately after the surge sparkover. Figures 6 and 7 show the occurrence of a delayed flashover with a single or double pulse, similar to the pattern for 120-V bulbs, respectively in Figures 4 and 3.

The peak values of the power-frequency flashover observed in the Austrian laboratory are different from those obtained in the U.S. laboratory because the available generators in the two laboratories have different effective back-filter impedances.



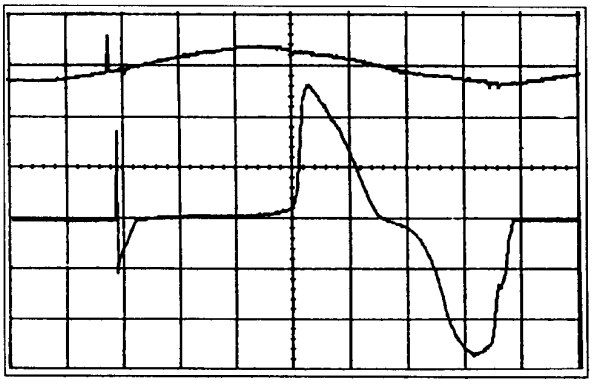
Top trace: Voltage across bulb terminals, 1000 V/div
Bottom trace: Current in bulb, 50 A/div
Sweep: 2.5 ms/div

Figure 5: Voltage and current in 230-V bulb during application of a 1.2/50 µs - 8/20 µs surge at 90°. Surge sparkover is followed immediately by power-frequency flashover



Top trace: Voltage across bulb terminals, 500 V/div
Bottom trace: Current in bulb, 50 A/div
Sweep: 2 ms/div

Figure 6: Voltage and current in 120-V bulb during application of a 1.2/50 µs - 8/20 µs surge at 90°. Surge sparkover and delayed one-pulse power-frequency flashover



Top trace: Voltage across bulb terminals, 500 V/div
Bottom trace: Current in bulb, 20 A/div
Sweep: 2.5 ms/div

Figure 7: Voltage and current in 120-V bulb during application of a 1.2/50 µs - 8/20 µs surge at 350°. Surge sparkover and delayed two-pulse power-frequency flashover

Table 2 shows a summary of test results obtained in the Austrian and U.S. laboratories for 120-V bulbs and 230-V bulbs, under various parameters of surge application. These results show some differences in the thresholds for the tests conducted on the same type of bulbs.

Table 2 - Comparison of results from Austrian and U.S. laboratories

	Austrian Laboratory			U.S. Laboratory		
Lamp Type	Surge type Source imp.	Angle	Typical threshold	Surge type Source imp.	Angle	Typical threshold
120 V 100 W	'Combination' 24 Ω	90 30	1100 V 1400 V	Combination 2 Ω	90 30	800 V 1500 V
	Ring Wave 22 Ω	90 60	1600 V 2600 V	Ring Wave 12 Ω	90	2100 V
230 V 100 W	'Combination' 24 Ω	90 60	2200 V** 2800 V	'Combination' 10 Ω	90	1800 V
(**=75 W) (*=40 W)	Ring Wave 22 Ω	90	3100 V	Ring Wave 30 Ω	90	2200 V*

The differences in the threshold levels observed for the two types of lamps shown in Table 2 are likely the results of many parameters, as listed in paragraph 3.1. One is probably the filament configuration. In the 120-V, 100-W bulbs, the filament is a 22 mm long straight section strung between the two stems, with a single support at mid-span which does not affect the straight line aspect. This configuration offers the easiest path for a sparkover to occur. In the 230-V, 100-W bulbs, the 25 mm long filament has a shallow c-shape obtained by two intermediate supports that deflect the filament from a straight line between the two stems. This configuration creates a slightly longer path than that of the 120-V bulbs. In a few anecdotal tests on a 120-V 40-W bulb which has a 40 mm long horseshoe shape, we found that sparkover occurs along the filament or straight from stem to stem, typically about 4000 V.

Another possible reason for the higher threshold voltages found in the Austrian laboratory using its "Combination Wave" generator might be that its source impedance is 24 Ω, compared to the Combination Wave generator used in the U.S. laboratory, with its conventional 2 Ω source impedance. The difference will be in the surge current following sparkover, creating less plasma in the case of the Austrian laboratory, and therefore requiring a higher surge voltage to ignite the flashover. Nevertheless, oscillograms show similar patterns.

4. High-speed video observations

On the basis of the oscillograms, the most likely mechanism which we could propose was that a sparkover occurs when a surge of sufficient voltage amplitude is applied, producing an ionized path which enables the much lower power-frequency voltage to initiate an arc. In turn, this arc would produce enough heat at its point of attachment to cause local melting of the filament. During discussions with colleagues, other possible mechanisms were mentioned, such as a local melting of the filament caused by the surge current alone, mechanical shock on the hot filament, and the possibility that the reignitions of the power-frequency arc, such as that of Figure 2 and 7 might be associated with a broken filament that would oscillate and sweep by the stem close enough for a reignition.

In an attempt to settle this uncertainty, we obtained a high-speed video system consisting of two image converters, a digital acquisition memory, display monitor, and video recorder. The image converters had a capability of 1000 full frames per second, with the possibility of multiple scans of a limited field during the 1 ms basic full-frame scan time.

Figure 8 shows the arrangement of the two converters, with the left converter (L) controlled to perform four scans limited to the filament area, and the right (R) converter controlled to perform a full-frame view of the filament and fuse contained in the base stem of the bulb. The recording system was triggered by a signal from the surge generator, providing the beginning of the recording a few milliseconds before the surge, and lasting about 100 ms after the surge.

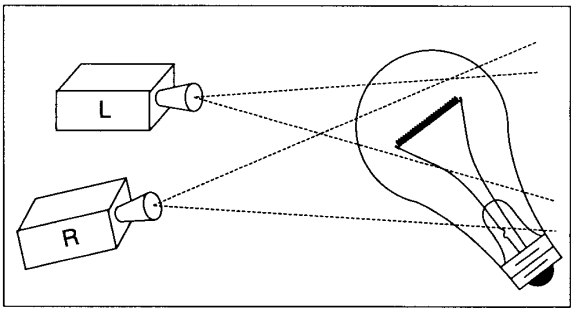
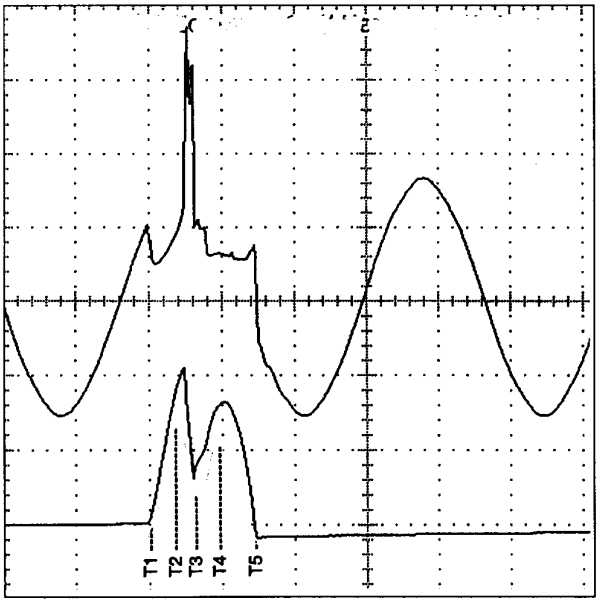


Figure 8: Arrangement of image converters to scan sparkover and flashover limited to the filament (L) and a full frame (R) including the base where the fuse is located

With this arrangement, recordings such as those shown in Figure 9 and Figure 10 were obtained. As an example of many oscilloscope recordings, Figure 9 shows the electrical record of the failure of a 230-V, 100-W bulb triggered by a 100 kHz Ring Wave applied 60 electrical degrees after the zero crossing. At time T1, sparkover of the filament occurs, accompanied in this case by immediate flashover of the power frequency arc, which rises to a first peak at T2, about 2.3 ms after its beginning. At that time, the current is throttled while the voltage increases sharply, indicating operation of the fuse. The fuse does not force a current zero at time T3, but allows a second peak of current at time T4, before decaying to a natural current zero at time T5.

This type of oscilloscope recording was the only one that was available until the video system was obtained. From such oscillograms we could only draw speculative inferences on the mechanism and behaviour, hence the motivation to enhance our tests by video recording. Figure 9 shows the voltage across the lamp terminals (top trace) and the current through the lamp (bottom trace). With the sweep set to cover 2 cycles of the power frequency, neither the surge voltage nor the surge current are resolved in this oscillogram. In this test series performed after the preliminary series, a separate oscilloscope with faster sweep was used to record the surge voltage and the surge current, as was done in the case of Figure 1. To conserve space, these surge recordings are not shown here, but the peak values of the resulting sparkover voltages recorded by the second oscilloscope are listed in Table 2 in the column "Typical threshold".

We now will examine in Figure 10, opposite page, four frames of video recording corresponding to the electrical record of Figure 9. The left half of the screen shows four scans from converter L of Figure 8, proceeding from top to bottom and each scanned in 250 µs. The right side of the screen shows the full frame, scanned over a period of 1 ms. The timing of the frame is shown in the lower right corner of the picture, such as "ET + 0000000010" which indicates the 1 ms window during which the surge was initiated. Other descriptive data in the margins are not significant to our story. Figure 10 shows the four frames respectively in the sequence from top to bottom for 0-1 ms; 1-2 ms; 2-3 ms; and 4-5 ms.



Top trace: Voltage across bulb terminal, 200 V/div
Bottom trace: Current in bulb, 20 A/div
Sweep: 5 ms/div

Figure 9: Failure of a 230-V, 100-W bulb triggered by a 100 kHz Ring Wave applied at 30°, showing fuse operation

In the first frame, 0-1 ms, the Ring Wave sparkover is not visible because of its relatively low intensity/duration. The first 250-µs scan (top) of the left side shows only the filament glow. Starting with the second scan, the beginning of the flashover (time T1 in Figure 9) is visible, while the right side scan, adjusted for less sensitivity, only shows the filament glow without the flashover beginning.

In the second frame, the flashover growth is visible on the four left scans (T1-T2 in Figure 9), while the right scan now has enough light integrated over the full 1 ms time to show the flashover.

In the third frame, the first two (top) left scans still show the flashover around the filament, but the last two (bottom) scans show the flashover current being starved as the fuse in the lamp base begins to operate and transfers the current to the space around the fuse. This corresponds to the time T2-T3 in Figure 9. The right side scan shows the beginning of the glow in the base of the lamp as the current around the fuse grows.

In the fourth frame, the four left scans show the filament still glowing, ***but unchanged (not yet broken)***, while the right scan shows the integrated glow of the fuse operation, corresponding to the time interval T4-T5 of Figure 9.

These four frames, typical of many others recorded during our experiments, clearly show the mechanism of a flashover at the power-frequency current, and in this particular test sequence, the operation of the fuse in the base of the bulb. Other records taken with different light sensitivity show an intense glow near the connection of the filament, where the arc is concentrated at its point of attachment (the cathode hot spot) while the path around the filament is more diffuse. The concentrated heat near the point of attachment eventually causes a local melting of the filament. In other records, the filament is then seen separating from the stem and slowly falling in the time frame of about 20-50 ms after the flashover.

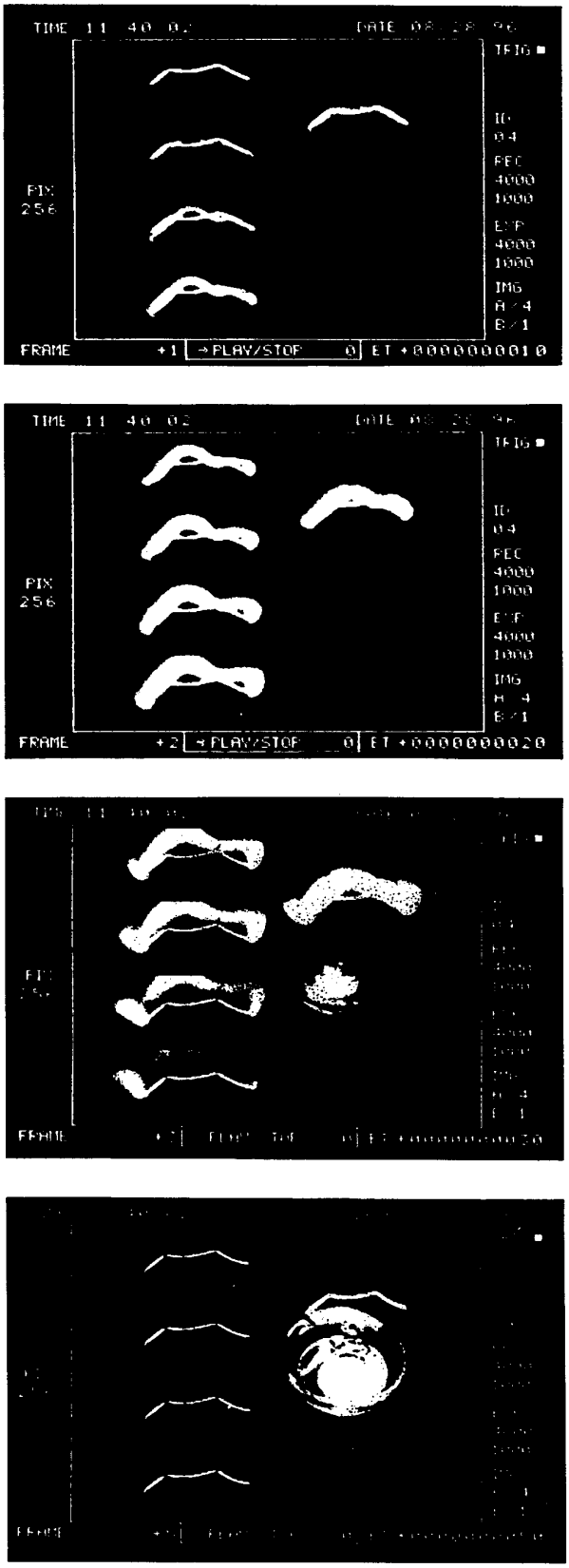


Figure 10: Sequence of flashover and fuse operation corresponding to the oscillogram of Figure 9

5. Discussion

Observation of the failure mechanisms and the levels of surges necessary to trigger the fatal power-frequency flashover as recorded in the two laboratories are consistent with each other and point out that a two-stage process is involved at lower amplitudes of the impinging surge, as shown by the video recordings and inspection of the oscillograms.

When the surge current ceases, and after some variable delay influenced by the instantaneous voltage of the power system voltage at that time, a flashover fed from the power-frequency source occurs along the path pre-ionized by the surge plasma.

It is noteworthy that the path along the filament is longer than the clearance between the two stems as they emerge from the glass envelope at the base of the bulb and yet the sparkover and the flashover occur at the longer (but hotter) clearance along the filament. By comparison, we found that a surge sparkover in a cold bulb which is not energized occurs for a much higher surge level, typically in the order of 5 kV to 6 kV, and that sparkover in that case does not occur near the filament but at the point where the metal stems emerge from the glass base, the shortest clearance.

According to this understanding of the mechanism, we can expect that a surge with a different waveform, the 100-kHz Ring Wave for instance, would require a different level to produce a sufficient amount of plasma necessary for ignition of the power-frequency arc. This is indeed the case as seen in Table 2. Applying the 100-kHz Ring Wave, sparkover can occur for open-circuit levels as high as 3 kV (pinging is heard) but without the following power-frequency flashover. Thus, the assessment of the surge environment severity given by the thresholds of bulb failure not only tracks the amplitude of the surge but also its waveform. There is a blessing as well as a curse in this situation: the assessment we can obtain reflects the energy-delivery capability of the surge as well as the peak voltage level of the surge. The two are not separable and thus the information remains imprecise, but still valuable as giving an indication of the severity of the surge environment.

This application of bulb failure levels to assess the surge environment must be made with the understanding that it rests on observations of in-use failure rates, a common experience to millions of users, noted before the proliferation of surge-protective devices (SPDs). Nowadays, the observed surges in low-voltage power systems are much lower than the threshold levels identified in this paper for bulb failures because of this proliferation of SPDs [4], [5].

It should also be noted that this assessment is limited to the surges occurring in the line-to-neutral mode at the location of the bulb. Depending upon the neutral grounding practices of the installation, surges impinging at the service entrance will propagate toward the victim light bulb in different manners. In the U.S. practice, where the neutral and earth conductors are bonded at the service entrance, a surge impinging from the power system in the common mode is converted into a differential mode, that is, a line-to-neutral surge is always applied to the bulb. In some countries where the service entrance bond is not present, an impinging surge in the common mode remains as such as it propagates within the house wiring, and thus the stress applied to the bulb from an external surge, such as a lightning-induced surge, may have different consequences for the light bulb. This point is important and should serve as a reminder of the significant differences in the effectiveness of surge-protection schemes according to the grounding practices in use among different countries.

6. Conclusions

Light bulbs failures levels and mechanism

1. The principal failure mode of light bulbs involves a power-frequency flashover triggered by the surge which produces a sparkover and sufficient plasma around its path to ignite an arc fed by the power-frequency source. This arc then melts the filament at its point of attachment. High-speed video recordings confirm tentative conclusions derived from observation of the current and voltage oscillograms.

3. The surge level necessary to trigger the power-frequency flashover depends on the phase angle of the surge with respect to the power-frequency sine wave. When applied near the peak voltage, the necessary voltage may be less than 1000 V peak for an 8/20 surge. When applied near zero crossing, the necessary voltage may be twice that sufficient near the peak.

4. Tests performed at two different laboratories show good agreement on the mechanism, with some differences attributable to some differences in the surge generators which could not be matched exactly. Such a difference serves to show that the phenomenon covers a range of thresholds, not a single sharp value.

5. For surges with high energy delivery capability, such as the 1.2/50-8/20 μs Combination Wave, typical 120-V bulbs experience failures with surges as low as 800 V under the most sensitive phase angle of timing. For typical 230-V bulbs, the corresponding level is as low as 1800 V.

6. For surges with low energy delivery capability, such as the 100 kHz Ring Wave, typical 120-V bulbs experience failures with surges as low as 2100 V under the most sensitive phase angle of timing. For typical 230-V bulbs, the level at the most sensitive time is as low as 2200 V.

Application to standards on the surge environment

Knowledge of failure mechanisms of light bulbs and the levels at which failure occurs in a surge environment brings a sense of perspective and helps developing realistic assessment of the surge environment because surge-induced failures are rare. From this assessment, proposed standards for performance and application of surge-protective devices can be reconciled with reality and avoid under- or over-specification of the devices.

7. Acknowledgments

Support and encouragement for this work was provided by the parent organization of each author. Additional support was received from Delmarva Power Company, and from Pacific Gas & Electric Company. Tom Conrad, Gerald FitzPatrick, and Don Worden contributed comments on the draft.

8. References

[1] Horacsek, K. "Properties and Failure Modes of Incandescent Tungsten Filaments," *IEE Proceedings*, Vol 127-A No.3, April 1980 (58 references).

[2] Martzloff, F.D., "Keeping up with the Reality of Today's Surge Environment," *Conference Proceedings, Power Quality Solutions*, Intertech Pub., Ventura CA, USA, September 1995 (15 references).

[3] Mansoor, A., Martzloff, F.D., and Nastasi, D, "Applying Reality Checks to Standards on the Surge Environment," *Proceedings, 23rd International Conference on Lightning Protection (ICLP)*, Florence, September 1996 (19 references).

[4] Dorr, D. "Point of Utilization Power Quality Results," *IEEE Transactions IA-31*, No.4, July/August 1995 (15 references).

[5] Martzloff, F.D., "Surge Recordings that Make Sense: Shifting focus from voltage to current measurements," *Proceedings, EMC'96 ROMA Symposium*, Rome, September 1996 (18 references).