Some observations regarding leading-edge dimmers

The German Federal Minister for the Environment would like to ban the use of incandescent tungsten-filament light bulbs. For instance, one of the issues raised is that of dimming. As most of the dimmers installed are used to control incandescent bulbs, it's worth taking a closer look at the issues involved.

It's fair to say that a tungsten-filament incandescent light bulb is, relatively speaking, a first-class waster of energy. Any type of fluorescent lamp can produce the same amount of light as an incandescent bulb, but using a quarter of the power – a 75 % saving in energy! That is in itself a pretty impressive figure.

1 Compact fluorescent lamps and their effects on power quality

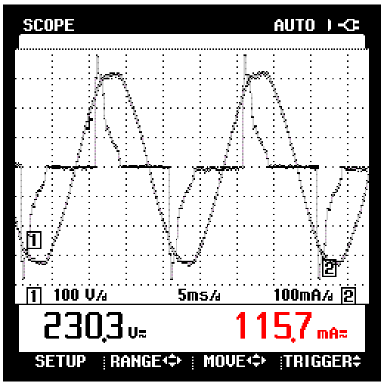

Fig. 1: Current in a 21 W compact fluorescent lamp: 115.7 mA

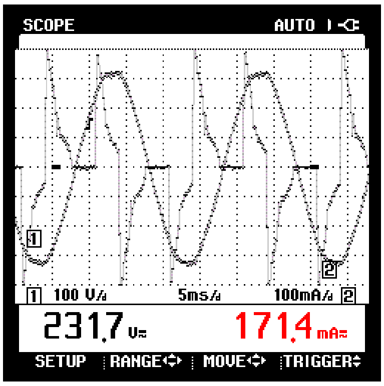

Fig. 2: Current in the neutral conductor when two 21 W CFLs are connected to a two-phase supply: 171.4 mA (plot shows the voltage of L1 relative to N and the current in N)

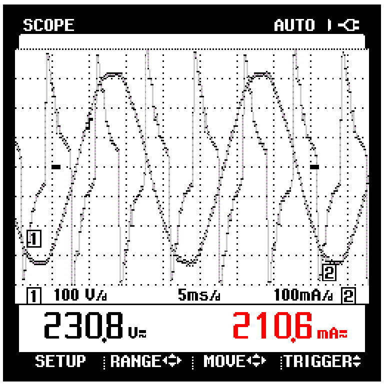

Fig. 3: Current in the neutral conductor when three 21 W CFLs are connected to a three-phase supply: 210.6 mA (plot shows the voltage of L1 relative to N and the current in N)

There is widespread unease about whether the harmonics generated by compact fluorescent lamps (CFLs) could 'pollute' mains power quality if, as has been proposed, all the incandescents currently in use were to be replaced by CFLs. However, if the actual 'mains pollution' potential of this scenario is calculated, it turns out that no significant deterioration in power quality is to be expected. According to Osram, around 11 % of the electrical energy generated in Germany is used for lighting. But about 75 % of the light is already being generated by fluorescent lighting, which consumes only about half of the 11 %. These figures give one a rough estimate of the energy efficiency of fluorescent lamps. And compact fluorescent lamps are not the only alternative to incandescent bulbs. For instance, a variety of high-pressure discharge lamps (with efficiencies similar to those of CFLs) are used predominantly in street lighting. LED lamps are also being used increasingly as an alternative to traditional tungsten-filament light sources. But it is easy to be dazzled by conventional incandescent lamps. Their importance as a modern light source is often overestimated by consumers because these lamps are still the main form of domestic lighting. Interestingly, the level of illumination in most homes is several times lower than what is officially prescribed for work spaces or is desirable in, say, sales areas. The level of brightness specified and necessary for the working environment is often perceived as uncomfortably bright for a domestic living space. So it is not 11 %, but more like 2 % of the electrical power generated in Germany that is actually used at present to power incandescent lamps. And if at some future date, these incandescent bulbs were all to be replaced by CFLs, they would consume not 2 % but only 0.5 % of the electrical power generated in Germany due to their greater efficiency. It therefore seems unlikely that replacing those tungsten-filament lamps still in use by CFLs will cause significant power quality issues. While no problems have as yet arisen from the use of CFLs in private households, the situation is different in other residences, such as hotels. Some hotels previously replaced all their old tungsten-filament bulbs with CFLs with the result that a large number of these non-linear loads were present in a relatively confined space. This can cause overloading in the neutral (return) conductor because even if these non-linear loads are distributed symmetrically between the three phase conductors, the currents will not sum to zero in the neutral conductor. In low-voltage distribution networks designed with a TN-C or a TN-C-S earthing system, this can result in significant currents in extraneous conductive elements such as the shielding of data transmission cables (Fig. 1 to Fig. 3).

2 Dimming: The conflict between convenience and energy efficiency

Dimmer systems for incandescent lamps are becoming increasingly popular in homes. But home owners are not looking to reduce light levels to save energy, they simply want to have local control of the brightness levels in their rooms. Quite apart from the fact that the Minister for the Environment doesn't seem to have realized just how badly the (often-not-so-) compact fluorescent lamps fit into conventional lamp holder sockets, and just how long it takes for a CFL fitted in a spare bathroom or an understairs cupboard to actually pay for itself, there is also the fact that CFLs are typically not dimmable. Of course, the exception proves the rule – (see 'How efficient are compact fluorescent lamps?' on this website) Nevertheless, the fact that CFLs are seen as non-dimmable, is often enough to prevent them being used as replacements for conventional tungsten-filament bulbs in living areas.

A wide range of dimmers are available not just for incandescent bulbs that run directly off the mains but also for extra-low-voltage halogen lamps. The type of dimmer (trailing-edge or leading-edge) used to control these tungsten-halogen lamps will depend on whether the lamps are driven by an electronic or a conventional transformer. With such a large number of different dimmer systems available, a classification scheme has been introduced and has been discussed in detail in the trade press. Despite the great variety of dimmers on the market, most of those installed are of the leading-edge variety used to control ordinary tungsten-filament lamps.

Large fluorescent lamps can be dimmed if a dimmable electronic ballast is installed. Despite the impression often given in articles in journals and trade papers, electronic ballasts are not always dimmable. One thing that can be said with certainty about dimmable electronic ballasts is that they cost more. But that's not the worst of it: to be dimmable, these ballasts require an extra cable to carry the control signal and this cable is often missing in most existing installations. As a result, dimmable electronic ballasts tend to be installed, if at all, only in new public or commercial buildings. The private householder wanting to dim the lights in his home often has no other choice but to stick with the traditional tungsten-filament lamp or, in the worst case, to go back to using them.

3 So why dim light levels?

As already mentioned, homeowners want to dim light levels for the purely personal reason of greater home comfort; people don't dim lights to save energy. In fact, attempting to save energy by dimming an incandescent lamp is bound to fail because the efficiency of any incandescent bulb drops substantially with decreasing input power (see Fig. 4). In fact, if the decision to use a dimmer means that an incandescent bulb is retained rather than being replaced by a CFL, or worse still, if a CFL already in use is substituted by a tungsten-filament bulb, then the environmental impact is effectively negative, because even at full rated power, the energy efficiency of a tungsten-filament lamp is substantially lower (roughly four times lower) than any type of fluorescent lamp. The relative difference in the energy efficiency of a tungsten-filament bulb and a CFL is more than ten times the relative difference in efficiency between petrol and diesel engines or between the conventional boilers and condensing boilers used in central heating systems.

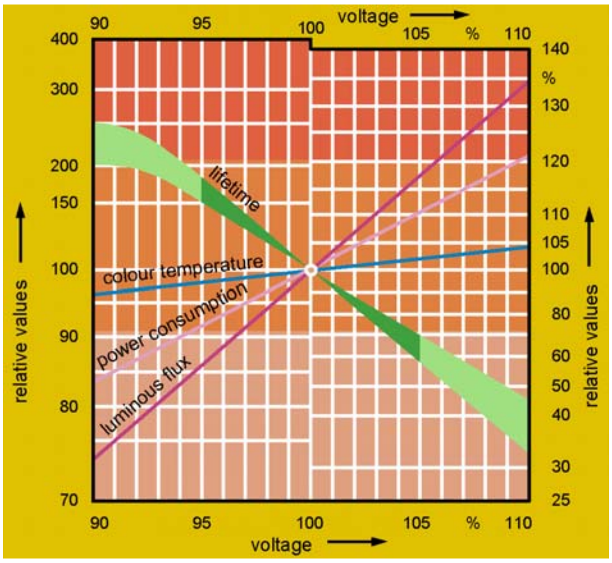

Fig. 4: Dependence of the lamp life and luminous flux of an incandescent lamp on the supply voltage (relative to the rated voltage) (Osram)

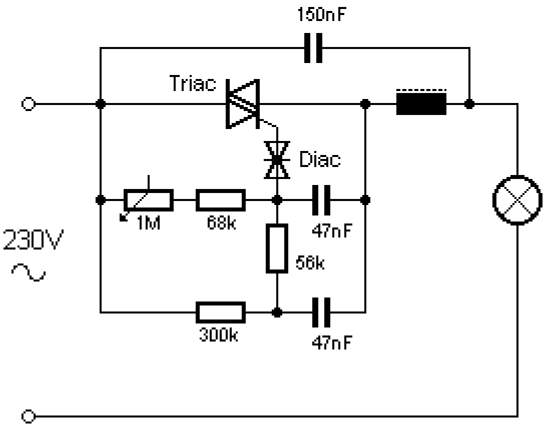

Fig. 5: Circuit diagram of a conventional leading-edge dimmer for an incandescent lamp

4 How dimmers work

In a conventional dimmer, the brightness of the lamp is adjusted by means of a series RC circuit containing a variable resistor (potentiometer). As the RC circuit is connected across the triac, it is at mains potential when the triac is in its non-conducting state (see Fig. 5). A triac is a semiconductor device comprising two thyristors connected in inverse-parallel (‘back-to-back’). Once triggered, a thyristor will continue to conduct (in one direction) until the current through it is stopped by some other means, which in the case of alternating current will occur when the current cycle next passes through zero. At that point the thyristor (or triac) will close, blocking current flow. A diac is connected in series in front of the triac’s gate electrode. A diac is a component that can block current flow in both directions up to its breakdown voltage of around 33 V. As soon as this voltage has been exceeded, current starts to flow and the voltage drop across the diac suddenly falls to about 27 V. This abrupt change in voltage creates a sharp pulse that is perfect for triggering a thyristor or triac. The diac therefore suddenly switches from its high-resistance, non-conducting state to its conducting state as soon as the capacitor has been charged to 33 V (Fig. 5). The voltage across the diac drops abruptly to 27 V, which triggers the thyristor to open, shorting the RC series circuit and thus preventing the capacitor from recharging until the next half of the current cycle is reached. The moment the voltage crosses the zero point, the triac turns off and the whole process begins again but this time with the polarities reversed. By varying the resistance of the potentiometer, the rate at which the capacitor charges can be controlled. The longer it takes for the capacitor to charge up to 33 V, the longer the time delay before the diac (and hence the triac) triggers, and the greater the so-called firing angle of the triac. But this also means that the output voltage of a dimmer can never theoretically be set to be fully equal to the mains voltage (Fig. 7) as the earliest the triac can ever fire is the time it takes for the input voltage to reach 33 V.

5 The side effects of dimming

Some of the side effects of dimming became apparent when the German Copper Institute (DKI) set up its power harmonics demonstration panel (Fig. 6). The panel is used to visualize the different perturbations on the power system that arise when incandescent lamps (both with and without a dimmer) and fluorescent lamps are run on a single-phase, two-phase or three-phase supply. The panel allows the neutral conductor to be connected to a loud speaker. All three dimmers produce a loud crackling noise that is caused by the repetitive firing of the triac and that does not fully disappear even when the dimmer is adjusted to give maximum light (minimum firing angle). By turning the selector switch to by-pass the dimmer, the sound changes to a quiet 50 Hz hum. If all three incandescent lamps are connected to a three-phase supply, the noise disappears entirely. Running three dimmed tungsten-filament bulbs on a three-phase supply is not only noisy, it can also result in the current in the neutral conductor (N) becoming greater than in any of the three phase conductors (L1, L2, L3) depending on the relative dimmer settings. The phenomena discussed above and other measurements (such as those shown in Fig. 12) clearly demonstrate that not only compact fluorescent lamps, but also dimmed incandescents can cause significant harmonic distortion in the local distribution network.

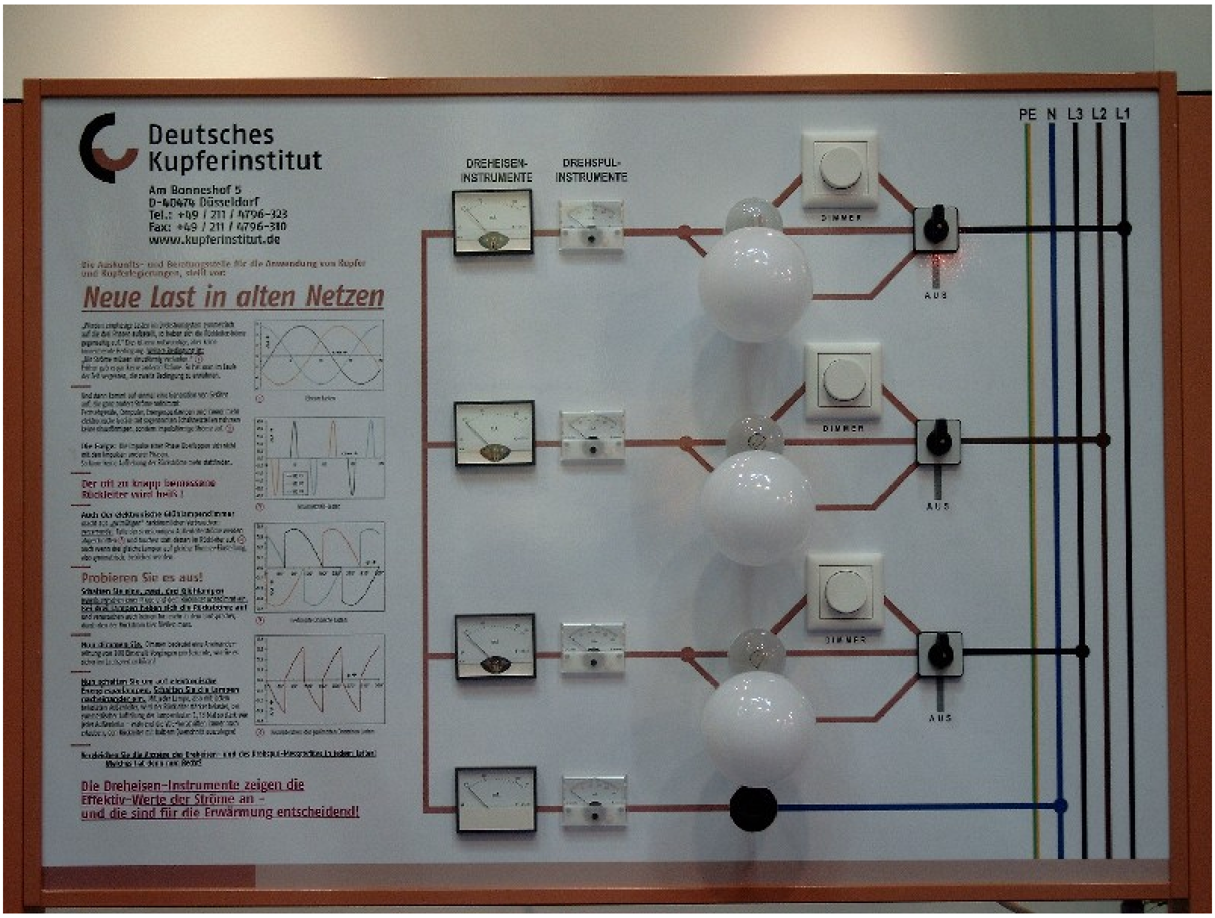

Fig. 6: The DKI's harmonic distortion demonstration panel

The delay between the voltage half-cycle passing through zero and the triac triggering (i.e. the firing angle) depends not only on the setting of the potentiometer (in the RC circuit), but also on the supply voltage. If the resistance of the potentiometer remains unchanged but the supply voltage is lower (Fig. 7), it will take longer for the capacitor to charge up to 33 V. The higher the supply voltage the shorter the charging time (Fig. 8). So if for some reason there is a drop in the magnitude of the supply voltage, all incandescent lamps connected to that supply network will lose brightness, but particularly those driven by a dimmer, because in that case the decrease in the voltage is accompanied by an increase in the firing angle. The dimmer therefore reinforces any drop in the supply voltage. Voltage fluctuations that are not perceptible on an incandescent bulb run directly off the mains can become a nuisance if the bulb is used with a dimmer.

Fig. 9 shows the lamp current in a 200 W tungsten-filament bulb that is receiving half the rated power from a conventional leading-edge dimmer. The fact that the firing angle required to generate half the rated power is not exactly 90° but slightly less is relatively easily explained by the temperature dependence of the filament's resistance. The electrical resistance of a cold tungsten-filament lamp is only about one tenth of its value when the lamp is operating at its rated power and has reached its normal operating temperature. The resistance of the lamp is therefore noticeably lower if driven at half power. In fact, reducing the voltage by only 10 % will have a discernible effect. When a variable voltage transformer rather than a dimmer is used to reduce the voltage applied to the 200 W incandescent lamp to 90 % of the supply voltage (lower tolerance limit: 207 V), the power is measured to be 174 W. However, in a resistive load one would expect a drop in voltage to result in a directly proportional reduction in current, and that the power would decrease with the square of the voltage.

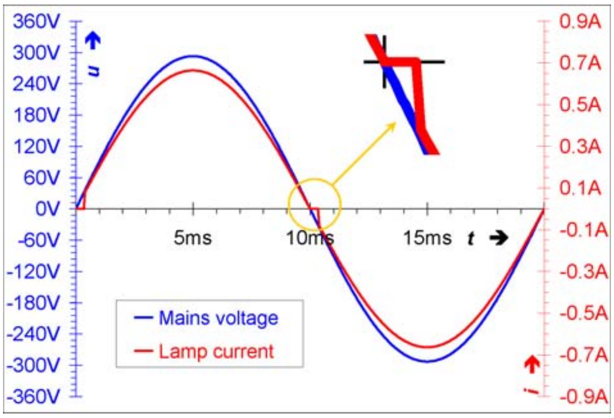

Fig. 7: Lamp current in a 180 W incandescent load controlled by a leading-edge dimmer adjusted to give maximum brightness and connected to a supply voltage of 207 V

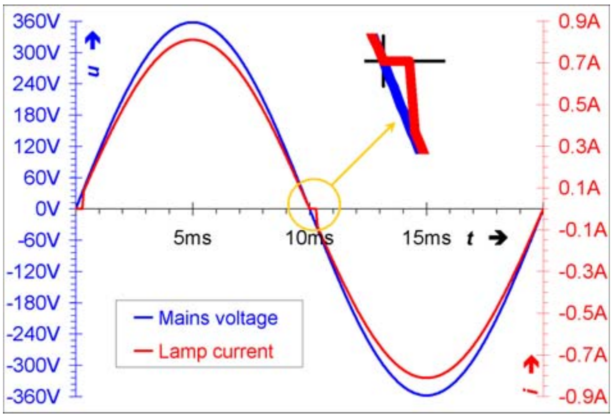

Fig. 8: Lamp current in a 180 W incandescent load controlled by a leading-edge dimmer adjusted to give maximum brightness and connected to a supply voltage of 253 V

The power dissipated in the lamp is therefore expected to be:

$0.9^2 \cdot 200\ \text{W} = 162\ \text{W}$.

When the voltage is raised to 110 % of the rated voltage (i.e. to 253 V), the measured active power is ‘only’ 238 W rather than the computed value of

$1.1^2 \cdot 200\ \text{W} = 242\ \text{W}$.

We now install a dimmer and adjust it to reduce the power dissipated in the incandescent bulb to 100 W. If no change is made to the dimmer setting, but the voltage applied to the bulb is lowered by 10 % from the full nominal supply voltage (230 V) to the lower tolerance limit (207 V), one would again expect the power to decrease from 100 W to

$0.9^2 \cdot 100\ \text{W} = 81\ \text{W}$.

As the temperature of the filament will drop with decreasing power dissipation, the power in the lamp should actually be greater than the theoretical 81 W and is calculated to be 87 W, about half the 174 W measured in the undimmed bulb at 207 V. However, the power measured in this case is only 72 W (Fig. 10). Similarly, if the voltage applied to the lamp is increased to 110 % (253 V), one would expect the power in the lamp to be

$1.1^2 \cdot 100\ \text{W} = 121\ \text{W}$.

If the increased temperature of the filament is taken into account, the expected power in the lamp is calculated to be 119 W or half of the power expected in the undimmed lamp. Measurement, however, yields a power level of 133 W (Fig. 11).

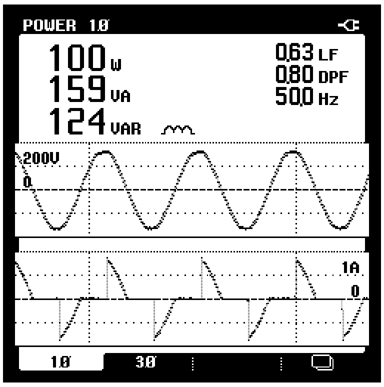

Fig. 9: Current in a 200 W incandescent lamp connected to a supply voltage of 230 V, dimmer set to yield a power of 100 W

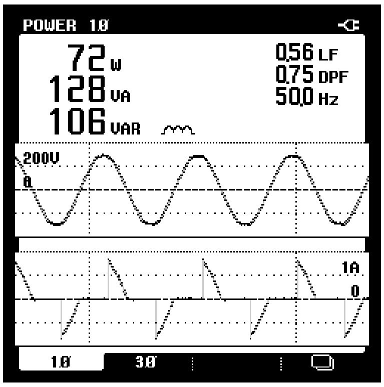

Fig. 10: Current in a 200 W incandescent lamp connected to a supply voltage of 207 V, dimmer setting identical to that in Fig. 9

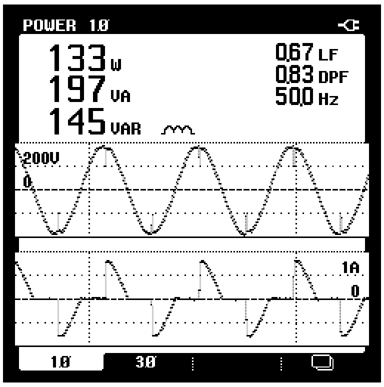

Fig. 11: Current in a 200 W incandescent lamp connected to a supply voltage of 253 V, dimmer setting identical to that in Fig. 9

Careful comparison of the Fig. 9 against Fig. 11 reveals the reason for these discrepancies: the firing angle of the triac has altered even though the adjuster knob on the dimmer was left untouched. As the relative values in the diagrams below show: the higher the supply voltage, the smaller the firing angle.

At a supply voltage of	90% (207 V)	100% (230 V)	110% (253 V)
the power dissipated in the lamp is:			
Theoretical value, temperature effects neglected	81%	100%	121%
Voltage measured on transformer (sinusoidal voltage, temperature effects included)	87%	100%	119%
Voltage measured across dimmer (leading-edge phase control, no readjustment)	72%	100%	133%

The voltages measured on the transformer reflect the influence of fluctuations in the supply voltage on an undimmed tungsten-filament bulb. The voltages measured across the dimmer reflect the relative influence of such fluctuations on a tungsten-filament bulb dimmed to half power.

The momentary voltage sags evident in Fig. 11 (and that are absent from Fig. 9 and Fig. 10) arose because the toroidal-core transformer operating in economy mode could not be adjusted beyond 230 V and a second transformer had to be connected in series. The influence that transformers can have on electrical measurements has been discussed in [1].

Despite the above observations, leading-edge dimmers are suitable for use with inductive loads and can therefore be used to control the brightness of tungsten-halogen bulbs connected to a conventional transformer. While it is known that even minor DC components in the supply voltage can cause excessive currents especially in toroidal-core transformers due to core saturation and DC components in the primary coil, even quite severe asymmetry errors in dimmers do not result in increased current flow – contrary to what one might expect. The two cases are actually quite different from one another and are not comparable at all [2].

If, on the other hand, an electronic rather than a conventional transformer is used to drive the tungsten-halogen bulb, the dimmer should be of trailing-edge design. Trailing-edge dimmers are designed for use with capacitive loads (e.g. electronic transformers) and should not be used with inductive loads (e.g. conventional transformers) as they can cause the triac to fail.

6 Understanding incandescent bulbs

It is perhaps worth reiterating here that a tungsten-halogen bulb is merely another type of incandescent bulb, whose efficiency is only marginally better than a conventional tungsten-filament bulb. Standard tungsten-halogen lamps have nothing in common with compact fluorescent lamps (CFLs, a.k.a. energy saver lamps). The low-voltage halogen lamps are somewhat more efficient than the relatively new mains-voltage halogen lamps, but the savings made are typically lost in the transformer. Which type of transformer consumes the most energy has also been studied and the results will be published in the near future in ‘de’. The reason low-voltage halogen lamps have slightly better efficiencies and the reason they emit a whiter light is because the filaments are shorter and, more importantly, thicker. The low-voltage lamps can be designed with less reserve material as the relative tolerance range is lower and the filament can therefore be designed to operate closer to the melting point of tungsten. This is the same reason why high-wattage tungsten-filament bulbs are significantly more efficient than those that dissipate much less power – the filament in a 200 W incandescent bulb is much thicker than that in a 25 W bulb. In fact the 200 W bulb is almost twice as efficient as a 25 W bulb, and therefore produces not eight but about fifteen times as much light. Running a low-wattage incandescent bulb with a dimmer is therefore particularly inefficient. On the other hand, it is far more efficient to run a low-power incandescent lamp at full power than it is to run a higher power with a dimmer. That in itself is somewhat unusual in electrical engineering. The efficiency of most pieces of electrical equipment is higher if they are not operated at full power. This is also apparent in the case of CFLs, particularly those with magnetic ballasts. While dimming an incandescent bulb feeds less power to the lamp and thus saves energy, the reduction in electrical power is accompanied by a far greater relative drop in the intensity of the emitted light. Often, only a small reduction in the power fed to the lamp will produce the required drop in light intensity. So, as already mentioned, dimming is not a particularly effective means of saving energy. However, it can drastically lengthen lamp life (see Fig. 4).

The following caveat applies to halogen lamps: the halogen cycle responsible for the extended lifetime of halogen lamps may be interrupted if the operating temperature is too low. The quartz envelope of a tungsten-halogen lamp is filled with a halogen, such as bromine [3]. The tungsten that vaporizes from the hot filament cools as it moves away from the filament and combines with the bromine to form tungsten bromide. Because tungsten bromide remains in the gas phase, it does not condense or sublime on the inside of the quartz envelope. If no halogen was present, the tungsten vapour would indeed deposit on the inside of the envelope, making the lamp more and more opaque with time. Eventually the tungsten bromide molecule will find itself in the vicinity of the hot filament again, where it will thermally decompose. The tungsten atom released will either be redeposited on the filament or it will move away from the filament where it will once again form tungsten bromide. However, if the lamp is not hot enough, this vaporization / deposition cycle cannot occur. Most manufacturers provide information on how far the power to the lamp can be reduced before the tungsten-halogen regenerative cycle will no longer operate.

7 Reactive power and dimming

Several years ago ‘etz’ published an article [4] (by an author with plenty of practical experience) in which it was claimed that reactive power associated with the fundamental harmonic cannot be generated when dimming a resistive load, because the instantaneous power is never negative; the current and voltage are always in phase and therefore always have the same sign. True enough. However, a number of academics argued, and offered calculations to back their case, that the fundamental mode of a current waveform that has been chopped by the dimmer circuit will lag behind the waveform of the supply voltage – and that constitutes reactive power. Also true – so who or what is right? As Fig. 12 shows, it’s all a question of where and what you choose to measure. If the voltage is measured immediately behind the dimmer, the voltage and current waveforms are essentially identical. Although neither the voltage nor the current is anything like purely sinusoidal in form, the displacement power factor (DPF or cosφ) and the power factor (PF or λ) are both measured to be equal to one. If the voltage is measured on the supply side, both the DPF and the PF are now less than one, though the latter is significantly smaller than the DPF (cosφ) value. This indicates the presence of both harmonic reactive power, hardly surprising given the distorted (non-sinusoidal) nature of the voltage and current waveforms, and conventional fundamental reactive power. One aspect that is somewhat confusing is that when the voltage is measured across the dimmed lamp (Fig. 12, top), both the DPF and PF are shown to be equal to one even though the voltage and current waveforms are highly distorted. But we'll happily leave the solution of that particular problem to the academics.

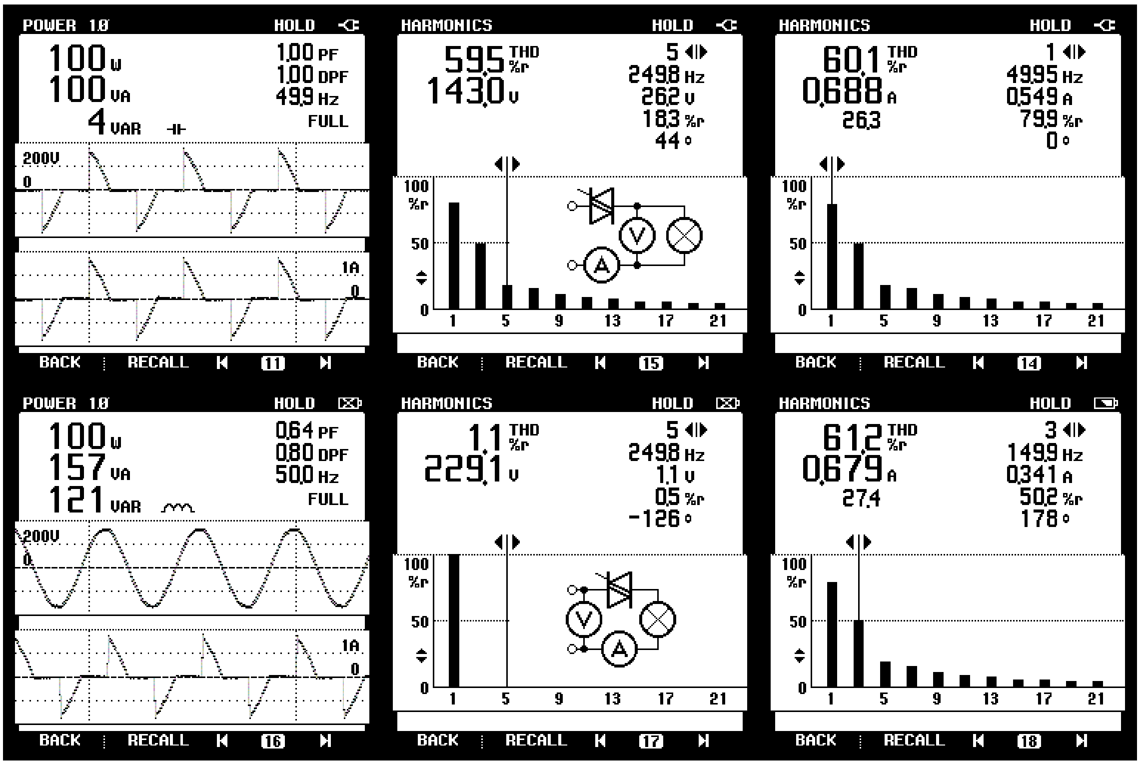

Fig. 12: Does a leading-edge dimmer generate fundamental reactive power? The answer depends on what and where you measure.

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[1] Stefan Fassbinder: 'Ungewöhnliche und unerwartete Messfehler (3)' *['Unusual and unexpected measurement errors']* in de, vol. 7/2004, p. 26

[2] Stefan Fassbinder: 'Netzstörungen durch passive und aktive Bauelemente' *['Supply system distortion from passive and active circuit components']*. VDE Verlag, Offenbach, 2002

[3] The halogens (Greek: 'salt former') comprise the elements in Group 7 of the periodic table: fluorine, chlorine, bromine, iodine and astatine.

[4] Hofmann, W.: 'Blindleistung sichtbar gemacht' *['Making reactive power visible']* in etz, vol. 120 (1999), no. 10, p. 18–21; and Glavitsch, H.: letters to the editor (in response to Hofmann, W. ibid.) in etz, vol. 120 (1999), no. 15, p. 74