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2021-10-06 street lighting and nuclear war

Let's consider, for a while, electric lighting.

The history of electric lighting is long and interesting, and I don't expect to cover it in much depth or breadth because it's somewhat off of my usual topic and not something I have a lot of expertise in. But I do have a fascination with the particular case of large-area outdoor lighting, e.g. street lighting, and there are a few things to talk about around street lighting that are really rather interesting.

As a very compressed history, the first electric street lights usually took the form of "moon towers," tall masts with arc lamps at the top. Various types of open and contained arc lamps were experimented with early on, but generally fell out of favor as incandescent lamps became cheaper and lower maintenance. The only remaining moon towers in the US are in Austin, Texas. They were expensive and high-maintenance, so they were fairly quickly replaced with low-height incandescent in most applications. Later, mercury vapor and metal halide arc lamps would begin to replace incandescent street lighting, but let's stop for a while in the era of the incandescent street light [1].

Let's say that you were installing a large number of incandescent lights, for example to light a street. How would you wire them?

In our homes, here in the United States, we wire our lights in parallel and apply 120v to them. This has convenient properties: parallel wiring means that the lights all function independently. A fixed voltage means that the brightness of a given light can be adjusted by using bulbs of different resistances, which will result in a different power (say, 60 watts). That makes a lot of sense, which is why it may be surprising to some to learn that incandescent street lights were wire in series.

Series wiring had multiple advantages, but the biggest was conductor size: in a parallel-wired system, wiring near the power source would need to carry a very large current (the combined current of all of the bulbs), and lights further from the power source would be dimmer due to voltage drop unless the conductors were prohibitively large. In a series-wired system, the current is the same (and much lower, approximately equivalent to a single bulb) at all points in the wiring, and voltage drop is seen across the entire length, and thus consistent across all of the bulbs.

These street lighting circuits are referred to as *constant current* circuits, as opposed to the more conventional *constant voltage*. All of the bulbs were designed to operate at a specific current, 6.6A was typical, and a specially equipped power supply transformer adjusted the voltage on the circuit to achieve that 6.6A. The voltage would be fairly large, typically something like 5kV, but that wasn't a problem because the streetlight wiring ran overhead with power distribution wiring of similar and higher voltages.

In early street lighting systems, the constant current regulator was a complex mechanical device using magnetic coils and levers. Today, constant-current incandescent lighting circuits are still in use in some applications and the constant current regulators have been replaced with more robust electronically controlled systems. But the regulators aren't really that important, except to understand that they simply apply whatever voltage is required to get 6.6A to flow.

Of course, connecting lighting in series introduces a major problem that you have probably realized. If any bulb burns out, the entire series circuit will be broken. That's unacceptable for street lights, and a few different solutions were invented but the most common was a cut-out disk. The cut-out disk was a small fuse-like device, but operated somewhat in the opposite way of a fuse. In fact, they're sometimes amusingly referred to as antifuses.

The cut-out disk is wired in parallel with the bulb. Should the bulb burn out, the voltage across the two sides of the disk rises, which causes an arc that "burns out" a film material separating two contacts. The contacts then touch, and electricity flows freely through the cut-out disk, restoring the circuit. When the bulb is replaced, the cut-out disk is replaced as well with a fresh one.

"Stay-Lit" Christmas light strings employ a very similar method, but use a thermistor instead of a cut-out disk so that it is not an additional consumable part. But the concept is the same: a device in the bulb base begins to pass current if exposed to the full 120v power supply, instead of the few volts normally seen when the bulb is present.

Constant-current lighting circuits have an interesting safety property, which this discussion of cut-out disks may have brought to your mind. A short circuit in a constant-current lighting circuit is actually pretty safe, as the regulator will reduce the voltage to near zero to maintain only 6.6A. But, when no current flows, the constant current regulator will increase the voltage applied to the entire circuit in an attempt to restore current flow. Modern electronic regulators mitigate this somewhat by detecting this condition, but it gives constant-current lighting circuits a particularly sharp edge. An open circuit can be rather dangerous as the regulator will increase the output voltage to the upper limit--potentially something like 10kV. Everything on the lighting circuit needs to be rated for this maximum voltage, which leads to more demanding requirements than typical 120v or 240v commercial lighting.

With that preamble on the concept of constant-current street lighting, let's take a look at a particularly interesting bit of history that closely relates to these technical details [2].

On July 9th, 1962, the United States conducted its 7th high-altitude nuclear test. While an earlier series of high-altitude demonstrations had shown the tactical potential of detonations far from the ground, significant advances had been made in the science and instrumentation in the intervening years, and greater resources had become available for geopolitical reasons (resumed Soviet testing). The new test, named Starfish Prime, was thus expected to contribute significant information on the effects of high-altitude detonations.

The approximately 1.5Mt detonation occurred at about 400 km altitude, well into space. It was expected that a detonation at such a high altitude would create a substantial electromagnetic pulse effect, since the “horizon” was far from the detonation allowing wide coverage and less cancellation by ground reflections. Prior to the Starfish Prime test, however, EMP had not typically been viewed as a major consideration in the use of nuclear weapons... while the effect clearly existed, the magnitude was not such that it was likely to cause substantial disruption [3].

Starfish Prime seemed to suggest otherwise. Effects that are out of scope for our purposes resulted in damage to several US military satellites. Moreover, unanticipated effects resulted in higher EMP field strengths at the ground than had originally been estimated. This effect extended over a very large area, including the nearly 1,500km straight-line distance from the detonation near Johnston Atoll to Honolulu.

Various effects observed in Honolulu (from which the detonation was visible in the sky) were attributed to the explosion. It can be difficult to sort out which of these reports are accurate, as something as dramatic as a nuclear detonation tends to get tied up with all kinds of unrelated events in people’s memory. One thing that was particularly widely reported, though, was streetlights in Honolulu going dark at the instant of the detonation.

Was this actually an example of EMP having a significant effect on a civilian power distribution system, as has long been theorized but seldom validated?

The answer, it turns out, is yes and no. Honolulu, like many jurisdictions in the early ’60s, made extensive use of series-wired street lighting circuits. Also like many municipalities, Honolulu had gone through growth and changes that resulted in various ad-hoc and sometimes confusing adjustments to the electrical distribution system. Part of this had involved changes in distribution voltage on existing lines, which created problems with the safety separation distances required between lines of different voltages attached to the same pole. The result was somewhat odd arrangements of lines on poles which complicated the installation of street lighting circuits.

On some Honolulu streets, it had become impractical to install series-wired street lighting circuits at medium voltage (6kV being fairly typical) and still have adequate safety separation from 240v split secondary wiring supplying power to homes. Honolulu adopted a solution of mixing series-wired high-voltage and parallel-wired low-voltage street lighting. On residential streets with crowded poles, street lights ran on 500v so that their lines could be run directly alongside the residential power supply.

At this point in time, the modern norm of photocell switches installed on each light did not yet exist. Instead, streetlights were turned on and off by mechanical timer switches (or occasionally manual switches) attached to the constant current regulators. So, the 500v lighting used on residential streets still needed to be connected to the series-wired system in order to run off of the same controls. The solution, which simplified the cabling in other ways as well, was to power the 500v constant-voltage lighting off of the 6.6A constant-current system. This was implemented by connecting autotransformers to the series-wired system that reduced the voltage to 500v. The constant-current regulator meant that the autotransformer could cause an arbitrary voltage drop, at 6.6A, as necessary to provide adequate power to the 500v lights connected to it.

Essentially, the autotransformer acted as a particularly large 6.6A light on the series circuit. This made it subject to the same series disadvantage: if the autotransformer failed, it would cause the entire series circuit to shut off. The solution was to equip the autotransformer with a cut-out disk just like the lights, albeit one rated for a higher voltage.

It was determined that the street lights which failed in response to the Starfish Prime EMP all seem to have been the low-voltage lights attached to constant-current circuits. Perhaps you can see what happened.

Some of the low-voltage lighting circuits were positioned such that their length was oriented perpendicular to the EMP field. The altitude and location of the detonation was such that the EMP field reached Honolulu with horizontal polarization nearly parallel to the ground. The combination of these factors created a near-worst-case for induced voltage in certain low-voltage lighting circuits. The induced voltage backfed the autotransformer, resulting in a higher voltage on its constant-current side that fused the cut-out disk, shorting the autotransformer and cutting off the power supply to the low-voltage lighting circuit.

The solution was simply to replace the cut-out disk.

This should illustrate two things about the effects of nuclear EMP: First, it is possible for nuclear EMP to have damaging effects on power infrastructure. Second, it is not especially *easy* for nuclear EMP to have damaging effects on power infrastructure. The Honolulu incident resulted from a specific combination of factors, and specifically from the use of a “weak-link” design element in the form of the cut-out disks, which performed as expected in response to an unusual situation.

None of this is to say that EMP effects are insubstantial, but they are mostly confined to digital and especially telecommunications systems due to their far higher sensitivity to induced voltages. Power systems with long enough wiring runs to pick up substantial induced voltages also tend to be designed for very high voltages, making damage unlikely. The same cannot be said of telephone lines.

By the ’60s series-wired constant-current lighting systems were falling out of favor. The future was in mercury-vapor lamps running at 240v and controlled by local photocells, so that they could be powered directly off of the secondary distribution lines. This is still basically the arrangement used for street lighting today, but mercury vapor has given way to LED.

Constant-current lighting still has its place. While airfield marker lighting is mostly being converted to LED, it’s still generally powered by constant-current loops. Many airfields still use 6.6A tungsten bulbs, which were at least perceived to have reliability and visibility advantages until relatively recently. Airfield constant-current regulators usually provide three (occasionally more) output settings with different target currents, allowing for a low, medium, and high intensity. While less common with today’s better marker light optics, you will still sometimes hear pilots ask the tower (or use radio control) to turn the lights down.

When it comes to LEDs, most non-trivial LED lighting is actually constant-current. The use of a small solid-state constant-current regulator (usually called an LED driver in this context) improves efficiency and lifespan by keeping LEDs at an optimal current as temperature and supply voltage changes.

Despite staying reasonably close to their ’70s state, streetlights have become hubs for technology projects. They’re convenient, widely-distributed power sources that are either owned by the city or operated on contract for the city. Many “smart city” technologies like environmental sensors and WiFi/municipal LTE/smart meter radios are offered in packages intended to be clamped directly onto streetlights and powered by tapping their cables. The fairly standardized screw socket used for photocell switches on street lights has itself become a form of power outlet, with some smart city devices screwing in to use it as a power feed and incidentally also turning the light on and off.

In this way the line between “light controller” and “sensor package” can become blurry. The City of Albuquerque now installs networked controllers on new street lights that primarily allow for remote monitoring and management of the light itself--but also support environmental data collection and traffic monitoring via Bluetooth sniffing.

The humble street light today reminds me a bit of the cigarette lighter socket in cars... barely changed in decades, and yet a major factor in enabling a huge technology market.

Or at least that’s an optimistic way to look at it. The pessimistic way is to observe that we now live in a world where streetlights are being repurposed to detect gunshots. Cheery.

Addendum: I am not personally a fan of aggressive street lighting. It tends to create a substantial light pollution problem that is thought to contribute to health problems in humans and environmental disturbances. Further, it’s been the common wisdom for some time now that street lighting is likely not actually effective in reducing crime. That said, a recent 2019 study conducted in New York City is the first randomized controlled trial of the impact of additional street lighting on crime, and it actually did find a reduction in crime, and not a small one. That stands in opposition to a history of studies that have not found any crime reduction, but none of those studies were as rigorously designed. Hopefully more research will be conducted on this question.

[1] Incandescent street lights are typically the ones fondly remembered as “historic” street lamps anyway, with many “antique style” streetlamps installed in historic districts today being loose replicas of various common incandescent models, such as the GE or Novalux “acorn” glass globes with frilly metal reflector. That is, assuming they are replicas of electric and not gas fixtures, although makers of vaguely historic light fixtures often mix the two anyway.

[2] Much of the information on this incident comes from the aptly titled “Did High-Altitude EMP Cause the Hawaiian Street Light Incident?”, SAND88-3341. Charles Vittitoe, Sandia National Laboratories, 1989. As far as I can tell this paper, prepared well after the fact, is one of the only detailed case reports of a real EMP incident in the public literature. The fact that there was, reportedly, very little rigorous investigation of the Starfish Prime test’s EMP effects in Hawaii for over twenty years after has interesting implications on how seriously EMP effects on civilian infrastructure were taken at the time.

[3] I discuss this topic a bit more in my YouTube video on EMP simulation facilities at Kirtland Air Force Base.