The development of electric light

Some aspects of efficiency in the production of electric light

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In a contribution of a group engaged in the historical aspects of electrical engineering, it shouldn't come as surprise if the history (or etymology, for that matter) of the word efficiency is given some attention.

The term efficiency is directly related to the term effect, which comes from the Latin ex (from, resulting from) and facere (to do, to make). Hence, effect is the result of an action. In the Concise Oxford Dictionary, the term efficiency is described as "the state or quality of being efficient, (Mechanics & Physics) ratio of useful work done to total energy expended or heat taken in". Hence, the term efficiency introduces a relation between two issues: roughly spoken: "the work done versus the actual result". In the Concise Oxford dictionary, the field of application is already confined to Mechanics/Physics, which means that we are rapidly inclined to think of effective power related to total power (power factor). In this contribution, we will briefly discuss the evolution of the efficiency when converting electrical energy into light.

How electric light evolved

In the past two centuries, the conversion of electrical energy into (visible) light has shown a tremendous increase in efficiency, i.e., the fraction of electric energy that is converted into light, often expressed in terms lm/W (lumen per Watt). The remaining energy is converted into lost heat. In the early nineteenth century, it was discovered that an electric current passing through a thin filament could produce light (e.g. in an incandescent light bulb). However, the efficiency of an incandescent light bulb is in the order of 2 - 3 %. The efficiency could be improved to around 5 - 10 % by placing the filament in a high-pressure halogen filled bulb. In particular, a quartz bulb showed to be the most efficient since this allows for much higher filament temperatures. A different principle for the production of light is used in the electric arc lamp, in which an electric arc causes vaporized carbon to produce an intense light stream. The efficiency of this lamp is in the order of 5 – 10 %. Again, the remaining energy produced heat. A problem with the latter light source is the production of a significant amount of UV-light, which makes it hazardous if a direct view of the actual arc is possible. Figure 1 shows a carbon arc lamp as present in the EWI Historical Collection. Two individual carbon electrodes are shown as well.

A much higher efficiency could be obtained with the fluorescent lamp, developed in the twenties and thirties of the last century. These lamps are mercury vapor filled glass tubes with a phosphor coating on the inside. An electric current generates UV-light which causes the phosphor coating to glow in the visible part of the spectrum. The efficiency of this light source is in the order of 30 %. This improvement led to the production of Compact Fluorescent Lamps (CFL) that could easily replace filament lamps. Some examples of fluorescent lamps, a CFL-lamp and a typical LED-bulb (to be discussed below) are shown in figure 2.

Figure 1. An electric arc lamp and two carbon rods as present in the historic collection of the Faculty EEMCS (photo: Han Geijp).

So far, electrical production of light could be envisaged as the production of heat with light as a (highly desired!) side effect. In the early 70's of the last century, it was shown that in some semiconductor PN-junctions photons are produced under the influence of an electric field. The device showing this behavior was called LED (Light Emitting Diode). These first LED's, however, were useless for practical applications as a light source since they produced just one color. However, in terms of efficiency, the principle was very promising. It was only in the first decade of this century that practical (i.e. producing broad spectrum visible light) LED-based lamps could be produced. Nowadays, LED-based lamps are flooding the market and are more or less becoming a standard, which is not surprising if we realize that their efficiency is in the order of 50 % or more and that they produce some 150 lm/W, with experimentally even 200 lm/W!

In summary, the efficiencies of different light sources are shown in the table. Interestingly, the order in which they are listed corresponds to the historical order of appearance.

Tabel 1. Different light sources with their efficiency.

Type	lm/W
Electric arc	3
Incandescent	14
Halogen	17
CFL	55
LED	150

Figure 2. An electric arc lamp and two carbon rods as present in the historic collection of the Faculty EEMCS (photo: Han Geijp).

Reactive and non-linear light appliances

So far, we have discussed efficiency in terms of the light producing the fraction of energy dissipated by the device. This energy is usually delivered by the electrical network (mains). In case of linear resistive devices (i.e. exhibiting a linear relation between applied voltage and resulting current, and no phase shift between voltage and current), all delivered energy is dissipated by the device (in the form of both heat and light). Incandescent light sources are linear resistive devices.

Halogen lamps, CFL's and LED-lights cannot directly be connected to the mains but need a (usually built-in) converter to transform the 230 V 50 Hz AC voltage into a suitable voltage or current. These converters give rise to reduced efficiency, which is due to their reactive and often, non-linear load to the network. Therefore, when discussing the efficiency of these devices, we have to introduce another factor of interest, i.e. the *power factor*.

First, consider a device exhibiting a reactive load. It is well known that the real power P (as dissipated by the load) is related to the apparent power S (as delivered by the mains) through:

$$P = S \cos \phi$$

in which ϕ represents the phase shift the between voltage and consequent current. See figure 3. The so-called power factor η is now defined as:

$$\eta = \frac{P}{S} = \frac{V I \cos \phi}{V I} = \cos \phi$$

where V is the effective value of the applied voltage and I the effective value of the resultant current. Obviously, $\eta \leq 1$. However, if the load is non-linear, things become a bit more complicated. In a non-linear load the current is distorted. This means that the periodical mains voltage V gives rise to a number of harmonic components I_n $(n = 1,2,3,4,\ldots)$ such that the RMS value of the total current I follows from:

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots}$$

where I_1 is the first harmonic (same

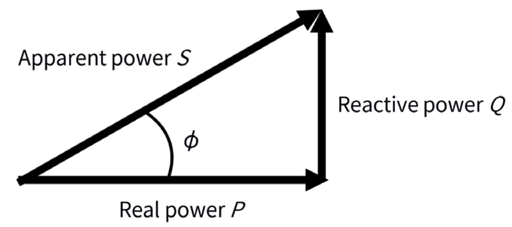

Figure 3. The power triangle with ϕ the phase shift between applied voltage and the consequent current.

frequency as the mains voltage V). A measure for the harmonic distortion is THD (Total Harmonic Distortion), obeying:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots}}{I_1^2}$$

Since only the first harmonic I_1, being in synchrony with the applied voltage, contributes to the consumed power P, the power factor now becomes:

$$\eta = \frac{P}{S} = \frac{V I_1 \cos\phi}{V\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots}}$$

$$= \frac{\cos\phi}{\sqrt{1+(THD)^2}}$$

When no harmonic distortion is present, $THD = 0$ and consequently $\eta = \cos\phi$.
In conclusion, the power factor η is reduced with:

- increasing phase shift between voltage and current.
- increasing harmonic distortion.

Early fluorescent tube appliances had typical power factors of 0.3. LED-appliances also showed poor power factors, mainly due to a high THD. This heavy distortion introduced serious noise on the mains, a reason for incidental disturbances in equipment sensitive to RF-interference.

Though a poor power factor may be of less importance when only a few LED-systems are employed, undesired reactive power and/or RF-interference can be introduced if a large number of incandescent light systems are replaced by LED systems. Fortunately, over the recent years the converters for driving LED-light systems have drastically improved, so that, nowadays they show power factors in between 0.9 and 0.95.

Conclusions

In this contribution, it has been shown that the development of light sources has shown a drastic improvement when looking at the efficiency of the conversion of electrical energy into light. Care should be taken when the appliances form a reactive and/or a non-linear load to the mains network, because this may introduce loss of efficiency. This may be overcome by appropriate measures as is usually the case nowadays.

Acknowledgement

The useful remarks and consequent discussions with Kees Pronk are gratefully acknowledged.

The Studieverzameling (the historic collection of the faculty EEMCS), which can be found in the basement of the low rise building since November 1969, houses an extensive collection of nostalgic, mostly electronical, equipment.

The collection includes various objects in which electrical engineering took such an important role in our lives. Developments in sound and vision, calculators, typewriters, telephony, photography, high voltage, radar technology, navigation systems, measurement and control equipment, vacuum tubes and computer, just to list some topics. Also a lot of books, magazines and documentation are in the collection.

The historic collection of EEMCS is open for visits on Mondays from 10:00 till 16:00. The volunteers will welcome you with much enthusiasm.

From the Study Collection EWI: PASCAL (Philips Akelig Snelle CALculator) from the end of the 50s. This computer once was the fastest computer in the world. It consists, among other things, of 1250 dual triodes, 10000 germanium transistors and 15000 germanium diodes. In operation it uses approxamatly 10kW.