Some basic facts and some advanced information on ballasts for fluorescent lamps

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1 Introductory notes

Gas discharge lamps, this meaning lamps using the principle to make a gas electrically conductive and thereby light emitting, are a relatively old technique. Especially fluorescent lamps represent a very widespread lighting system. It is not possible to apply the line voltage directly to such lamp, be it AC or DC, a higher or a lower magnitude. Traditionally these lamps have always been operated on AC mains by means of a so-called magnetic ballast, which is nothing more than a reactor or choke, for limiting the lamp current. In recent years, as power electronics techniques came up, an alternative way of operation was introduced, the so-called electronic ballast, which converts the incoming mains frequency into a much higher frequency, usually in the range of 20 kHz to 80 kHz, to operate the lamp with.

The magnetic ballast method creates a huge amount of inductive reactive power, significantly exceeding the magnitude of active power, but this reactive power can easily and cheaply be compensated without risk of any interferences, if done adequately (see section 5). The electronic ballast does not – or should not – produce substantial amounts of fundamental reactive power (displacement power factor DPF or cosφ). It need not but may be designed to operate on different mains frequencies, including DC, and different voltages, thereby also compensating any input voltage variances. The decisive argument put forward for its use is, however, the energy saving achieved, not so much by lower internal losses in the ballast itself, but rather by an efficiency improvement of the lamp when operated at the high frequency supplied from the output terminals of such electronic ballast. For this reason they feed less power into the lamp than a magnetic ballast does. However, electronic ballasts are several times more expensive than the plain passive magnetic models and much more susceptible to certain disturbances and are likely to become themselves a source of disturbances. Unlike the magnetic ballasts, which as a law of physics can follow only one principle of working and only one basic design, power electronics provide a lush choice of design variants and working principles to design electronic circuits for operating fluorescent lamps.

2 The basics of physics

Gases are generally not electrically conductive but may become so under certain conditions, just as any insulant becomes in a way conductive as soon as the breakdown voltage is exceeded. With gases the initiation of conductivity proceeds in three steps. Getting the procedure started at all requires the presence of at least a few charge carriers, traces of which are always present in atmospheric air and other gases, mostly showing up as ions, but also as free electrons. Their quantity is normally too low to get a current flowing. The dielectric strength of gases, however, drops as pressure drops. This looks like a contradiction at first sight, for less gas per volume of course also contains fewer charge carriers per volume, assuming the relative content remains the same. Strangely enough, fewer charge carriers indeed induce conductivity sooner, whenever this happens in a more indirect manner: You have to bear in mind that the conductivity is generated because the ions see themselves exposed to a force in the electric field and are accelerated (Greek ιονειν = to migrate). Of course »migration« is a severe »dis-exaggeration« in this context. In fact the »migration« speed of the particles is to be measured in kilometres per second. Ions may have been detected in aqueous solutions first, where indeed they just creep along at less than 1 millimetre per second like electrons in metallic conductors, wherefore they may have been called ions.

If the charged particles reach their target and get into touch with the electrode, they give away their charge and become a neutral molecule or atom, respectively the free electron is absorbed by the electrode metal. The way to get there, however, is not an easy one. Hardly have the charged particles gained some speed, they collide with other, uncharged particles and need to gain momentum again. If the density of air or other gas is very high, the next collision will occur rather soon before the ion has gained any nameworthy kinetic energy. But as density decreases the average free length of flight increases and thereby also the likelihood for the ion to gain enough kinetic energy to hit one or more electrons out of the next struck gas molecule, or to smash same gas molecule and thus generate two or more new charge carriers. As soon as at average each charge carrier before reaching the respective electrode has generated more than one new charge carrier an avalanche effect starts, and this explains why for operating fluorescent lamps and for light arc welding appropriate measures have to be taken to restrict the current flow: A plasma has been generated, which is to say a mixture of gas molecules in their original unchanged state with substantial shares of ions and free electrons. These individually travel from one electrode to the other, the positive ones in the opposite direction as the negative ones, forming the current flow, which in atmospheric air now only more takes some 30 V to maintain, at high current densities even less than that. In this state the plasma protects by contracting and separating itself from the surrounding air through the magnetic forces of the current, which enhances the current density and reduces the heat dissipation. It must not be forgotten, however, that at these extremely high temperatures a lot of heat is dissipated through heat radiation. Heat dissipation through radiation increases by an exponent of four with absolute temperature!

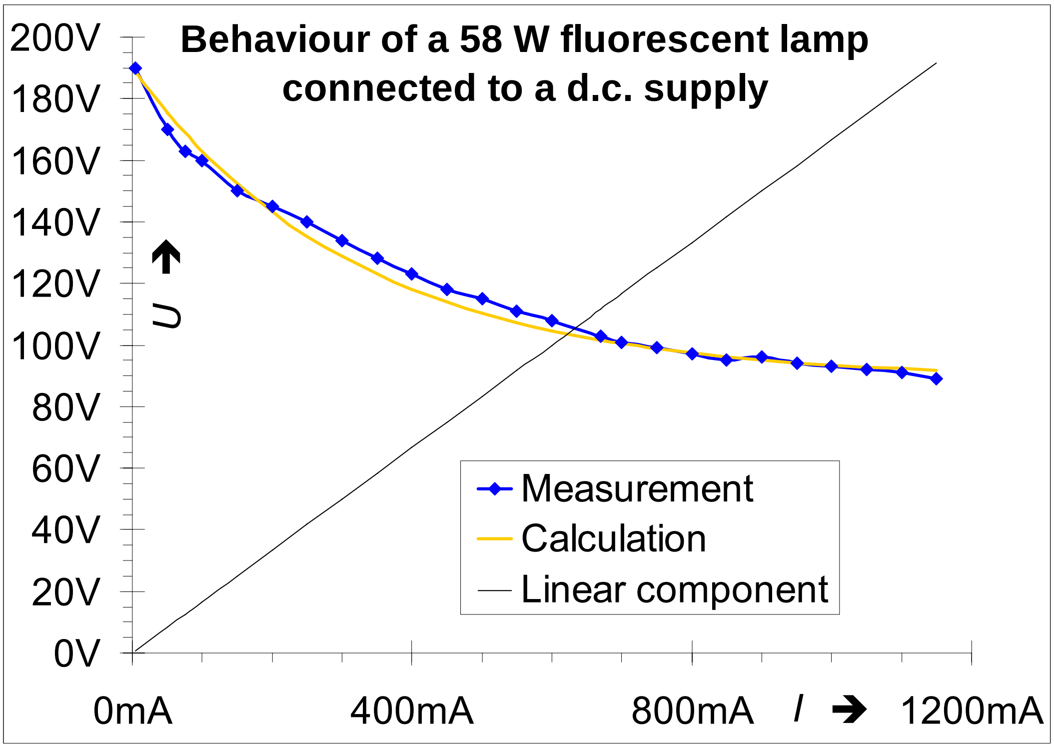

Fig. 2.1: Characteristics of a 58 W fluorescent lighting tube, measured with DC and approximated with an empirical formula

But this is already the final stage of conductivity in a gas. The first stage occurs at very low current densities around 10 nA/mm² and without any light emission. The second is the glow discharge stage at current densities up to about 1 mA/mm² and is thereby the one that is used in electric luminaires from the glow lamp to the fluorescent lamp. The working principle is the same in both types of luminaires. In the fluorescent lamp the luminous section of the gas column is artificially very much extended. The light itself is ultraviolet and therefore invisible but causes the fluorescent layer inside the tube to shine. So by varying the composition of the layer the colour of the light can be varied. The third stage then is the one called light arc, ranging up to some 10 A/mm². What all of the three stages of gas discharge have in common is that the voltage required to sustain the current flow drops as current increases. Ohm's Law seems to be perverted into its opposite. With some justification you could speak of a »negative resistance«, for the differential quotient du/di indeed is negative (Fig. 2.1). However, this seems comprehensible in this case, since the higher the current, the more charge carriers are generated.

3 The working principle with magnetic ballasts

3.1 Important for getting started: The correct starter

When commonplace line voltage, 230 V 50 Hz or something similar, is applied to a fluorescent light tube, normally nothing will happen. The withstand voltage of the gas inside, usually low pressure mercury vapour, 1.3 mg in a 58 W tube, is higher. When the filaments are being heated, they start to emit additional electrons but this still does not suffice to reduce the breakdown voltage below the regular periodic peaks of the mains alternating voltage. With a cold 8 W T5 type lamp (room temperature) self-ignition without any sort of firing was observed at 480 V TRMS (≈680 V peak). This value could be reduced to 380 V by pre-heating the filaments with a separate transformer. A 58 W tube was found to start off from the cold state at 1300 V sine wave, dropping to 550 V with pre-heated filaments. A further reduction occurs when the voltage is applied strikewise, from 0 to full, instead of slowly increasing it by means of a variable transformer, but still self-start at 230 V 50 Hz does not occur. Therefore a starter is connected in parallel with the lamp, usually the commonplace glow starter (Fig. 3.1), with any luck an electronic starter (Fig. 3.2). The basic wiring is given in Fig. 3.3. When applying the mains voltage a glow discharge is initiated inside the glow starter (Fig. 3.4) which heats up the bimetallic contacts and causes them to close (Fig. 3.5). Now current flows from the mains via the ballast, the cathode filament, the starter and the second filament. This way the cathodes are pre-heated. But since the glow discharge has solely been shorted by the bimetallic contact, the bimetallic contact cools down and opens again few seconds after closing. By interrupting the current through the (relatively great) inductance of the ballast a substantial voltage surge is generated across the ends of the fluorescent lamp, starting a current flow through the tube (Fig. 3.6).

Fig. 3.1: Conventional glow starters

Fig. 3.2: Electronic starters are available for all possible situations of application

At least this is what you hope. In fact the luminaire is fed with AC, and whether the instantaneous current value at the instance of ignition, that is, of contact opening, is high enough right at that moment to generate a sufficiently high voltage impulse is an open question. But not now does not mean never ever. Since now, if the strike is not successful, the full voltage comes to be applied across the starter's terminals, glow discharge starts again, and a few seconds later the next firing attempt follows and so on until some very fine second the instant of firing coincides with a sufficient instantaneous current amplitude. Only then a small current flow through the lamp is initiated which immediately generates more charge carriers so that the avalanche effect of conductivity increase according to Fig. 2.1 of the gas inside the tube is started. The ballast's inductive resistance now prevents that on account of this conductivity increase also the current increases with avalanche effect right up to the big bang. The voltage across the starter, which at any instance is identical with the voltage drop across the lamp, is now so small that no new glow discharge is initiated in it. At least preliminarily this is so. As the lamp ages, the lamp voltage gradually increases until at some moment it is so high that glow discharge inside the starter does start again (re-closing voltage): The starter is triggered even though the lamp is still in operation and shorts it out. Thereby the lamp is turned off – and of course it is ignited right again. There you have your flashing thunderstorm.

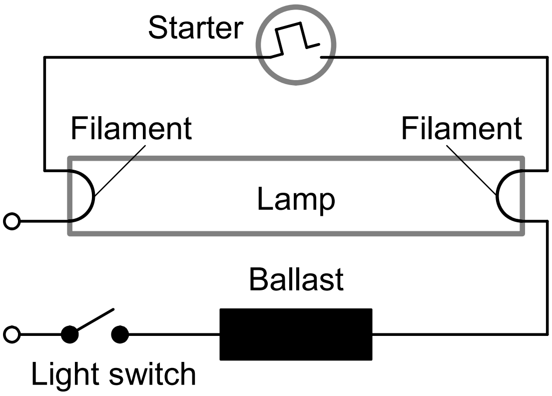

Fig. 3.3: Wiring diagram of a fluorescent lamp with magnetic ballast and glow starter

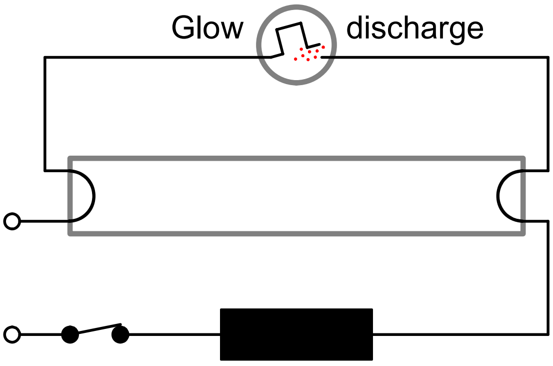

Fig. 3.4: A glow discharge heats up the bimetallic contacts…

So statistically, this primitive, incredible technique called glow starter replaces any one start of a given lamp with several starting attempts, while especially the number of ignitions is reported to be a crucial lamp ageing factor. In fact, a company producing both magnetic and electronic ballasts assigned the designation »deliberately loose contact« to the primitive, commonly used glow starter. Nevertheless it is exactly these that are used in lifetime test procedures of fluorescent lamps, the results of which are proudly presented to the public as featuring a 30% to 40% longer lifetime with electronic ballasts (as far as these are provided with filament preheating, which **with electronic ballasts** does **not** come by default – see Section 3.3)! This result could as well be achieved with electronic starters.

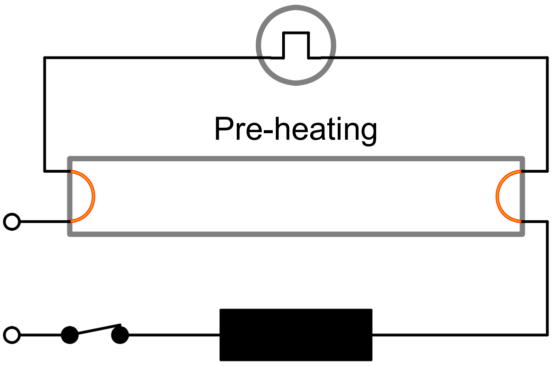

Fig. 3.5: …the contact shorts out the glow discharge, while a current limited by the ballast is flowing through the filaments…

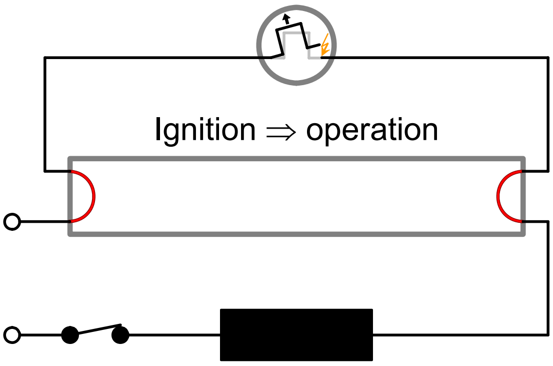

Fig. 3.6: …the contact cools down again, which causes it to open, and a self-induction impulse fires the lamp – hopefully!

During pre-heating, the current exceeds the rated lamp current by about 35%, since it flows only through the reactor (Fig. 3.7, bottom right) – and also through both of the filaments so as to pre-heat them. Their voltage drop, however, is low, only some 10 V, while the great voltage drop across the lamp is shorted out.

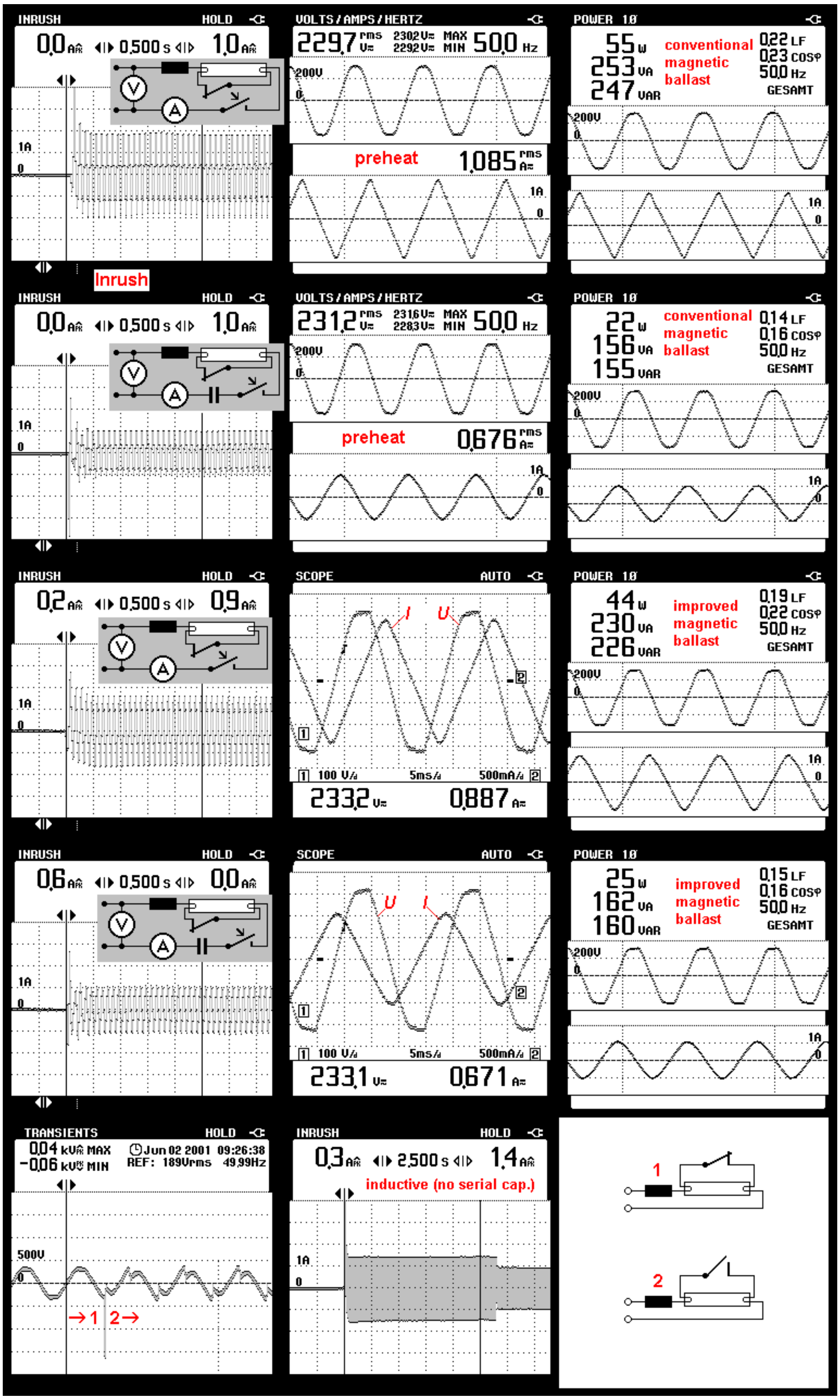

Fig. 3.7: Starting voltage pulse (bottom left), inrush and warm-up currents on a 58 W lamp, rows 1 and 2 with low quality magnetic ballast, rows 3 and 4 with energy efficient magnetic ballast, rows 1 and 3 without and rows 2 and 4 with serial, so-called lead-lag compensation.

With an old poor quality ballast that obviously operated way too close to the range of magnetic saturation, if not right within, the current during cathode heat-up rises clearly more than mentioned 35% above the rated 0.67 A, namely as high as 1.15 A. The heating power of each filament reaches 13.5 W, which makes the filaments shine in a bright white even without any voltage between the two of them applied. This provides more likelihood to get started because the instantaneous current amplitude at the instance of contact opening is more likely to exceed the necessary minimum for ignition, which then also lies lower because of the plenty of free electrons emitted. Unfortunately it also adds to the ageing impact of start-ups if current is really excessive, while pre-heating is basically essential to reduce the wear effect of starting procedures. The much better choice is a combination with an energy efficient ballast, which by design operates still more or less within the linear range of the core material even during pre-heat, and an electronic starter, since electronic starters:

Fig. 3.8: Glow discharge heats up bimetallic contacts, contacts short out glow discharge, cool down again and open …

Fig. 3.9: …and when this game has been going on for long enough, this can be clearly seen when opening the starter (left; on the right an unused sample with filtering capacitor)

Fig. 3.10: In the end of a day (or a week or a month) the contacts weld together, and the lamp persists in permanent pre-heating operation

- Start after optimum pre-heat time for maximum lamp life.
- Start at a defined point of the phase (current peak), so each firing is successful, no flickering.
- No replacement of starters, unlike recommended to do or even required (Fig. 3.10) with conventional glow starters along with each lamp replacement.
- No residual current through the filtering capacitor as contained in a conventional glow starter.

Also improved glow starters already provide a 20% lifetime expectancy increase, but of course the glow technology cannot offer any of the other advantages of electronic starters. All the more amazing it does appear, though, that this polished-up version is being offered by an international lamp and electronics producer,[1] unlike electronic starters, as one should have expected. Howsoever, it makes the lamp lifetime advantage of electronic ballasts dwindle to some 10% or 20%, anyway.

It would lead too far to delve into the electronic details of such starters at this point. The working principle, after all, is the same as with conventional ones (Fig. 3.11): A normally closed contact that opens a certain time lag after powering. Fig. 3.7 shows the current during firing and during warm-up. In rows 2 and 4 a capacitor was connected in series with the lamp and ballast that substantially reduces the warm-up current, which is often argued to be a disadvantage. However, if this is a disadvantage then the circuit, especially the ballast, is poorly designed, which is not attributable to the basically brilliant method of serial compensation (in a so-called lead-lag connection, see Section 5). Indeed the mentioned high pre-heat current with a poor quality ballast drops as low as 0.676 A when serial compensation is applied, which is only more 60% of the prior value. Yet, the same measurements when carried out with a high efficiency ballast provide readings like 0.994 A in the lagging circuit (without compensation) and 0.698 A in the leading circuit (with serial compensation), so the ratio between the two is still 70%.

As a comparison the starting procedure was recorded with the transients recording function of a power analyzer, more precisely speaking the voltage across the ends of the lighting tube was recorded. So the voltage input terminals of the meter were connected to the poles of the starter, which are permanently connected to one of the filaments each.

It needs mentioning at this point that the meter was a usual power quality analyzer with a transients capture function among others, not a dedicated transients recorder. This requires that the device always needs to wait for at least a few mains frequency periods to recognize the amplitude, frequency and waveform of the regular line voltage. Only then can it decide what deviates far enough from this to be called a transient. Everything which – depending on setting – deviates by 20%, 50%, 100% or 200% from its expected instantaneous value is supposed to be a transient and is recorded as such. Unfortunately the threshold value can only be fixed to these per cent values but not to absolute voltage amplitudes. At the first instance of switching a fluorescent lamp on, however, the starter represents a closed switch, shorting the input terminals of the meter, which caused the automatic range selection to step down to the lowest range of 4 V. This did not enable the recording of the transient. Apart from this, the recorder continuously recorded transients, about 2 per second, even when set to 200%, since the voltage across the input terminals was practically 0, and 200% of nearly nothing is still nearly nothing. Any minor coupled disturbance was therefore recorded as an assumed transient.

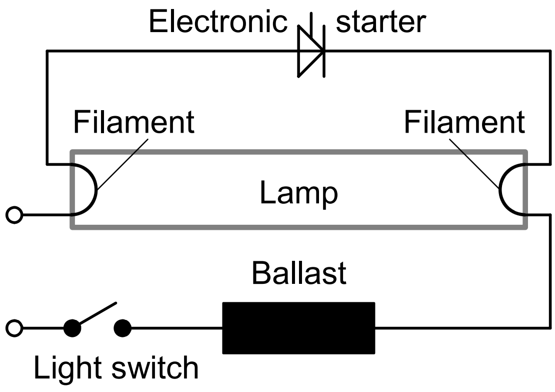

Fig. 3.11: Wiring diagram of a fluorescent lamp with magnetic ballast and electronic starter

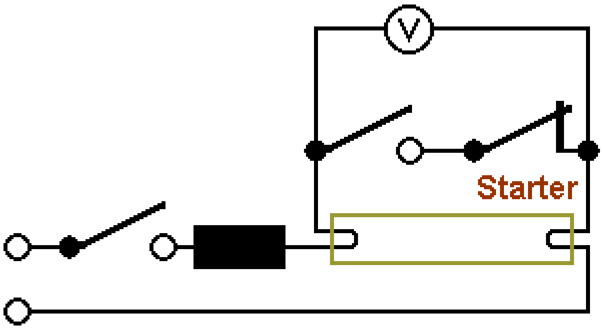

Fig. 3.12: Test circuit for recording the lamp firing transient

Therefore the starter had to be wired in series with a supplementary switch (Fig. 3.12), to be closed only a few seconds after line voltage had been applied to the meter for at least a few seconds, to allow it to adjust to the appropriate voltage range. Only then the transient capture function was activated, and only afterwards the lamp firing was enabled via the switch. The results were pretty unambiguous:

When turning the system on with a glow starter, 6 transients were recorded in total (a mean value – between 1 and 13 recordings were taken during a series of attempts, for glow starters play a game of lottery with the lamp and ballast).

In Fig. 3.13, Transient 1, you first of all recognize the sine voltage across the terminals of the not yet burning lamp and subsequently the closing of the supplementary switch. Obviously its contact bounces and causes a self-induction impulse in the ballast, triggering the meter.

In Transient 2 apparently nothing has happened. In fact a firing process did very well occur, but the transient was minute, since the starter contact opened very close to the current zero crossing. The meter's trigger threshold had already been stepped down at that instance because there had not been any voltage across the input terminals for about half a second, since the starter had already been idling in preheat state with its contact closed. Therefore the trigger threshold had already dropped from 200% of 500 V to 200% of 4 V. As the display scale does not step down as soon as the one for the trigger threshold does but would rather have followed only several seconds later, *this* scale continues to be 500 V/div. For this reason the self induction pulse which was very low in this case cannot be seen in the screenshot but still sufficed for triggering this shot. In fact a noise could be heard inside the starter at the instance of this shot, verifying that any activity was going on inside.

In Transient 3 the procedure of Transient 1 repeats. Here the meter obviously registers the closing of the contacts, because they, too, bounce, but has missed the actual firing attempt, possibly because it struck precisely the current zero crossing.

In Transient 4 the procedures of Transient 2 repeat.

In Transient 5 it is obvious that the starter contact has opened for barely 2 periods of the mains frequency. Again the lamp was not fired, as can be seen from the sinusoidal voltage waveshape in the time section between opening and closing. It has to be doubted that this thermo-mechanically operating component has realized within such a short time span that the firing was not successful and that it has even drawn the right consequences from this and closed the contact again. Rather, it has to be assumed that the contact re-closing would also have occurred if the lamp had been fired successfully, and that the success had thus been made void. This would explain the frequent flashings of fluorescent lamps when fired with such starters. Apart from this it would have been next to a miracle, had this attempt been successful, since at the instance of contact opening as well as of closing a heavy oscillation can be observed, absorbing a substantial share of the energy needed for firing – and dissipating a large part of it as radiated disturbance. Probably the contacts just opened too slowly, so that the energy stored in the ballast discharged between the two of them instead of doing so inside the lamp.

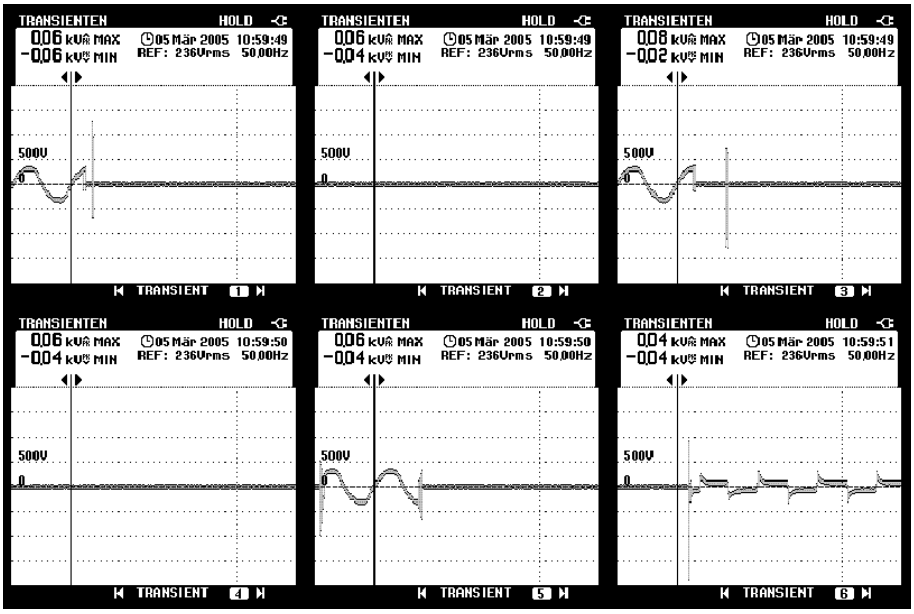

Fig. 3.13: Starting a T8 lamp 58 W with conventional starter

In Transient 6 the approach of trial and error – he who searcheth findeth – it has finally been possible to place a clean self-induction pulse close to the current peak, and the lamp goes into operation. This becomes clear from the typical voltage waveform across the lamp electrodes that shows up on the right side of the ignition impulse.

It has to be seen as quite peculiar, however, that none of the impulses really starts at the time zero line but a few milliseconds later. There must be some latent pre-impulses present, which do not become visible in the diagrams but act as trigger signals. Once again, this underlines the dirtiness of impulses generated in this way.

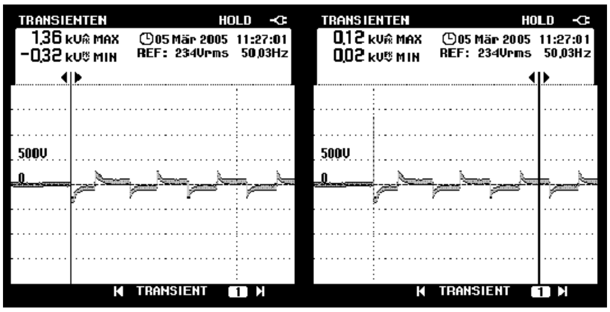

Fig. 3.14: Starting a T8 lamp 58 W with electronic starter

Fig. 3.15: Fluorescent lamps in a residential washroom with magnetic ballasts and electronic starters: Only one lamp replacement within well over 30 years

Fig. 3.16: Removal of the cover reveals: One of the two lamps is still of the old T12 type and still working well

Fig. 3.14, however, provides evidence of how clean such a starting process can be and always will be using an electronic starter. You can take this recording as often as you like, and it will always look alike: There is a high, narrow peak at a precisely defined point of time. For this reason this recording is displayed twice – these are two different views of the same event. In the right view the cursor line was merely moved to the right. This provides the advantage of making the very narrow peak visible at all, whenever it is difficult, since it is very high but extremely narrow, just as it is supposed to be. The left view, on the other hand, provides the opportunity to read (at the top of the screen) that the impulse ranges from -0.32 kV to 1.36 kV. That's enough – and quite sure causes less conducted and radiated disturbances than the multitude of blurred impulses of the glow starter.

In the washroom of a single-family home new lamps were installed around 1970 (Fig. 3.15). The new luminaires were refurbished with electronic starters in their very early days. Since then, one of the lamps has been replaced once and the other one never ever. Neither has any of the starters, of course. You can see that the old 38 mm diameter T12 lamp is still in place and working (Fig. 3.16), while these were taken over by the 28 mm thick T8 lamps already in 1980. The washroom is at the same time the passage to another cellar room so that the lights are switched relatively often, at average about 5 times a day, while the average operation time is low, barely an hour a day. So this lamp has done around 10,000 service hours and 50,000 starts to date.

3.2 Operation

Under the assumption that the voltage be unaffected by any distorted currents from non-linear loads and therefore still sinusoidal, which you rarely ever find these days, the curves theoretically deducted from Fig. 2.1 and the underlying formula look like those in Fig. 3.17: Of course the extremely non-linear behaviour of the lighting tube distorts the voltage measured across the two filaments very much, for while the current is highest the voltage drop is lowest. Yet this voltage is unable to distort the current to a nameworthy extent because the distorting lamp load is connected in series with the very high inductance of the ballast, in this case ≈780 mH, which suppresses current distortion, respectively suppresses the flow of harmonic (higher frequency) currents. So the current curve looks nearly sinusoidal, apart from a crease at each zero crossing. Of course there is a long time lag between the voltage peak and the current peak, which means a high share of fundamental reactive power, but this is by far the minor problem. Real power quality problems arise when the **current** curves in a network become substantially distorted, say having high harmonic contents.[2,3] Fig. 3.18 shows that these characteristic waveforms of the lamp current and the voltage across the lamp do not only occur in the theoretical model but also in practical measurements.

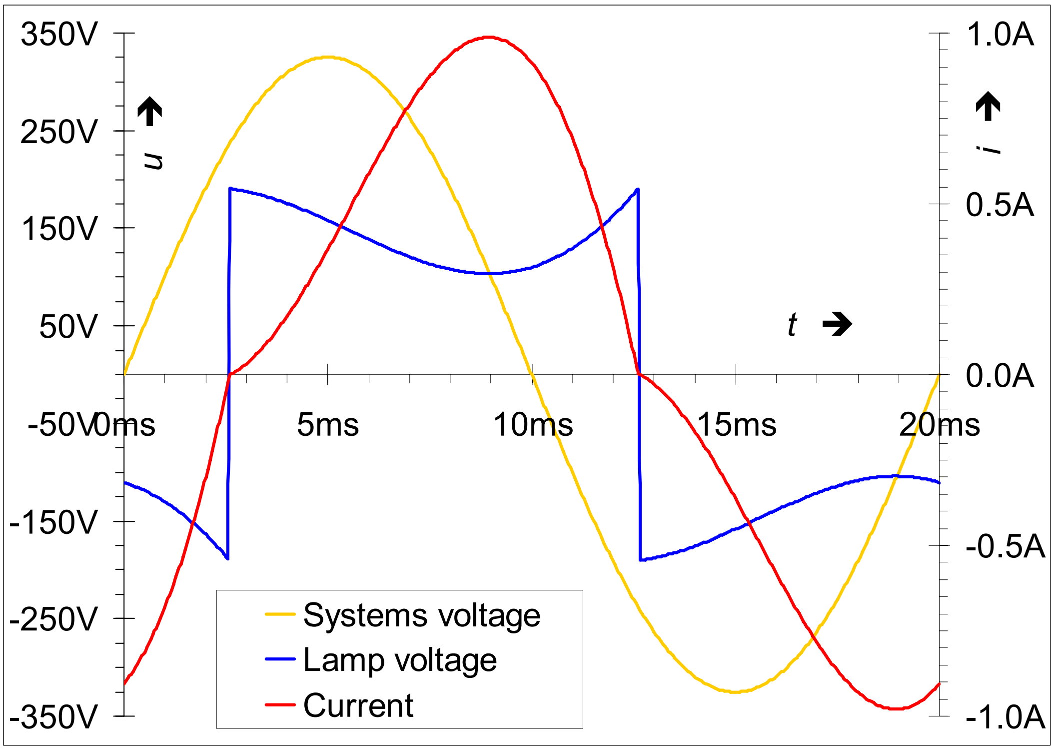

Fig. 3.17: Voltage and current of a 58 W fluorescent lamp in theory…

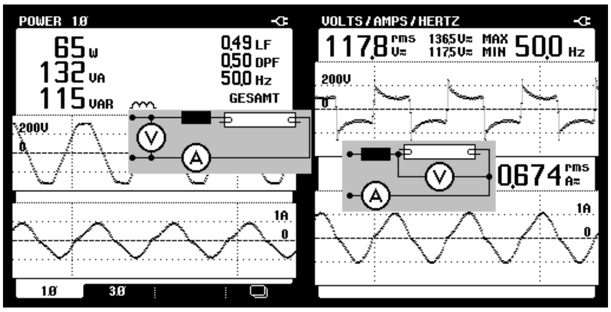

Fig. 3.18: …and in practice

Fig. 3.19: An electronic ballast is not by default dimmable

3.3 Dimmability and its price

There have been various methods around to achieve the dimmability of fluorescent lamps with magnetic ballasts, ranging from phase angle control to an inverter feeding a whole lamp arrangement with a variable frequency. The problems were, especially in the former case, the increasing flicker when dimmed down low and to keep the lamp from extinguishing completely. Methods such as longitudinal electrodes paralleling the lamp and permanent filament heating were the more or less satisfactory solutions, the latter of which decreases the energy efficiency and makes dimmability doubtful if used in order to cut electricity costs. The variable frequency was not so much different from the use of electronic ballasts today, only the frequencies were lower and the magnetic ballast on top of electronic frequency inversion still needed. At 50 Hz, the full power was fed into the lamp, while as frequency rose, impedance of the ballast became higher, so the current dropped, while the voltage across the complete luminaire remained largely stable. Therefore and on account of the higher frequency the light flux was also more stable than with phase angle control, but after all the method was not so much cheaper than equipping each lamp with an individual dimmable electronic ballast. A new dimming technique for magnetic ballasts is presently being developed in Canada[4], which seems quite promising but is not yet commercially available on the market. So until today, if dimmability is required, the choice is still an electronic ballast, while the stand-by consumption of these (mind Section 8.9) remains an issue! Moreover, the dimming feature does not come together with an electronic ballast without mentioning (Fig. 3.19), as is sometimes believed, but rather doubles the price once again (Table 3.1), which is already very high in comparison to even a high-quality magnetic ballast. The quoted prices per piece are valid for a quantity of one unit package, which is usually about 20 pieces, and possible rebates for larger lots range from 0% to a maximum of 50%. For OEM equipment being traded to the luminaire industry in tremendous piece numbers a substantially higher rebate may be possible. The unfortunate consequence of this is that the luminaires are then equipped with electronic ballasts by default, and customers who do not purchase huge quantities will be served with magnetic ballast luminaires not even on demand, however justified their desire may be (see Section 7).

Catalogue prices for a 230 V, 50 Hz, 58 W ballast	ordinary magnetic		magnetic low loss		electronic (warm start)		
	D	C	B2	B1	A3	A2	A1
Relco (2002)	4.54€					24.78€	60.73€
Vossloh-Schwabe (2003)		8.50€		13.50€		55.50€	106.50€
Vossloh-Schwabe (2008)			13.94€	14.56€	33.00€	50.00€	106.50€

Table 3.1: Catalogue prices for 230 V, 50 Hz, 58 W ballasts

The prices of electronic ballasts are valid for those with a warm start as well as the so-called cut-off features, which is the only fair comparison. A cold start electronic ballast without cut-off technology comes at 47.50 € from Vossloh-Schwabe[5]. Both warm start capability and cut-off technology are appreciated as a valuable extra with electronic ballasts, while they come without mentioning, enforced by the principle, with magnetic ballasts, be it with electronic starters or with the poor conventional glow starters.

4 Possible disturbances with magnetic ballasts

4.1 Emission of disturbances

As mentioned before, magnetic ballasts provide a mature and long-proven technique unlikely to cause any trouble or damages to other power consumers or the supplying voltage. One possible source of disturbance, which is more likely today to cause damage or malfunction to modern sensitive equipment than was the case in the past, is the voltage peak generated by self-induction in its high inductance at the instance of turn-off. Normally this will not be a problem, since lamps are hardly ever operated in parallel with such equipment on the same circuit with a common switch, but in one case it did happen. This rather uncommon damage could only occur on account of this exotic constellation (Fig. 4.1) but it should be mentioned that it may be a bit less exotic to parallel magnetic ballast fluorescent lamps with electronic halogen lamp transformers. Cases have been reported where the latter have repeatedly been destroyed by the turn-off self-induction surges of the former, and a special surge protector has been developed. Yet the problem could as well have been avoided by paralleling the two lamp-ballast-units with a capacitor. An appropriately dimensioned compensation capacitor will form a resonance frequency equal to the mains frequency, and the AC will therefore softly sway out after the supply voltage is turned off. With a smaller capacitor the resonance frequency is higher, and the turn-off voltage peak is »only« substantially attenuated, not entirely avoided, but the height of peak is not as crucial for the likelihood of disturbances as the rise time edge, which is attenuated very much through even a small capacitance.

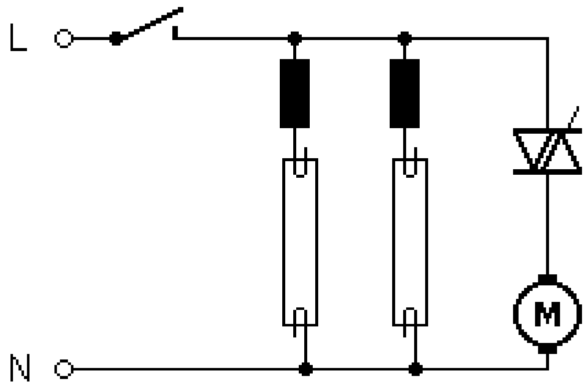

Fig. 4.1: Unhealthy parallel connection of an electronic load and a highly inductive load on one common power switch

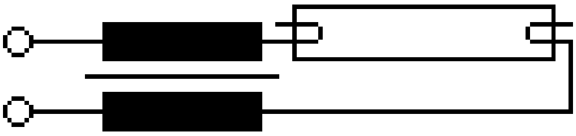

Fig. 4.2: Symmetric ballast

In another case an old Commodore computer locked up every second time the 18 W fluorescent lamp in the bathroom of an old residential building was turned on. The home was TN-C wired, without a dedicated earth / protective conductor but only two cores in all single-phase supply lines and an interconnection between the neutral and protective earth connectors inside each single socket. This alone may have been the cause for the trouble or at least may have contributed to it[2], but anyway a capacitor connected in parallel with the ballast and lamp solved the problem.

It remains to be amended that there is no voltage nor current surge when turning **on** the current in an inductance. The mentioned lock-ups in fact did not occur when pressing the light switch but when the starter tried to fire the lamp, which is basically a **turn-off** process of a reactor current, intentionally generating a voltage surge to get the lamp started (Section 3.1).

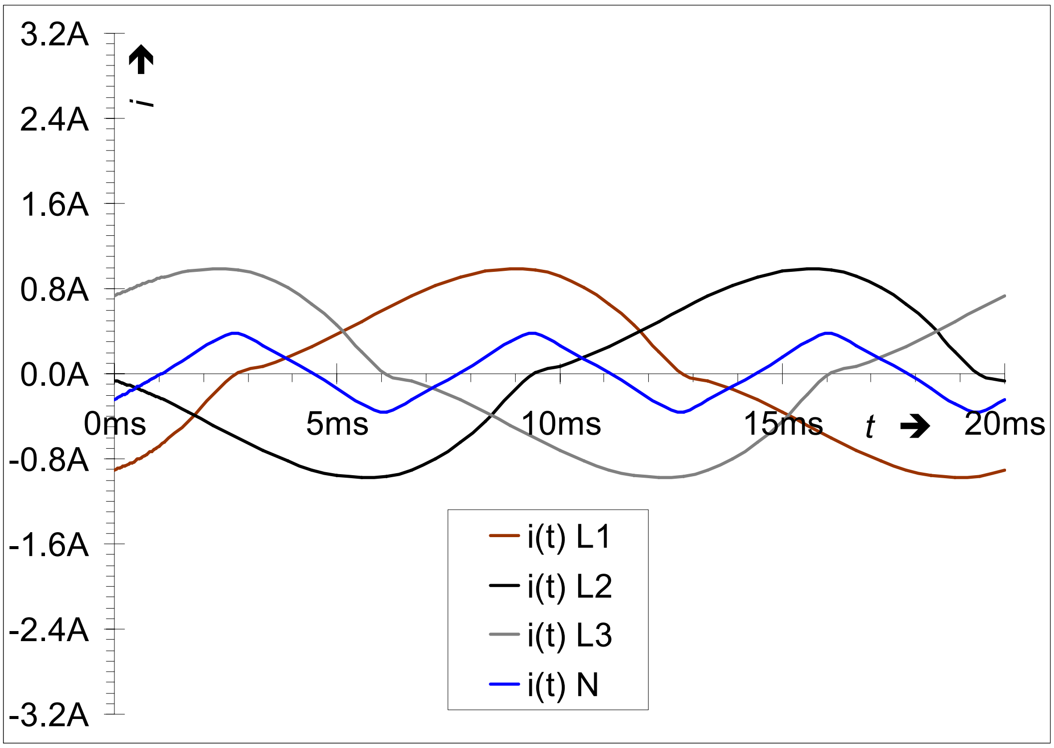

Fig. 4.3: Operating 3 fluorescent 58 W lamps with magnetic ballasts on 3 phases, sum of the phase currents forming the neutral current

In some cases sensitive equipment may be disturbed by the high frequency emissions that the lamp as a gas discharge device emits, even if operated at mains frequency. In these cases it sometimes helps to just swap the polarity. Care should be taken that the ballast is always connected to the phase and the lamp to the neutral as an earthed conductor, not vice versa. This reduces the likelihood of described trouble. If it still occurs, a so-called symmetric ballast may help, the inductance of which is split in two halves, each of them to be connected to one end of the tube (Fig. 4.2). Beyond, only the usual commonplace filters will help, whenever these, if used excessively, may cause a leakage current problem. Inrush currents, however, are generally not a problem with magnetic ballasts. Their inrush currents are not that high. Further attenuation can be achieved when serial compensation is applied (bottom of Fig. 3.10), while parallel compensation (Section 5) adds the inrush current of the capacitor, which has very steep rise time edges and may therefore very well become a problem.

When talking about the harmonic disturbances of electronic ballasts it is frequently alleged that magnetic ballasts also cause current harmonics, while this is not really so. The ballast itself is a linear element if designed properly, so as not to let the core material enter the range of magnetic saturation under normal operating conditions, which would be highly disadvantageous from a power quality as well as an energy efficiency viewpoint. Rather, the non-linear behaviour of the lamp itself causes an extreme magnitude of voltage distortion (Fig. 3.7, Fig. 3.7) but which on account of the high inductance of the ballast causes only little current distortion. So no disturbance worth mentioning appears across the terminals of the luminaire. The harmonic load on the neutral conductor with lamps spread equally across the three phases is correspondingly low, in the case of 58 W lamps the simulation reveals about 35% of the phase current (Fig. 4.3).

Sometimes acoustic noise is mentioned as a type of disturbance from magnetic ballasts but this, if it occurs, is a case of faulty lamp design or fabrication. A faultless ballast alone does not produce any noise, but if it is fixed to a metal sheet surface in the luminaire this has to be done adequately: Tightly but including washers made of rubber or plastics. Otherwise mains frequency humming or buzzing may occur.

As another disturbance the inevitable permanent flicker at double the mains frequency is often mentioned. In some locations, where rotary machines are worked with, this can become dangerous on account of a stroboscopic effect that may make the rotating machinery appear to stand still or at least cause heavy optical misconception of its rotary speed or even the direction of its rotation. This, however, can easily be avoided by spreading lights equally across the three phases of the supply or by simply applying lead-lag connection (Section 5). Apart from that, it remains to be noted that with TV sets the 100 Hz technique is regarded as the latest flicker free development.

4.2 Susceptibility to disturbances

This is a short chapter. Fluorescent lamps operated with magnetic ballasts are almost entirely unsusceptible to commonplace network disturbances. The high inductance connected in series with the lamp suppresses surges, peaks and harmonics, i. e. if the likes of those are present in the line **voltage** they will be able to drive only a fraction of the proportional **current** through the lamp.

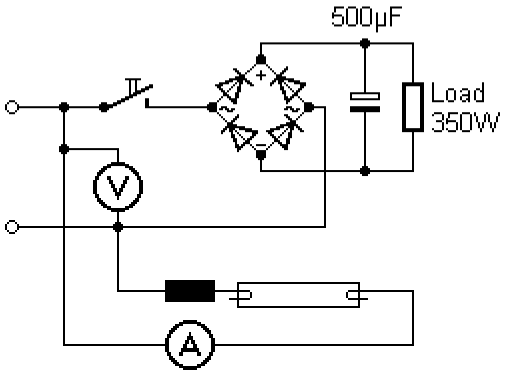

Fig. 4.4: Test configuration to provoke a voltage sag

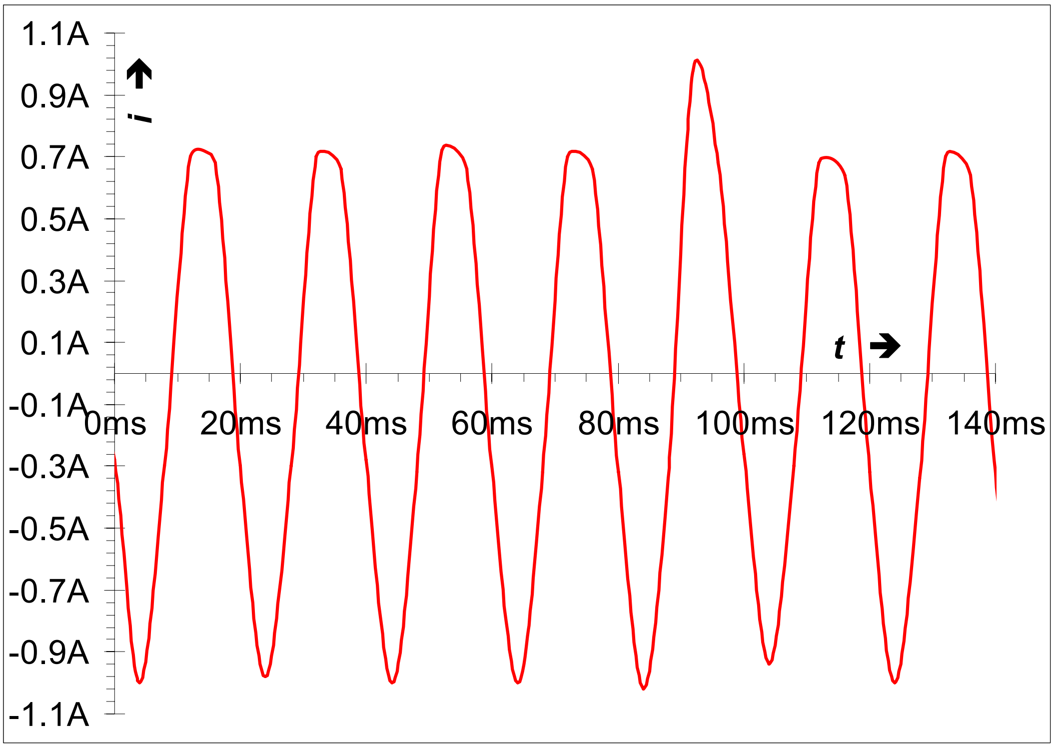

Fig. 4.5: Current peak caused by an asymmetric voltage dip

What may cause trouble – not really damages but flickering of the light – are voltage dips. Especially if these cover more or less one semi wave, during this semi wave the current will drop over-proportionally with the voltage dip: Since current starts to drop during the voltage dip, voltage drop across the lamp rises (Fig. 2.1) and leads to an acceleration and amplification of the current decrease. Subsequently, the full flux density of a normal current peak is by far not reached, which turns the next (opposite) current semi-wave into a milder form of starting process with excess current peak (Fig. 4.5) if the voltage is normal during that next semi wave. This way a positive flicker may occur, i. e. excess brightness above normal peak value, even though the voltage is normal during this particular semi wave and has even been sagging the semi-wave before. If the inrush current or other current peak caused by some nearby device (Fig. 4.4) happens to hit more or less equal parts of two subsequent semi-waves, only a normal current sag with consequential brightness sag occurs, but also slightly amplified beyond the proportional magnitude because of the non-linear behaviour (Fig. 4.6). This, however, would be alike with incandescent lamps, since the efficiency of these sags substantially along with power.

Basically the same occurs when DC impact causes a slight voltage asymmetry in the network. Old hair dryers, when operated at half power, normally use only one semi wave, and when the network resistance is high, a fluorescent lamp with magnetic ballast operated on the same circuit may flicker visibly. After all a measurement showed that a direct voltage content of 6 V, representing 2.7% of the line voltage rating, caused a direct current of 92 mA to flow through a ballast and lamp circuit, representing 18.1% of the rated lamp current.

The »negative resistance« of the lamp also leads to an over-proportional variance of brightness with deviation from rated voltage, while electronic ballasts including compact fluorescent lamps (CFL) claim to compensate this by means of their electronic control. What remains left of this promise will be discussed in Section 8.5. Still, the loss of brightness at undervoltage is a lot less than with incandescent lamps, the efficiencies of which, performing poorly anyway, drop dramatically when operated below the rated power input.

But this is virtually all that may happen with magnetic ballasts. Adequate means to reduce the voltage flicker – and over-dimensioning of cables and especially transformers is in many cases enough to achieve this – just need to be provided, which will be necessary for other sensitive devices anyway and as a second effect reduce energy losses. Damages or failures of lamps or ballasts on account of poor power quality do not occur.

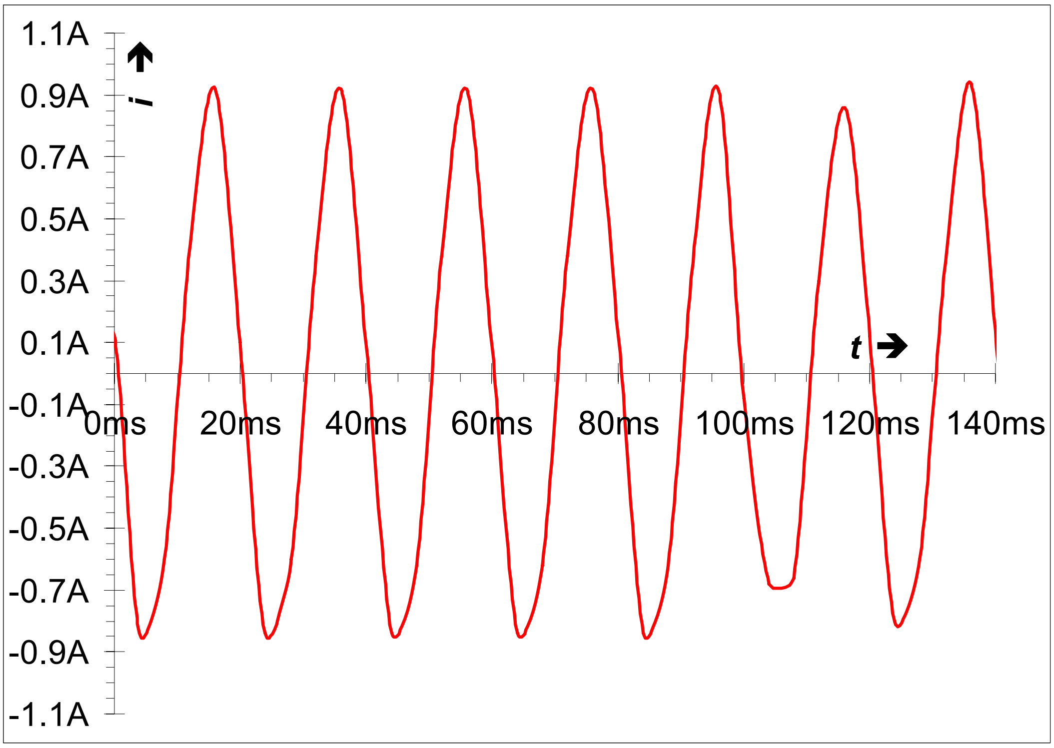

Fig. 4.6: Current dip caused by an approximately symmetric voltage dip

4.3 Reliability

Therefore, this chapter is even shorter than the previous one. The magnetic ballast itself hardly ever becomes damaged through surges or overvoltages because of its simple and sturdy structure and because it has to be designed to withstand its own self-induction pulse anyway. Surely it happens that a magnetic ballast fails on account of shorted turns in the winding, which produce excess heat and thereby further turn shortings, then current increase, even more excess heat and so on. It may take some weeks, however, before this process reaches this avalanche state and finally blows the fuse. By then the fault may have been detected because of charred smell or uncommon noises but in any case the ballast (and the adjacent lamp which is overloaded by the excess current) will under no conditions cause a fire during failure. This is the only type of failure that ever occurs with magnetic ballasts, and it is really the exception.

5 Proper compensation of reactive power with magnetic ballasts

5.1 General issues

Luminaires operated with magnetic ballasts cause a lot of inductive reactive power, much more than the share of active power normally is. The power factor (for a lamp together with its ballast under normal operating conditions) is always indicated on a ballast (Fig. 5.2). In fact a luminaire with a lamp rated 58 W and a magnetic ballast has an overall active power intake between 64 W and 70 W, so with the 0.67 A current rating the apparent power is around 160 VA and the reactive component some 144 VAr. So in the commercial and industrial sectors compensation becomes a must – which is old common practice and neither difficult nor expensive to realize.

The argument commonly forwarded for compensating is cost reduction, while in fact, as a rule, only prices are considered, the price the utility charges for reactive energy metered at the point of common coupling, not the cost the reactive current causes on its way from the device consuming (active) power to the PCC. Not (yet) so with lighting. As an exception, it is really common practice with ballasts to compensate the reactive power right in the place of origin, where this is most effectively done, say within the luminaire. This may happen in the usual way by paralleling the (approximately) ohmic-inductive load by a capacitance. However, the disadvantages or risks are as with any other static VAR compensator today:

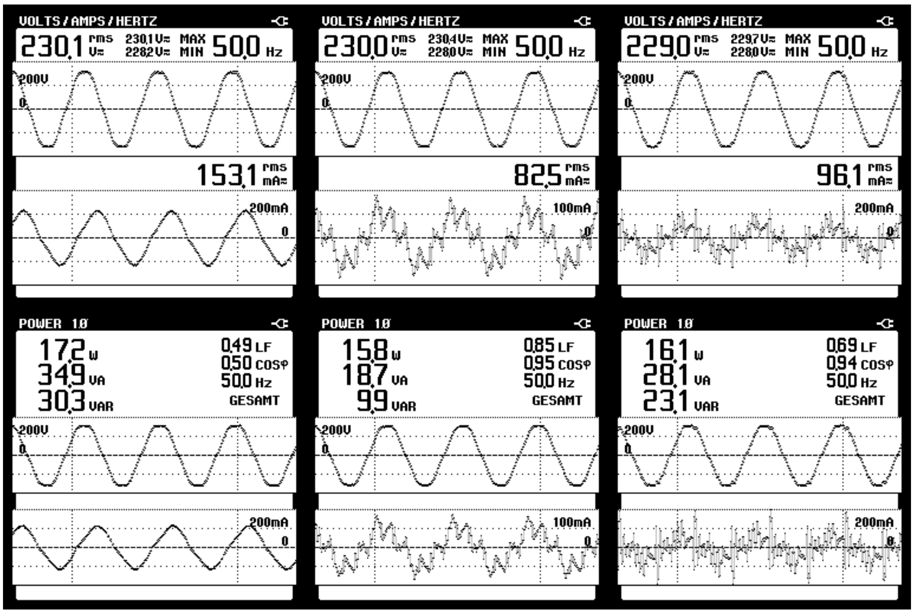

Fig. 5.1: An 11 W fluorescent lamp with magnetic ballast without compensation (left) and with parallel compensation (centre and right)

- Sound frequency signals in the mains, used for control of street lighting, night storage heating etc. may get lost.
- Capacitive reactance drops proportionally as frequency rises, so capacitors may be overloaded since there are a lot of harmonics and other frequencies higher than the mains frequency rating superimposed upon the line voltage. On the left of Fig. 5.1 the power intake of a small fluorescent lamp was recorded in an office environment without any compensation. The fundamental reactive power is really very high, with cosφ = 0.5 – while it nearly equals the load factor *LF*, which means that the current is approximately sinusoidal, as becomes obvious also from the graph. So compensation becomes a must, but a parallel capacitor adds a tremendous lot of distortion, say higher frequency constituents, to the overall current (centre of Fig. 5.1). Although the capacitance is properly dimensioned, the reactive current cannot be brought to zero. When nothing in the wiring is changed but just the inverter driven elevator in the building starts to operate, the distortion and thereby the reading of reactive power once again increases substantially (right of Fig. 5.1). This provides evidence that indeed the additional current must consist of higher frequencies flowing through the capacitor.

Now in static VAR compensators the usual approach to cope with these phenomena is detuning the capacitors, say connecting them in series with a reactance that at mains frequency compensates (takes away) only a few percent of the capacitor's reactive power rating.[6] But why bother about an additional reactor with fluorescent lamps where a reactor is already there? Since current and phase angle with fluorescent lamps are practically invariable, there is another option, namely to use the ballast simultaneously for detuning a serial compensation capacitor (the so-called lead-lag connection, Fig. 5.3). This means that every second lamp-and-ballast unit is (over-)compensated with a serial capacitor dimensioned – in theory – precisely in such a way as to make the current magnitude equal to that in an uncompensated lamp. The phase angle will then also be of the same absolute magnitude but with opposite sign.

Fig. 5.2: The power factor is always indicated on a ballast

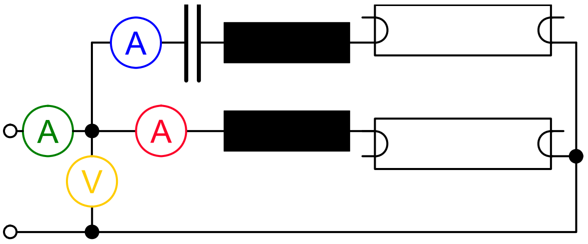

Fig. 5.3: Lead-lag compensation

So all the disadvantages of parallel compensation are avoided. Also the stroboscope effect is minimised through the phase shift between the leading and the lagging circuits usually installed within one luminaire. This is the reason why most luminaires come with 2 lamps. As a side effect, the compensated share of the lamps are much less sensitive to voltage variances and flicker (Fig. 5.4) and entirely insensitive to possible direct voltages superimposed upon the feeding voltage, which otherwise, even if minimal in magnitude, may heavily affect inductive components.

The only disadvantage of this compensation principle is the risk to dimension the capacitor wrong. A bit of over- or under-compensation does not matter much in parallel, but in serial it means more than that (Fig. 5.6, Fig. 5.7)! It means wrong lamp current, possibly lamp, capacitor and ballast overload or at least either higher loss level than necessary and premature failure or reduced light output. Therefore the tolerance rating of these capacitors is rather narrow, just 2%. Care has to be taken with the selection of replacement, which should not be a problem, since the correct capacitance for serial compensation always used to be indicated on a magnetic ballast (Fig. 5.2), but yet sometimes errors occur. Now that German lighting industry has decided to abandon serial compensation (instead of adapting the capacitance ratings to adequate values, which would be feasible without any risk, as both measurements and magnetic ballast experts confirm), the capacitance ratings on the rating plate (still to be found on the ballasts in Fig. 5.2 and Fig. 8.9) are now omitted.

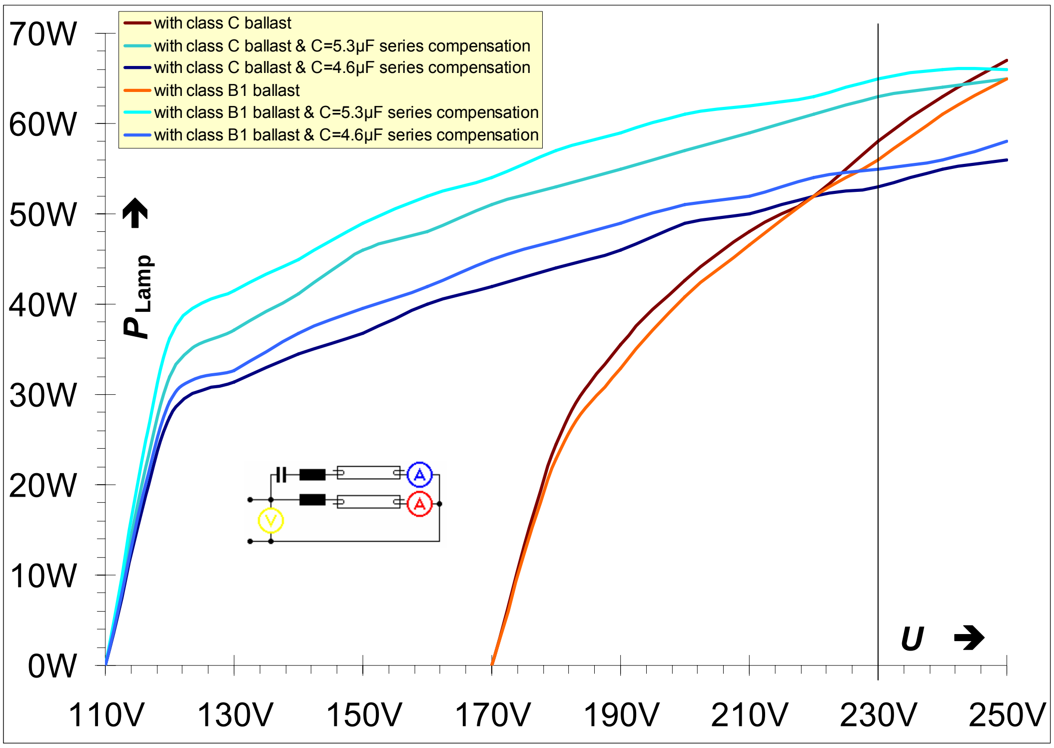

Fig. 5.4: Much better resilience to voltage variances with serial compensation

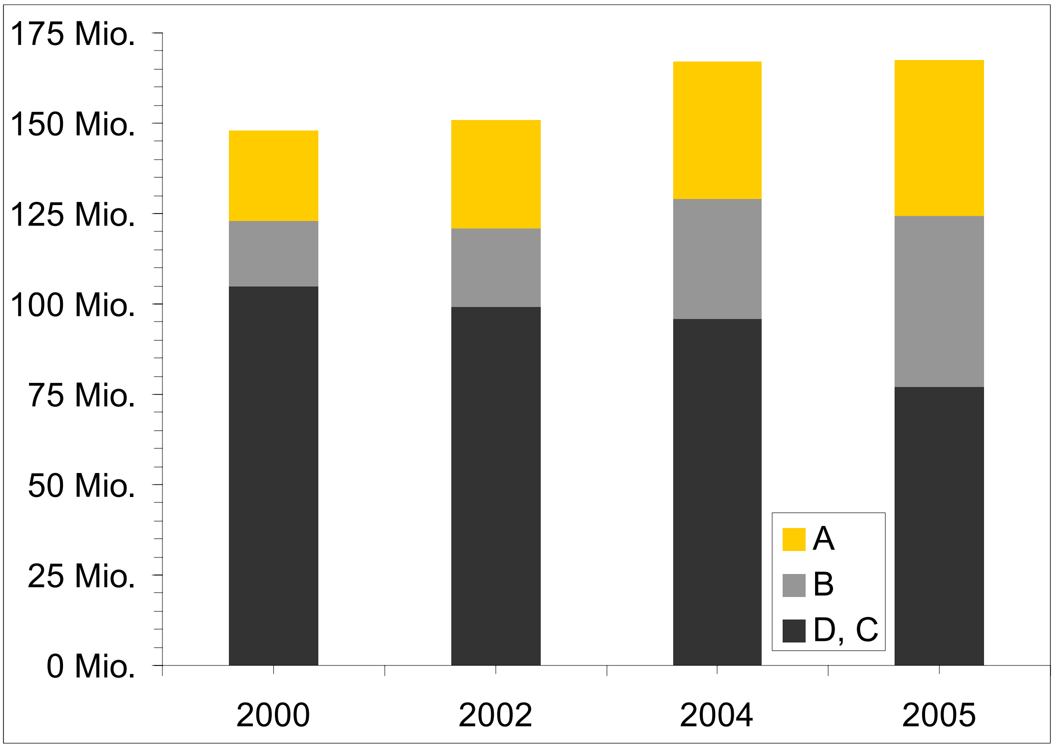

Fig. 5.5: Shares of the European ballast market

Another disadvantage – not of the principle but in common practice – is that the currents with and without serial compensation are not really equal. The ratings differ depending on whether inductive or capacitive coupling is applied (Fig. 5.2). At the rated current of a 58 W lamp, which is 0.67 A, the inductance of a 230 V 50 Hz ballast turns out to be 878 mH. This requires a capacitance of 5.7 µF to end up with a resonance frequency of 70.7 Hz, at which theoretically the lamp current magnitude at 50 Hz would be equal with and without the serial capacitor.

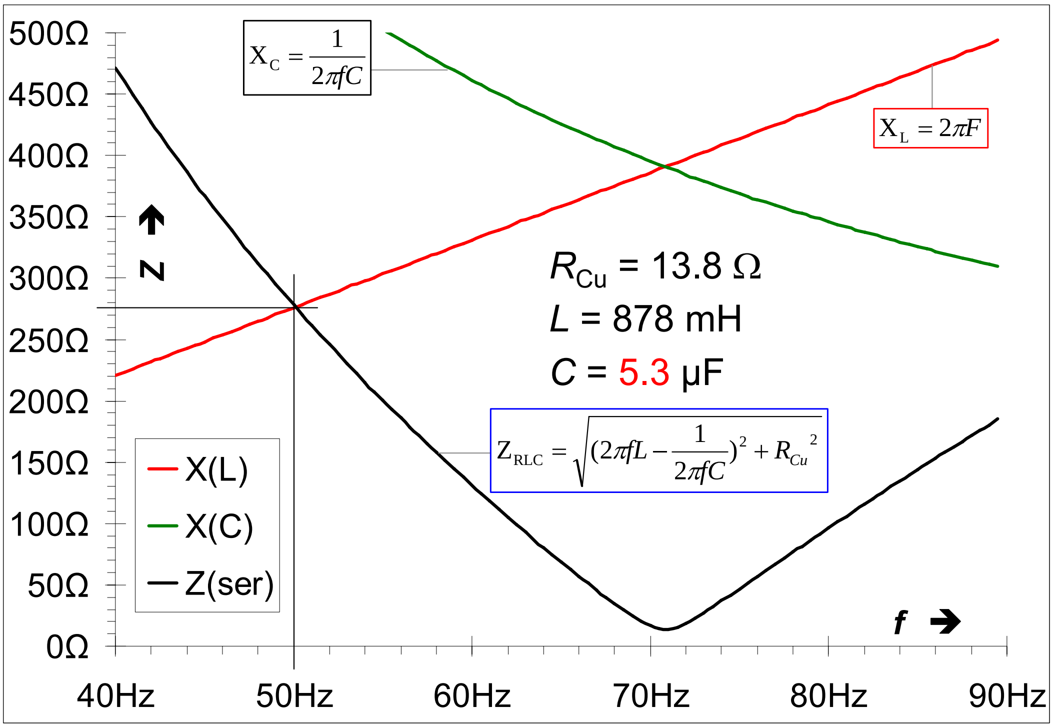

Fig. 5.6: Correct dimensioning of serial compensation capacitance

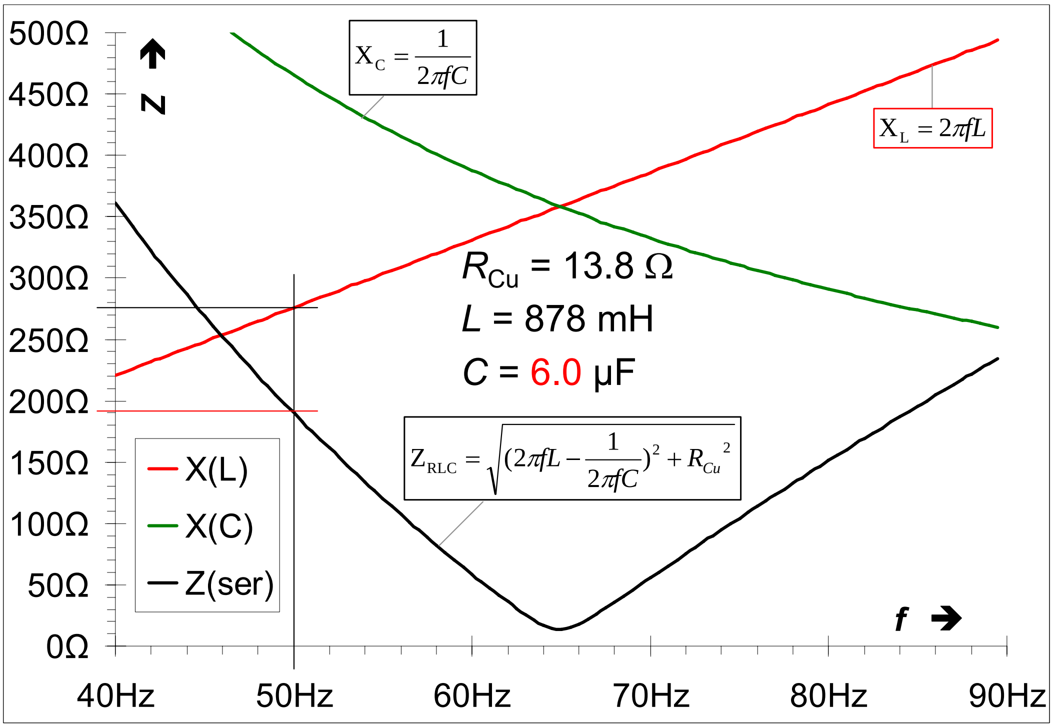

Fig. 5.7: Serial compensation capacitance dimensioned 20% wrong: Lamp, ballast and capacitor current 45% too high!

Yet, for some reason, possibly the extreme distortion of the voltage across the lamp (Fig. 3.17) or non-linearity of the ballast, currents turn out unequal. As a standard, 5.3 µF or 5.2 µF are used (Fig. 5.2) but this still by far does not offset the difference. A measurement (Fig. 5.4) shows that 4.6 µF would be the correct value but it is argued this could not be used in order to avoid starting problems with the lamps, especially in cases of undervoltage and extremely low temperatures. It has nothing to do with the principle as such, once the lamp has been fired successfully, and the firing problems could very well be overcome by the use of electronic starters, which are the better choice anyway (Section 3.1)[7]. Moreover, the question is whether there is any reason to worry at all. Rather, a further test revealed that absolutely no starting difficulties are to be expected: 3 electronic starters as well as 2 very old worn-out glow starters were tested together with 2 different types of 58 W lamps, both from the same manufacturer but of different light colour, with a modern efficient magnetic 230 V ballast. **Both** the reduced 4.6 µF serial capacitance **and** reduced voltage were applied, and all combinations started without any problems at first attempt with only 180 V, with just two exceptions where successful firing occurred »only« at 190 V. So it seems a revision of capacitance ratings is due here but industry rather seems to be hoping to replace all magnetic ballasts with electronic ones in the long run and therefore appears not too ambitious to adapt any old standards to new technologies as long as either of these refer to magnetic ballasts. However, even if the impression roused among experts may cause a different feeling, approximately 70% of the market is still being held by magnetics (Fig. 5.5). In some countries the ratio is even a lot more extreme (Spain 91% magnetic ones). At least in terms of sold pieces this is so. In terms of turnover figures the share is only more around 50%, due to the much higher added value. Or should we rather speak of higher added price in this case? Howsoever, it is understandable that the lamp and luminaire industry is much keener on the promotion of electronic ballasts. For reasons of justice, however, it also needs mentioning that electronic ballasts more often than magnetic ones provide the option of operating 2 lamps on 1 ballast.

5.2 Special aspects when compensating small lamps

The lamp voltage across smaller, i. e. shorter fluorescent lamps of the same type family is lower than with the longer types of the same series. Thereby a larger part of the voltage drops across the ballast, and this voltage drop is greatly – in the ideal case would be wholly – inductive. So on the one hand the smaller lamp has a lower active power intake, but on the other hand it has a higher reactive power dissipation. Commonly, these two effects lead to a substantially lower power factor for the lower lamp power rating. So the compensation investment increases inappropriately. This can be observed very clearly on TC-S lamps with 5 W, 7 W, 9 W and 11 W power rating, since these 4 models are all operated on the same ballast (Fig. 5.8).

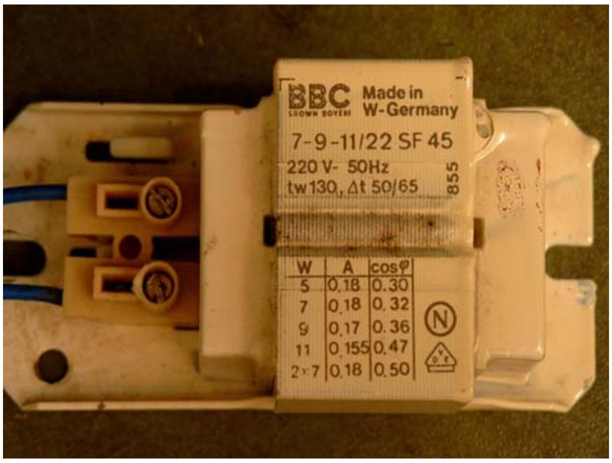

Fig. 5.8:One and the same ballast is designed for 4 different lamp types as well as for 3 tandem connections (only one of them listed here for reasons of space); the power factor increases substantially with the lamp power rating connected

However, the lamp voltage across the TC-S lamps rated 5 W, 7 W and 9 W is so low that the common mains voltage of 230 V allows two of these lamps to be operated in series on one ballast. In effect, this doubles the lamp voltage again, of course. Since the same ballast is used for this so-called tandem connection as for the single operation, the actual current when operated in tandem lies slightly below the lamp current rating – though not very much, since the inductive voltage drop still prevails. One of the advantages of this operating mode is that **two** lamps **together** use **less** reactive power than one of them already does in single mode (Fig. 5.9). But the tandem configuration may very well claim even more advantages than this (see Section 8.3).

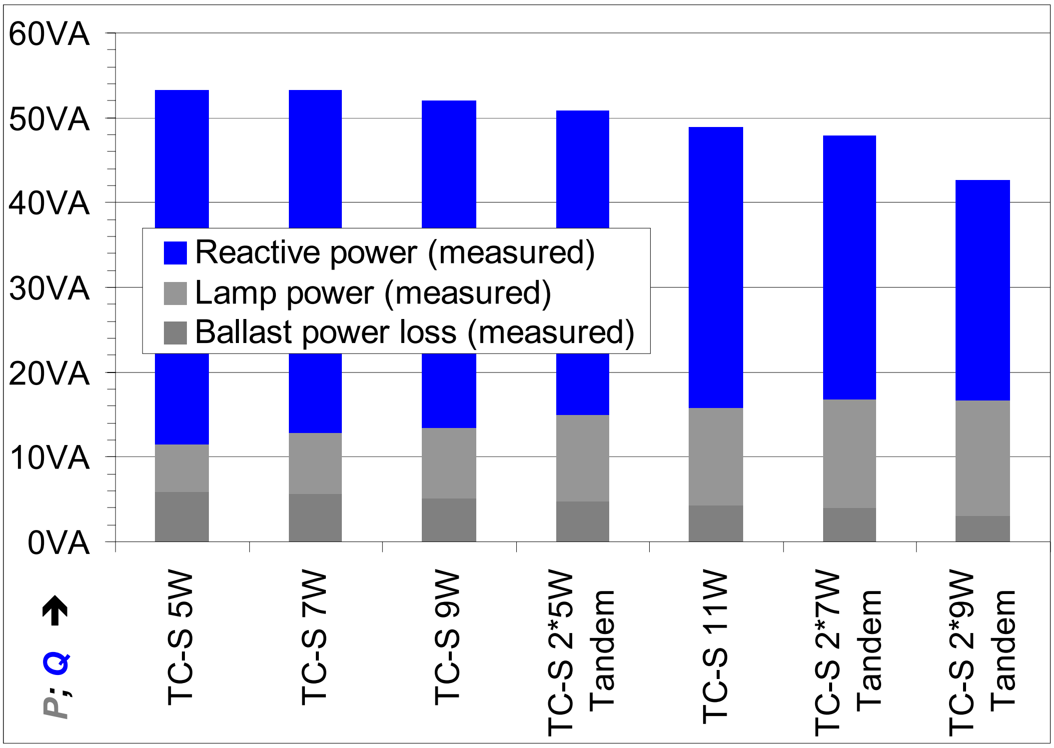

Fig. 5.9: Power factor as the ratio of active power (grey benches) plotted against reactive power (blue benches)

6 The working principle with electronic ballasts

As already explained in the introduction, it is the working principle of electronic ballasts to generate a high frequency AC to feed the lamp. This technique is also applied in a steadily increasing number of so-called switch-mode power supplies, there to facilitate the use of a very much smaller transformer. This advantage comes more or less as a by-product also to the electronic ballast because the principle of transforming at higher frequencies is the same. In most cases the complete ballast including the transformer and the conversion electronics has the same dimensions as an equivalent magnetic one but the weight is only one fifth (and thereby roughly reciprocal to the price).

As for CFLs, there is a wide span of final consumer prices. European high-price producers claim that the cheap far-East products often do not match the European quality level, especially as cheap models mostly dispense with filament pre-heating. Pre-heating in principle excludes immediate start – this being a weak argument against pre-heating, since it takes barely one second. Dispensing with it cuts design and production costs, but it cuts lamp life heavily with increasing number of starts. Also the initial brightness reduction after cold start and the loss of luminous density at low temperatures and old age varies widely and may be more a problem of cheaper designs.[8]

The working principle that used to be the general one during the »stone age« of electronic ballasts, and that is still applied on all CFLs and on electronic ballasts with lamp ratings up to 25 W, was to rectify the incoming AC via a B2 bridge and to smooth the DC output with an electrolytic capacitor (Fig. 6.1). Somewhat later an upgraded electronic ballast technique was developed to enable at least an approximate restoration of the current sine wave. The incoming alternating voltage here is superimposed by a pulse width modulation or other chopping technique so that the current base line, the interconnection of the current peaks, represents an approximate sine wave (Fig. 6.2). The possible variances of design are multiple, so this generic description of the principle cannot go into detail. Quite an illustrative description of the various principles can be found in the internet.[9]

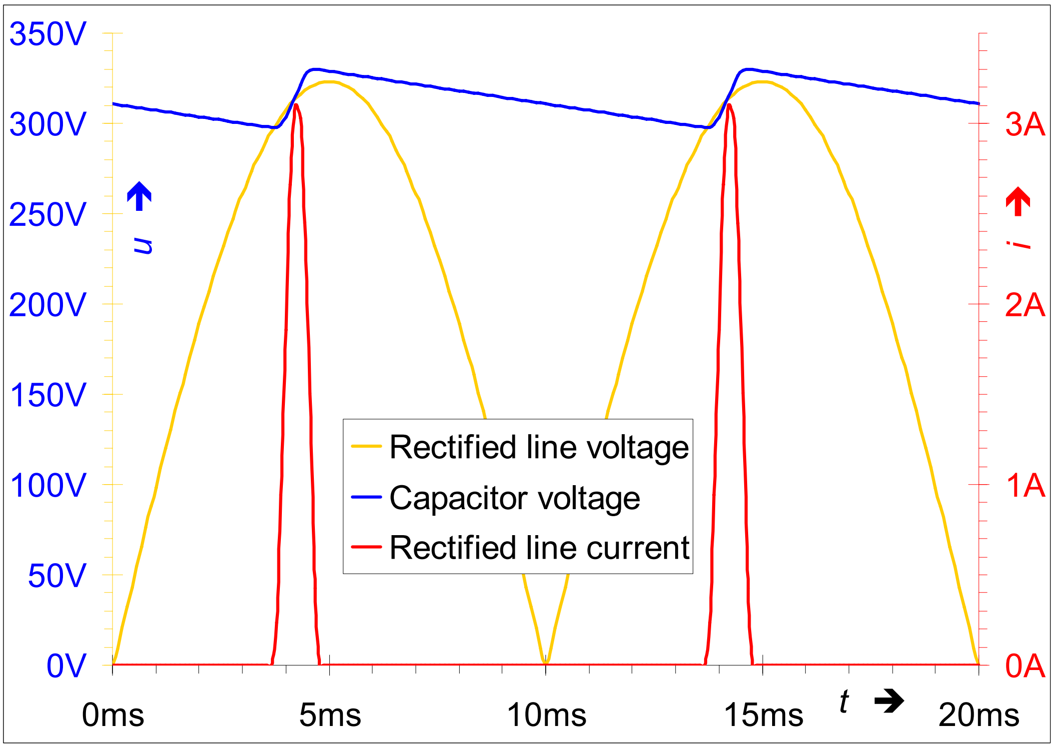

Fig. 6.1: Working principle of CFL or former electronic ballast

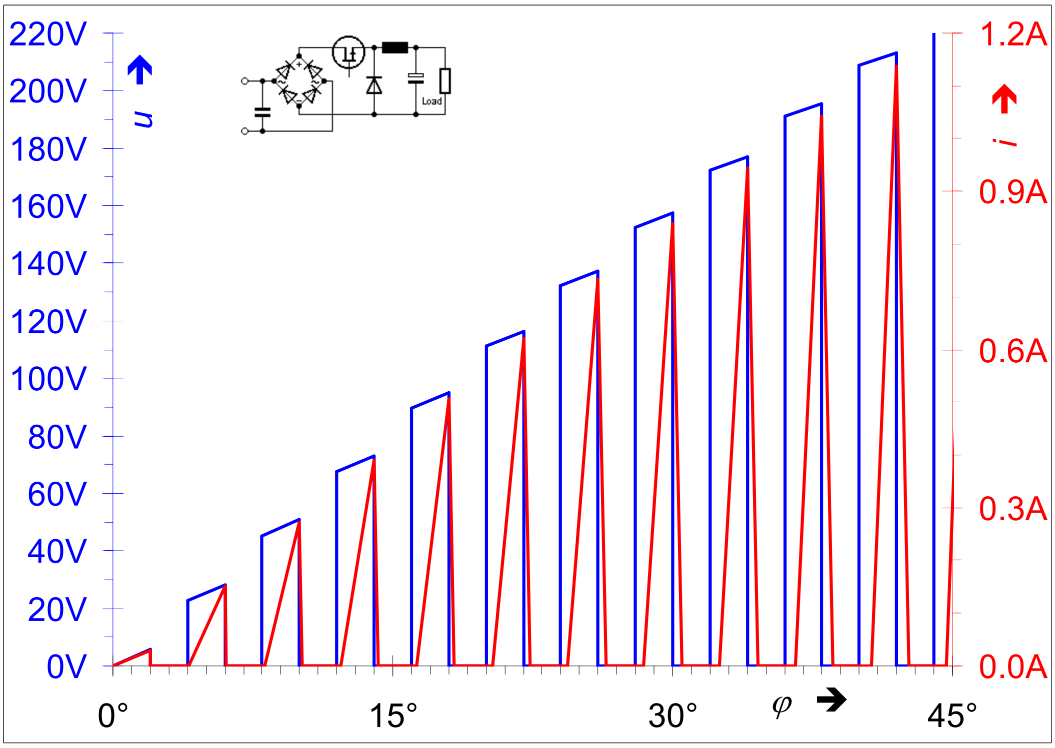

Fig. 6.2: Working principle of present electronic ballast above 25 W rating

7 Possible disturbances with electronic ballasts

7.1 Emission of disturbances

The former of these two styles of drawing electric power, the direct rectification of the incoming AC, generates extreme periodic current peaks somewhere in the proximity of the voltage maximum, while during the rest of each semi wave no current flows at all (Fig. 6.1). This current waveform includes a high harmonic content, especially of the third and its multiples, which add up on the neutral instead of cancelling out and cause a bunch of problems that have recently been analysed and described in detail in various sources: Neutral overload, transformer overheating, substantial distortion of voltage waveforms if network impedances are high, and in TN-C resp. TN-C-S systems these permanent operating currents on the neutral also intrude into all earthed metalwork, including the screens of data lines. There they can cause an additional bunch of problems such as magnetic stray fields, corrosion of pipework and earthing electrodes and especially malfunction and damage of IT equipment. While these harmonic currents in modern office buildings originate from the multitude of PCs, their screens and peripherals, electronic ballasts below 25 W including CFLs, because of their limited use, contribute only a smaller fraction to this problem. However, operating all fluorescent lighting following this simple principle would be virtually impossible, for which reason the upgraded electronic ballast technique with electronic power factor correction (PFC, Fig. 6.2) was developed. One source says about 30% to 50% of the price for an electronic ballast is spent on avoiding disturbances[10]. Most of this obviously goes into PFC – quite successfully, as a comparison shows (Fig. 7.1): The input current of a CFL without PFC, rated only 11 W, has approximately the same crest value as that of a ballast rated 58 W with PFC. The total harmonic distortion of the currents is 80% in the former case, but barely 19% in the latter. Although less than 12% were measured with a magnetic ballast, this value is low enough not to encounter any harmonics related problems.

This, however, gives rise to another type of disturbances. Since the pulse width modulation on the input side »chops« the incoming current into many »thin slices«, this is equivalent with releasing a high frequency current into the network, which is largely attenuated, but not completely extirpated by a capacitive filter on the input side of each electronic ballast (Fig. 7.4). So the possibility of conducted as well as transmitted disturbances remains. It has happened, for instance, that the frequency was 77 kHz, equal to that of the Frankfurt long wave transmitter which broadcasts the time signal of the Braunschweig atomic clock. The interference caused radio controlled clocks to malfunction inside buildings equipped with these ballasts. Typically these disturbances occur at two different frequencies, for obviously the HF transformer for generating the lamp current and the electronic power factor correction work at different clock frequencies (Fig. 7.5): The former is responsible for the radiated and the latter for the conducted disturbances. Moreover, this high frequency, since it is not sinusoidal, for itself consists of a theoretically infinite spectrum of harmonics, so that the highest frequencies occurring nearly reach right up into the megahertz range. In the meantime standards have been released to restrict the maximum permissible levels of such disturbances. Unfortunately the tests according to these standards are carried out individually in a lab on one sample of the ballast in question, while in the field some hundreds or even a few thousands of those are operated on one site, so the disturbance levels to some extend add up. Adding to this, there is a frequency gap in the standards, leaving a certain range of frequencies without any limitations. Witty engineers now design their appliances in a way as to displace all disturbances into this blank, just as if only standards did matter and disturbances did not. Lots of interferences have so far been reported informally but on account of the special market structure they never ever appear in print.

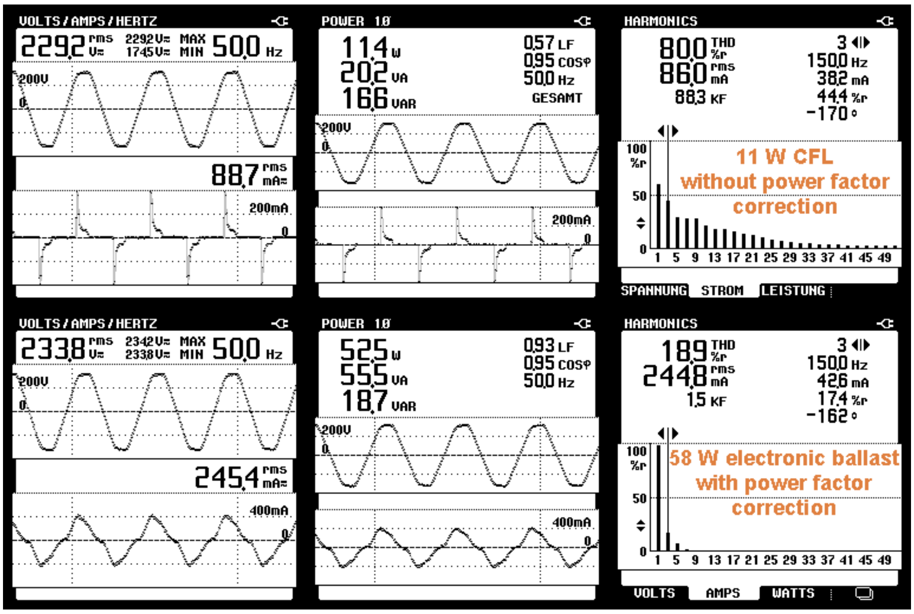

Fig. 7.1: Comparison of CFL without PFC (top) to electronic ballast with PFC (bottom)

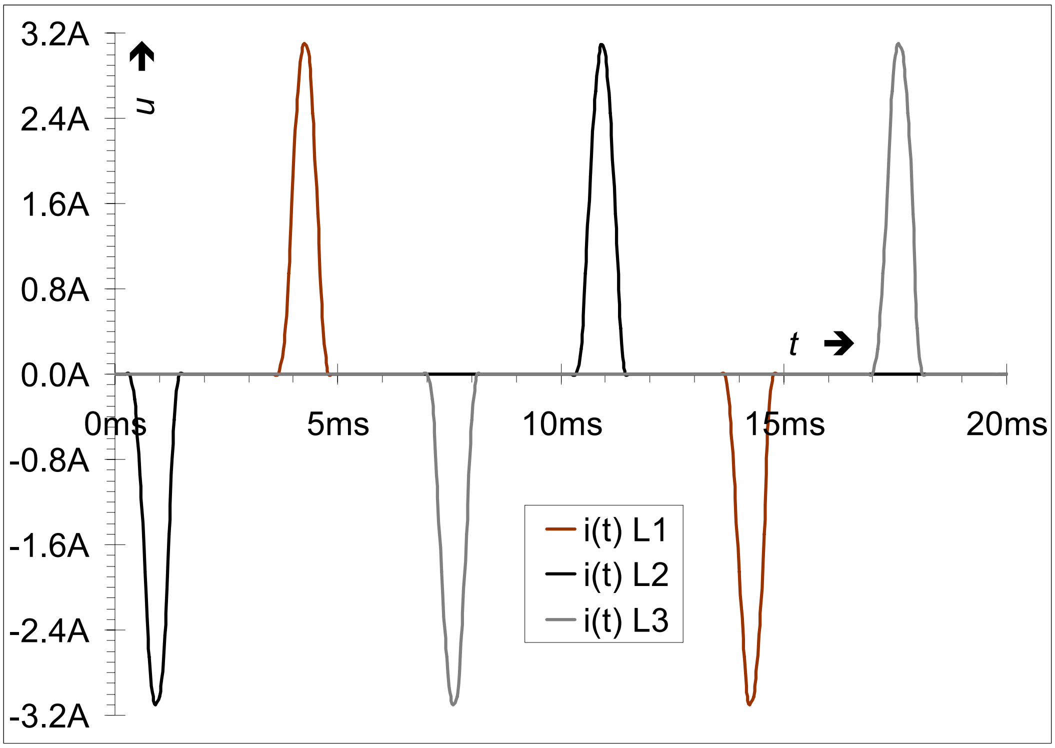

Fig. 7.2: 3 electronic ballasts of old design or 3 CFLs operated on 3 phases

Inspectors and official surveyors[11,12] repeatedly report about an oscillation of the voltage amplitude in installations where there is a large coverage of electronic ballasts. At the feeding point the same can be observed with the current but with opposite phase, so this current variance must be the cause for the voltage variance. The inspectors speak of frequencies up to 3 Hz but usually only 0.3 Hz or often even a lot less than that, one period per 30 seconds is typical. They see a coherence with the usually capacitive power factors they find in these installations, while this cannot really be the cause. Truly electronic ballasts usually have a slightly capacitive power factor (Fig. 7.1), and truly installations are usually not metered or monitored, so nobody realizes the power factor correction is no longer a correction but the opposite of that and should be switched off or stepped down, but an oscillation at such a low frequency would require tremendous lots of both capacitance and inductance. Rather, the automatic output power control of the ballasts may be the cause: When there is a voltage sag for some reason, the input current into the ballast must be increased to keep the output power stable, and if the share of the total power that goes into such lighting equipment is high enough, this will increase the sag palpably. The voltage will continue to drop, and the overall current will go on rising until the input current increase of the ballasts is offset by a decrease of the input currents to some loads where it decreases as input voltage decreases, such as ohmic loads. This is even indicated on the rating plates of electronic ballasts (Fig. 7.6). Now the process is inversed, and a voltage swell starts. The surveyors say the problem is usually solved by replacing the failing electronic ballasts (which they are called in for) with magnetic ones **without** adding any compensation capacitance. When the share of magnetics reaches about $^1/_3$ not only the electronic ballast failures stop but also the voltage oscillation ceases. So they think the shift of the power factor slightly into the inductive range was the solution, while the true explanation is probably that the behaviour of lamps with magnetic ballasts is inverse to that of electronic ones: Input current, both the active and the reactive share, drop over-proportionally as input voltage decreases. A linear drop might not suffice as an offset to stop the oscillation.

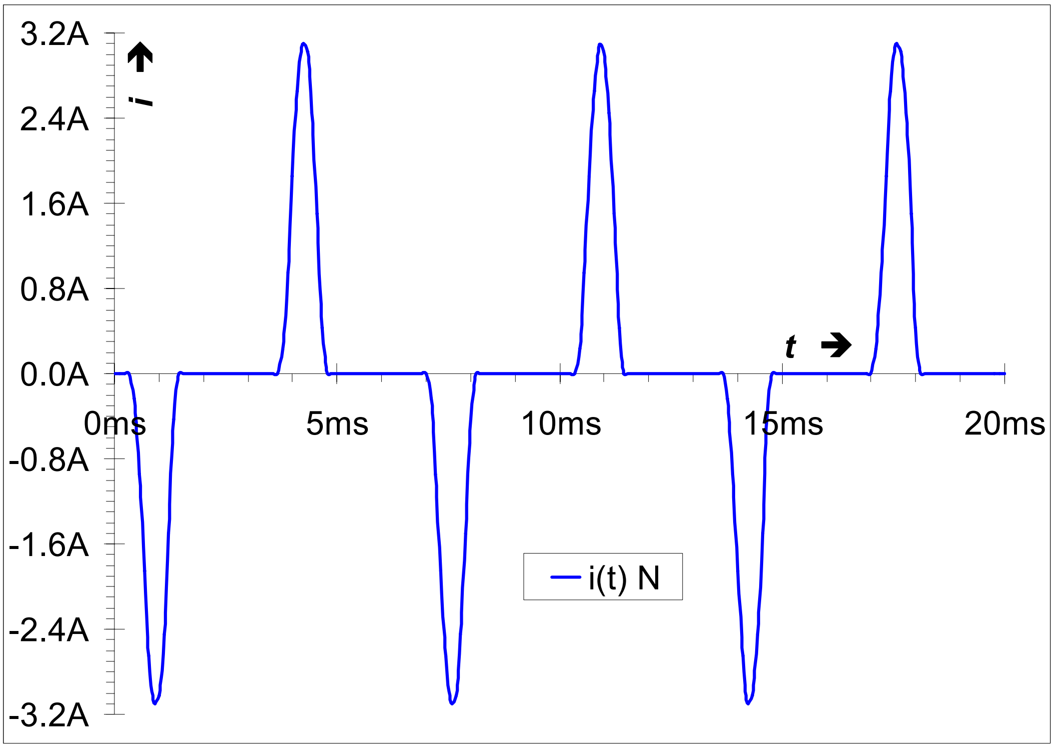

Fig. 7.3: Resulting neutral conductor current of phase loads as in Fig. 7.2

A high frequency expert[13] reported he had tested some electronic ballasts and found out that their HF emission frequency also varies. It periodically hops to and fro between at least 2 frequency bands, obviously deliberately, by design. The background is probably that the relevant standard allows a certain amount of radiated energy at a certain frequency band, integrated over a defined period of time. So this standard is dodged by dispersing the disturbance across a wider range of frequencies. Unfortunately the expert was not able to say which standard it is that defines these values and procedures.

In another case the surge diverters in a brand new supermarket kept on failing. The whole market was equipped with electronic ballasts and the feeding lines with a properly designed overvoltage protection, comprising coarse, medium and fine protection downstream. However, the protective devices at the last stage, the fine protection, continuously failed, looking charred after failure, without any tripping of the coarse and medium stages. So the protection would have to be built up the other way round, coarse indoors and the fine stage upstream, since the disturbance came from inside the installation in this case.

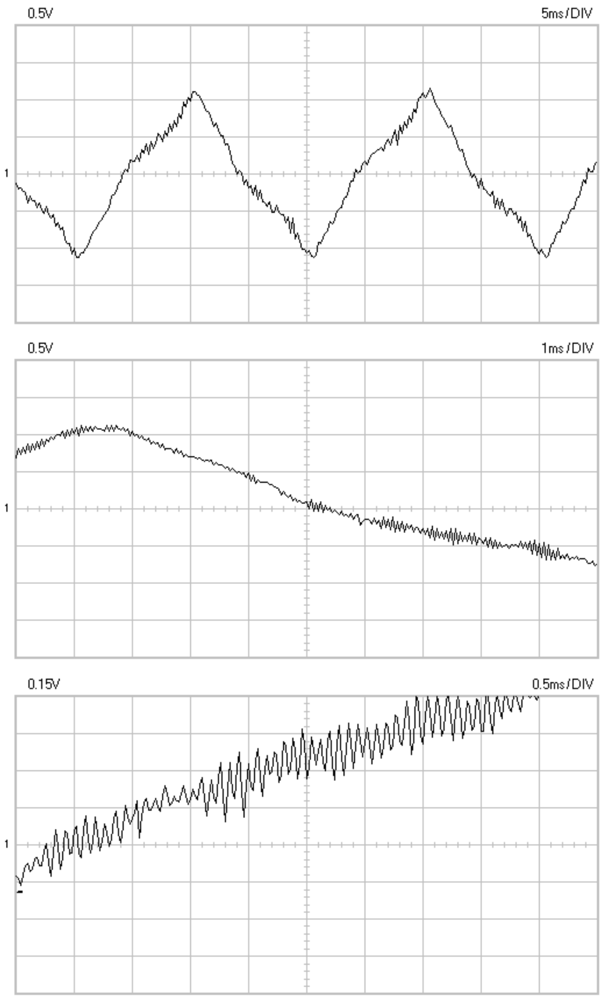

Fig. 7.4: Input current of an electronic ballast at different time resolutions

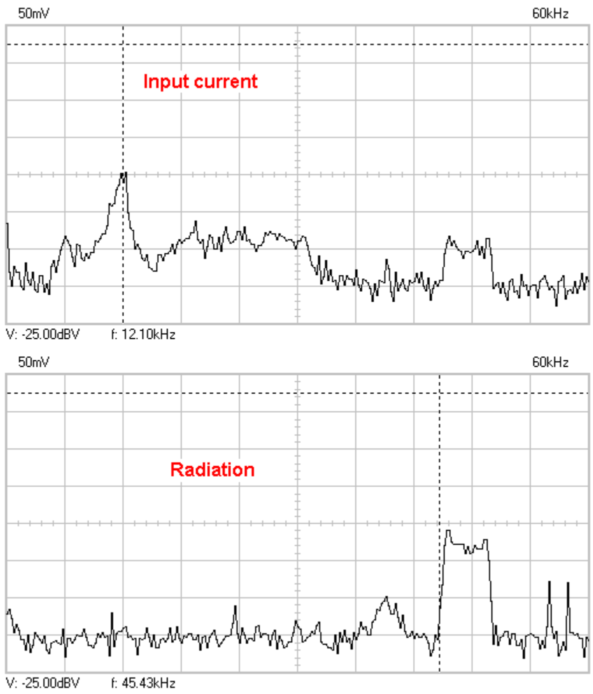

Fig. 7.5: Frequency spectrum of the same electronic ballast

7.2 Susceptibility to disturbances

The same goes for the vulnerability of electronic ballasts. It is frequently reported that under certain conditions they keep on failing (Fig. 7.7), while nobody is able to identify exactly which these conditions are. And again, there is an implicit vow of silence spelt over the affair. In one case, for instance, a major electrical contractor received a complaint from a customer where among a large number of newly installed electronic ballasts a substantial share malfunctioned right from the instance of installation. The contractor replaced the failed devices and passed the complaint on to the supplier, one of the European market leaders in lighting equipment. He got a letter back saying, in polite wording, an initial failure rate of 17% was absolutely normal for electronic ballasts. The electrician told this to his customer, who requested a copy of that letter but which was declined.

Only at Paderborn-Lippstadt airport, a small but rapidly growing regional airport in Germany, two cases could be documented:

- Out of ≈80 electronic ballasts no less than 30 had failed within 4 months in one part of the installation. The same luminaires with the same type of ballasts, same producer and even same batch, work without a single problem in an adjacent part of the installation being fed from a different subdistribution but from the same transformer. No indication of the reasons for these failures have been found so far, except that from the branch with the faults exclusively this lighting arrangement was fed, while the other one also fed some other loads. This would mean that the ballasts kill each other, unless other loads absorb their litter, and provides further scope for speculation about the causes, but still no evidence.

- About half a year later the same problem occurred in another location of said airport, but with different ballasts from a different producer.

Fig. 7.6: An advantage of electronic ballasts: Offset of voltage variances. Potential disadvantage of this: Current intake increases as voltage sags

Fig. 7.7: Electronic ballast failures at Swiss Federal Institute of Technology Zurich within one year

At Kaufbeuren hospital about 480 luminaires were integrated into the ceiling, each fitted with 2 fluorescent lamps, rated 2*13 W, with 1 common electronic ballast. By end of 2004, some 800 lamps had to be replaced. The filaments had blown. After long vain efforts to find out about the causes, the electrician in charge[14] found a coherence with the relatively long lines in the installation: On account of some very fast voltage fluctuation the electronic ballasts switched over to pre-heat mode. In the lab it was possible to reproduce this effect with a 50 m long line and a drilling machine, whereas it did not have to be a drilling machine but any other electronic device with a filtering capacitor at the input side did the »job«. It need not even be set into operation, just connecting it was enough to produce an extremely short (few microseconds) but very steep current rise time edge with an according voltage dip. The ballast misinterpreted this dip as an instance of switch-off and switch-on again and started to heat the filaments, waiting for the lamp current to rise as a signal of successful start, to shut off the heating current. But the lamp current did not rise because the lamp was already in operation, so the pre-heat current remained on and overloaded the filaments.

Another case occurred so to say right in place with a fluorescent lamp manufacturer at the final test of the production line for T5 lamps rated 80 W. The lamps are tested individually, so the test rack tests 1 piece every 6 seconds. Now the electronic ballasts installed in the test equipment did not bear this frequent switching and kept on failing, this making production stall each and every time it happened, along with all the cost impacts this brings about. But unfortunately T5 lamps cannot be operated with magnetic ballasts. Why can they not? With the 80 W lamp it does not work because the required lamp operating voltage is too high. At least as long as the applied voltage equals 230 V it is not possible but in commercial areas there is always a second supply level of 400 V available. At present a 400 V magnetic ballast is being developed with one of the ballast manufacturers. A prototype was exhibited at the 2004 Frankfurt Light & Building fair and is now being used in the shipment test procedure of said lamp manufacturer. Note that this implicitly means this manufacturer specifies its T5 lamps as fit for 50 Hz operation, since final test is carried out exclusively in this manner! The required 400 V electronic starter has already been made available[7] and is now being used in the test line – under the tough conditions of permanent response requirement, but without failure!

From another site it was reported the cause for permanent electronic ballast failures in a large hall had been searched for approximately two years until it was found out that they were due to mechanical oscillations. Fork lifters ran into and out of the hall all day long, and each time an automatic swinging door caused an air pressure wave that made the ceiling swing. Certain electronic components on the PCBs in the ballasts could not bear this and came loose.

A further very »adequately placed« case occurred in an office building of one of the four big German electricity utilities. Of one specific twin type ballast, driving two lamps with a 26 W rating each, 400 out of 1100 pieces had already failed within half a year. The 9-storey building had gone into operation in August 2000. Initially there had been failures of all types of electronic ballasts, while later on the failures concentrated on the type mentioned. The sort of failure was always the same: One capacitor, meant to filter disturbances from the AC input line, blew up (Fig. 7.8).

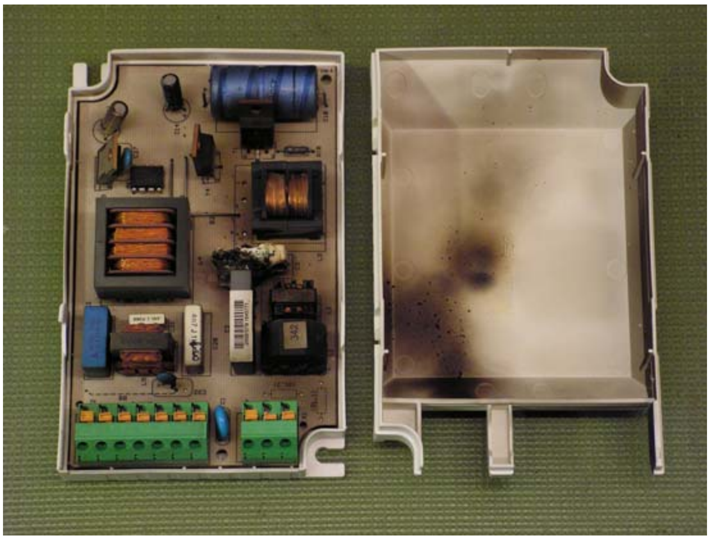

Fig. 7.8:Always the same type of failure: The filtering capacitor was overloaded …

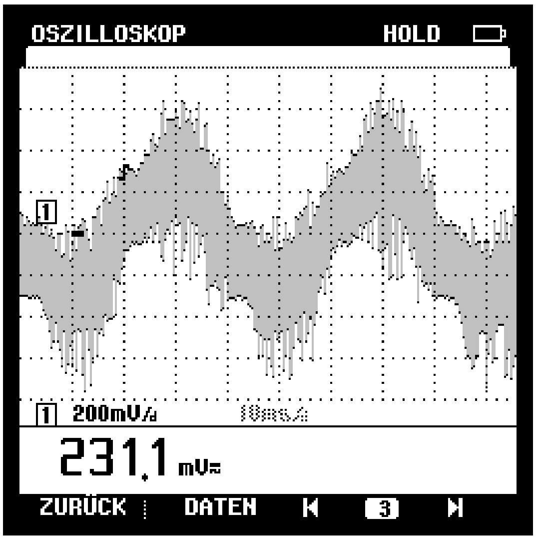

Fig. 7.9: … by a strong HF current due to a minor HF voltage superimposed upon the line voltage

Measurements brought no evidence of excessive HF on the line voltage, just the usual amplitude always found in such premises nowadays, but the ballast itself drew a current with heavy HF constituents of the ballast's own clock frequency (Fig. 7.9). On account of its lower reactance to higher frequencies, the capacitor rated for 400 V at 50 Hz was overloaded. So it has to be assumed that the multitude of electronic ballasts at this site, each of which dissipates a bit of HF current into the mains, is the basic cause for these frequent failures. Replacing the capacitor with a model for 630 V and thus providing more reserve might have been a remedial measure, although selecting a 400 V model already included a considerable reserve, but it was decided to replace all of the electronic ballasts in the questionable luminaires with magnetic models.

Strangely enough, none of such failures have been reported so far about CFLs, although they employ the same working principle except for the electronic PFC. This may be because they are not used in such large quantities within a constrained area. It is more likely, however, that the PFC electronics is the main source of failures in electronic ballasts, since it needs to be located right at the input side of the inverter, where it is exposed to all surges and other disturbances coming in from the network.

Of course there is no alternative to the use of electronic ballasts wherever one and the same lamp is to be used on various voltages and frequencies or on DC. On many railway vehicles, for instance, lighting can reasonably be fed on DC only, as the vehicle is fed on DC or 16.7 Hz. Since the DC feeding makes the active power factor correction in the ballast superfluous, no mass failures have been reported so far, which again confirms that the PFC is the weak point. The older German »InterRegio« railway carriages may be counted as an exception, where quite obviously the ceiling lamps, which can be switched individually by travellers, are operated with magnetic ballasts and conventional starters, as can be concluded from the well known flicker during start. This means that a dedicated power system is created inside the carriage, fed by an inverter converting either the 16.7 Hz power from the locomotive or the 24 V DC supply of the carriage into 50 Hz, since using the 16.7 Hz would end up not only with a ballast of triple volume and weight, which would be a serious issue on a vehicle, but also with a stroboscope light. It is reported that this was done because typical disturbances on a train, such as pantograph sparking, had caused failures of electronic ballasts, but obviously this problem has been overcome, and today's trains use electronic ballasts (but those without the dispensable electronic PFC) without causing any major trouble.

As for the voltage dependency or independency of the light output, one company in Germany carried out a test among various electronic ballasts and CFLs, an incandescent lamp (for comparison) and halogen lamps with electronic and conventional transformers.[14] Surprisingly enough, just one type of electronic ballast from each of the three leading producers performed a complete compensation of input voltage variance (constant light output). It may be speculated that these three were the top models of the three brands. Some of the CFLs at least managed to come from a square relationship between voltage and power, as for resistive loads, down to a linear behaviour.

7.3 Reliability

There is little quantitative evidence for the reliability of electronic ballasts. One statement speaks of a failure rate below 2% per 1000 hours of operation. That sounds quite nice, but for an average supermarket with 3000 h/a of operation this amounts to 6% dropouts per year. Under constant duty, like in a subway, it already means replacing more than 1 per every 6 ballasts annually. Considering this, it seems slightly strange to find this figure in a publication speaking very much in favour of electronic ballasts.[15]

It may be rather unspectacular if the producers of certain dedicated plant to be discussed further below do not state a single word in favour of electronic ballasts, since their products are applicable to magnetic ballasts only. But it is very well worth considering why official surveyors, inspectors and site electricians have serious qualms with the use of electronic ballasts. The use of electronic ballasts is, from today's viewpoint, inevitable if special high-end control functions including dimming are required, for as mentioned, dimming techniques for magnetic ballasts do no longer match today's ideas of functionality and comfort, such as in conference centres. Yet, for the common »area lighting« in warehouses, supermarkets, ordinary offices, subways, schools, industry, especially in EMC sensitive environments or under extreme temperatures or vibrations, the best EEI class (see Section 8 below) of magnetic ballasts will be the optimum choice. Their failure rates are next to zero in nearly all environments, as long as indicated maximum ambient temperatures are not substantially exceeded, while where a lot of electronics is integrated a lot can fail. Just like an instance of »the irony of destiny«, a severe power quality problem occurred during a power quality conference in a large modern conference building in Brussels. Sophisticated electronic lighting control got out of control and turned off the light every other minute. The conference centre management felt quite embarrassed and compensated the loss of usability to their client with a 50% price reduction. This financial loss may equal the electricity consumption of 1000 conferences and the energy savings achievable with high-tech lighting, if working properly, of at least 4000 conferences. It is evident that energy saving is not the prevalent reason for installing such technique in a conference room. It is the opportunity to provide optimal lighting for virtually everything one might want to do in a conference room. Even so, the loss of reputation caused by such embarrassing occurrence is probably a lot worse than through providing a less sophisticated, less versatile, less impressive technique but which just functions.

An advantage at least of many electronic ballasts is that they function with any frequency including DC. This cannot be expected from a magnetic ballast. Just by coincidence, a European ballast rated 58 W, 230 V, 50 Hz would do its job just as fine in an American 277 V 60 Hz office environment, but that is sure pure fluke in this individual case.

8 Energy efficiency

The efficiencies of technical devices and processes are normally rated as percentages. Just with light this does not really match, since with respect to the perception of brightness the human eye is differently sensitive to different colours. Therefore the sensitivity of a standardised average eye has already been integrated into the unit for assessing the brightness of light sources. This unit is called lumen (plainly the Latin word for light). Hence, the efficiencies of lamps and luminaires need to be given in lumens per watt. This and only this indication is appropriate to measure and compare which technical device generates most light per unit of drawn electrical power.

Theoretically an efficiency of 683 lumens per watt (lm/W) can be achieved. This, however, is only valid for mono-chromatic green light with a wavelength of 555 nm, where the human eye has its greatest sensitivity. So the »greenest« assumable lamp is indeed green. Irrespective of any political opinion, however, it remains more than questionable whether we really want to illuminate streets, squares, halls, offices, supermarkets or even living rooms in this way. White light – or what we consider white when mixing all colours from 380 nm to 780 nm wavelengths – yields a theoretical maximum of 199 lm/W. Setting this equal to 100% brings fluorescent lamps already considerably closer to the desired 100% ideal than a modern diesel engine is. Speaking in these terms, an incandescent lamp could merely be compared to an ancient steam locomotive.

The European Commission set out to support such trends towards such efficient lighting techniques and in June 1999 released the first draft of a directive with the objective to accelerate the transition of the Community industry towards the production of electronic ballasts and the overall aim to move gradually away from the less efficient magnetic ballasts and towards the more efficient electronic ballasts which may also offer extensive energy-saving features, such as dimming. This sounds as if it went without saying that an electronic ballast is

- always dimmable
- and always the more energy efficient choice.

Back to the latter item in Section 8.5. The misconception of the former has already been clarified in Section 3.3. Adding to this:

8.1 Do away with old rumours!

Let us first tidy up an old rumour which has it that fluorescent lamps consume a vast lot of electricity during start-up or warm-up – nobody specifies this precisely – and should therefore rather be kept in operation instead of turning them off when not needed for a shorter period. This rumour refers to magnetic ballast operation, since it is older than the invention of electronic ballasts, and is, of course, a balderdash, while the conclusive advice is largely correct: How could you ever draw such a high current out of a properly designed and fused system that within a few seconds a substantial amount of energy comes to be consumed? But still, even senior experienced electricians propagate this misconception, even though already their apprentices should be able to calculate that this is impossible. In fact, during pre-heating, when nearly all of the lamp apart from the filaments is shorted, the current is about 35% higher than the rating. Yet this is almost entirely reactive current. The reactive power during pre-heat actually rises about 90% and during cold operation about 30% above that of normal operation. The active – and thereby costly – share of the power approaches its rated value only slowly **from below** (Fig. 8.1). The truth about the story is, however, that it is not economical to switch fluorescent lamps very often because this contributes much to their ageing. This ageing effect, though, depends very much on the preheating conditions (being optimal with electronic starters) and is with today’s high quality lamps often found to be of minor impact in practice than the theory of fluorescent lighting wants it.

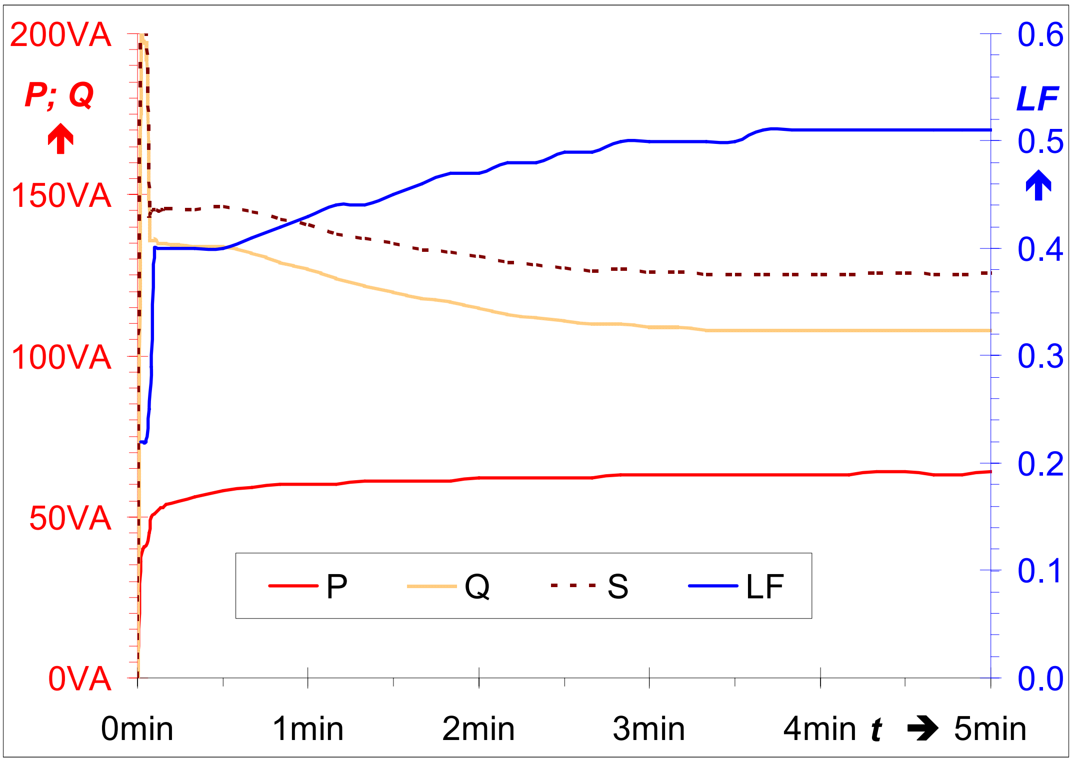

Fig. 8.1: Power intake of a 58 W fluorescent lamp with class B1 magnetic ballast during inrush, cathode pre-heat and warm-up phases: Moderate reactive overcurrent, no excess active power above rating at all!

8.2 Old EU Directive

The EU first of all classified fluorescent lamp ballasts by the overall power intake of the ballast and lamp circuit, targeting at gradually phasing out the less efficient models. For instance, the classes and limits for linear lamps are displayed in Table 8.1. The clue about class A1 is that these values refer to dimmable electronic ballasts. A ballast is classified A1 if it fulfils the following requirements:

- at 100% light output setting the ballast fulfils at least the demands of class A3;
- at 25% light output setting the total input power does not exceed 50% of the power at the 100% light output setting;
- the ballast must be able to reduce the light output to 10% or less of the maximum light output.

Lamp power rating		**Maximum input power of ballast and lamp circuits (ratings according to 2000/55/EU)**						
50Hz (magnetic)	**HF (electronic)**	**Class D**	**Class C**	**Class B2**	**Class B1**	**Class A3**	**Class A2**	**Class A1**
15W	14W	>25W	25W	23W	21W	18W	16W	9.0W
18W	16W	>28W	28W	26W	24W	21W	19W	10.5W
30W	24W	>40W	40W	38W	36W	33W	31W	16.5W
36W	32W	>45W	45W	43W	41W	38W	36W	19.0W
38W	32W	>47W	47W	45W	43W	40W	38W	20.0W
58W	50W	>70W	70W	67W	64W	59W	55W	29.5W
70W	60W	>83W	83W	80W	77W	72W	68W	36.0W

Table 8.1: Values and classes of linear fluorescent T8 lamps with ballasts

Now it would have looked somewhat ugly to see the losses decreasing from class D all through class A2 but then to come across the inconsistency of an increase again towards the »upper class« A1[16]. So an appropriate definition was invented that says the rated power is that measured at 25% light output, since a dimmable system will not always be run at full power. This is just as logical as saying a car's engine does not always need to supply its maximum power, so if the car's top speed is 200 km/h, let's rate the engine power necessary to drive the car at 50 km/h as the nominal engine power.

Supplementary to this comes the curious fact that electronic ballasts are promoted with lower heat losses inside the ballast being one of the chief arguments, while named Directive allows **higher** losses in an **electronic** ballast than in a magnetic one. For instance, in Table 8.1 we learn that a 58 W lamp together with a magnetic ballast must not exceed a consumption of 64 W to comply with the requirements of class B1. This allows for a loss level of 6 W. However, when we shift to class A3, the lamp power drops to 50 W and the systems power to 59 W, allowing for a loss level of 9 W for the allegedly better ballast (Fig. 8.2).

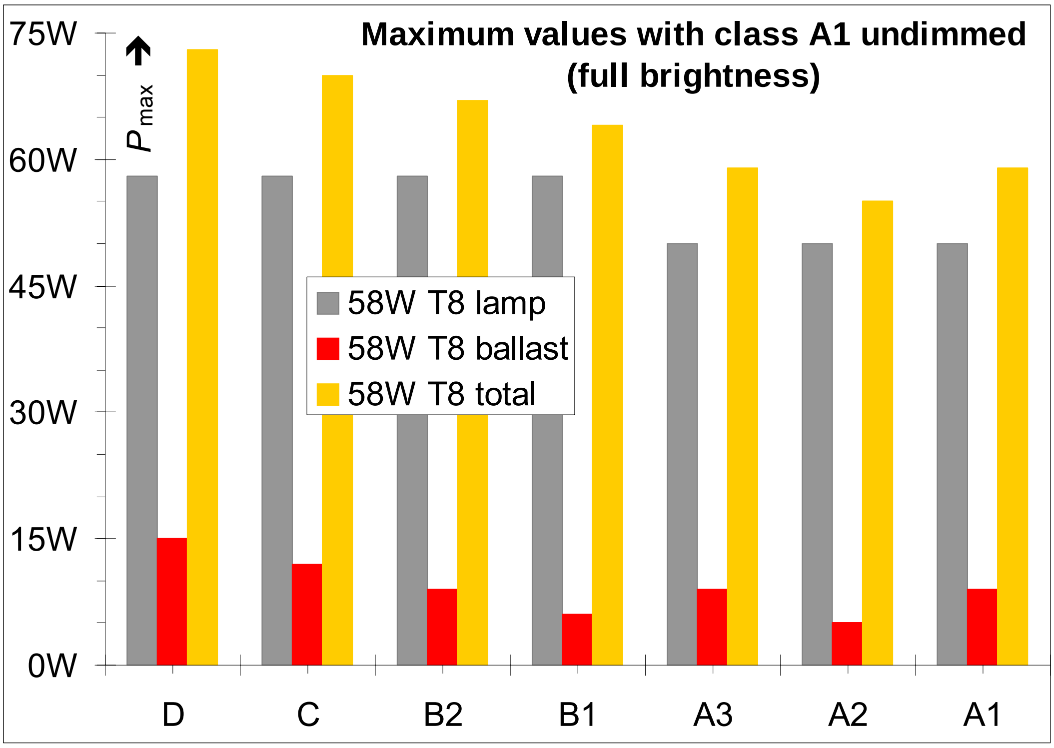

Fig. 8.2: Split of system input power across a 58 W T8 lamp and its ballast

This does not matter so much, though, since this Directive fixes the entire gross power consumption of a system as a criterion. Basically this yields a correct approach, yet the good idea turns out as a disadvantage for magnetic ballasts, because, as mentioned in the introduction, electronic ballasts feed less than the 50 Hz rated power into the lamp. It is argued that on account of the high operating frequency the lamp efficiency was better and therefore the luminous density nearly the same, only 4% less. First of all, the criteria neglect these 4%, as the Directive values and classes specify electric power only, not light output. Second, the EU realized later that the price premium for an electronic ballast was very high (Table 3.1, Section 3.3), while converting from a poor to a good type of magnetic ballast proved much more cost efficient (Table 8.2). Mind that these calculations were done without any consideration of interest rates for the invested capital!

Of course is has to be borne in mind that discounts of up to 80% from these prices may be achieved by industrial customers – not so much by electrical contractors. But then it should also be considered that mentioning the 4% difference in light output is not yet telling the full truth, since this difference does not refer to the rated power but to the deviating actual power intake of a lamp with a good magnetic ballast operated at rated voltage. A deliberate usage of the very generous tolerance margin, which in principle would not any longer be required for today's precise production methods, makes this possible. Still, even with this ballast design the same lamp is about 4% brighter than the same lamp with an electronic ballast, as will be seen in Section 8.5. The 5 W difference between a class B1 magnetic ballast and a class A3 electronic ballast for a 58 W lamp, which the values of Table 8.2 are based on, thereby dwindles away to leave hardly any more than 2 W. So the indicated payback periods remain valid even for the high rebates when real electrical values measured at equal light outputs are compared.

Therefore named EU directive so far aimed at phasing out merely the classes C and D, which was done in November 2005 and May 2002, respectively, and which indeed is not a pity. Then, the market and technologies available so far will be investigated and assessed once again and further steps decided according to the results. So this is by far not a displacement plan for magnetic ballasts, as had been the initial intention and is still often believed even within the lighting industry. After all there would have been little sense in doing so, since, as the directive itself mentions at a different point, the improvement steps so far defined can be achieved with a cost premium around 2 € per lamp, while all improvements necessitating a conversion to electronic ballasts comes at an additional cost of 20 € per lamp.

Payback periods (based on above Vossloh-Schwabe prices)			
Intensity of use: 3000 h/a	Rated values	Measurement at	
Electricity price: 0.12 €/kWh		$U=U_N$	$\Phi_M=\Phi_E$
Replacing a class C magnetic with a class B1 magnetic ballast	2.81a	2.23a	2.26a
Replacing a class B2 magnetic with a class B1 magnetic ballast	0.57a	0.87a	0.87a
Replacing a class C magnetic with a class A3 electronic ballast	6.19a	4.80a	9.06a
Replacing a class B1 magnetic with a class A3 electronic ballast	10.24a	7.74a	35.14a
Replacing a class C magnetic with a class A2 electronic ballast	7.69a		
Replacing a class B1 magnetic with a class A2 electronic ballast	10.94a		

Table 8.2: Payback periods for improved magnetic and electronic ballasts

8.3 New EU Directive

By and large it is time to decide about further steps. Therefore the EU is planning to repeal the Directive 2000/55/EU and replace it with the Commission Regulation for implementing the »Ecodesign« Directive 2005/32/EC (EuP Directive – Energy using Products) in the area of lighting components, but it is not yet certain when this will happen. Right now further comments are still being waited for. **However, other than frequently heard even from lighting experts, this Directive does not incur any plans to abolish magnetic ballasts!**

After confirmation the new Directive is planned to enter into force in three stages: One year after entry into force preliminary limit values become valid. Three years after entry into force they become one level stricter, and eight years after entry into force these levels will be replaced with yet stricter final limits. This way industry shall be given sufficient time for a conversion. At least this is the principle behind it. The practical implementation is somewhat more lenient. The most substantial novelties are:

- As an »Ecodesign« directive it does not only provide electrical values but also e. g. maximum limits for the mercury content and minimum values for the lifetime expectancy of lamps.
- Minimum values for complete luminaires are included – although the only »Requirement« is that »all luminaires … shall be compatible with ballasts complying with the first / second / third stage requirements«.
- Minimum efficiencies (light output efficacies) are introduced for all common fluorescent and gas discharge lamp types – i. e. for the lamps alone without consideration of the ballast.

- Apart from this, there are separate limit values for the energy efficiencies of ballasts, measured as the ratio of the lamp power rating divided by the sum of the lamp power rating plus the ballast power loss.
- A most substantial difference at this point is that Table 17 (in part reproduced here as Table 8.4) of this new implementing regulation distinguishes between three different power values of lamps: a nominal power, which is, so to say, only the name of the respective lamp, a rated power for mains frequency operation and a rated power for HF operation. The »nominal« power is usually identical with the 50 Hz rated power unless the latter is not an integer figure but has a decimal. Then the decimal is omitted. For instance, an FD-38-E-G13-26/1050 lamp according to ILCOS (International Lamp Codification System) with a power rating of 38.5 W for 50 Hz and 32.0 W for HF has a nominal power of 38 W and is hence called a »38 W (T8) lamp«. In the old Directive the difference between the nominal 38 W and the 32 W HF rating appeared like a 6 W advantage for the HF (electronic) ballast, which it has never ever been. The new approach is to measure, calculate and assess the energy efficiency of a »magnetic ballast for a 38 W T8 lamp« based on an output of 38.5 W and the energy efficiency of an »electronic ballast for a 38 W T8 lamp« based on an output of 32 W, rather than comparing the inputs only.
- For dimmable electronic ballasts and other remote controllable lamp operating devices there are maximum stand-by losses.
- Moreover, the power intake – of the lamp as well as the power loss in the ballast – is now to be measured at the point where the light output equals the light output rating of the respective lamp at 25°C ambient temperature. This is a substantial improvement against the present approach to classify only the power intake of the entire system and ignore any possible differences in light output between the uses of different ballasts on the same lamp. Thereby an impartial treatment of both magnetic and electronic ballasts is now granted. The application of two different measures but without respect to the light output comes to an end.

At this point unfortunately the widespread misunderstanding mentioned above arose. The pitfall is that the old designations A1, A2, A3, B1 and B2 continue to be used. A1 continues to stand for dimmable ballasts. Two new classes A1 BAT and A2 BAT (»best available technology«) have been introduced, whereas, again, the former is reserved for dimmable ballasts. However, none of these class designations relates to the old Directive 2000/55/EU, but they are redefined within the new Directive 2005/32/EC. As described above, this is done by means of the ballast energy efficiencies as a percentage value of the **real** electrical output power by **real** electrical input power ratio. Now no class is linked to any certain ballast technology any longer, as has been the case so long, such as A for electronic, B (and formerly also C and D) for magnetic except that A1 and A1 BAT are by definition dimmable ballasts. But their efficiencies are defined in terms of the other classes, as used to be the case before.

The lamp efficiencies, however, are not divided into classes. This would have gone way too far, since there are so many different types around. These limits must be taken directly out of one of the countless tables, starting with Table 1 splitting double-capped lamps into T8, T5HE and T5HO types. This table (reproduced here as Table 8.3) reveals rather clearly how far T5HO lamps fall behind not only T5HE but also behind T8 lamps. So T5 lamps are in no way generally more efficient than T8 lamps, as is frequently assumed and alleged (also see section 8.7). This becomes evident at the very first look at the new documentation. The changes in detail are, as far as energy efficiencies are concerned:

Lamp efficiencies

- **First stage requirements:** One year after the entry into force of the new regulation T5 and T8 lamps shall have at least the rated luminous efficacies as specified in Table 1 of said regulation (see Table 8.3), all measured at 25°C ambient temperature. This appears to be a bit unfair against T5 lamps, though, because for some good reasons they are optimized for an ambient temperature of 35°C.

- **Second stage requirements:** Three years after the entry into force the requirements for T8 lamps from the first stage will be expanded to all double capped fluorescent lamps. So this may mean that the T5HO lamp has to go, unless it undergoes some substantial improvement so as to match the requirements for T8 lamps!
- **Third stage requirements:** Eight years after the entry into force fluorescent lamps are not faced directly with any additional efficiency requirements. It only says they »shall be designed to operate with ballasts of energy efficiency class at least A2 according to Annex III.2.2«, but this can be said of any common fluorescent lamp already now. Note: It does **not** say, »The ballast / system shall meet the energy efficiency requirements of class A2 according to 2000/55/EU«, which would have been something entirely different!

Table 1 of Directive 2005/32/EC – minimum rated luminous lamp efficacies, 100 h initial values for T8 and T5 lamps					
T8 (26 mm Ø)		**T5 (16 mm Ø)**			
		HE (High Efficiency)		**HO (High Output)**	
Nominal wattage	**Luminous efficacy**	**Nominal wattage**	**Luminous efficacy**	**Nominal wattage**	**Luminous efficacy**
15W	63lm/W	14W	86lm/W	24W	73lm/W
18W	75lm/W	21W	90lm/W	39W	79lm/W
25W	76lm/W	28W	93lm/W	49W	88lm/W
30W	80lm/W	35W	94lm/W	54W	82lm/W
36W	93lm/W			80W	77lm/W
38W	87lm/W				
58W	90lm/W				
70W	89lm/W				

Table 8.3: Table 1 of Directive 2005/32/EC

Ballast efficiencies

- **First stage requirements:** One year after the entry into force of the new regulation the minimum energy efficiency index class shall be B2 (according to Table 17 of 2005/32/EC!) for ballasts covered by Table 17, and A1 for dimmable ballasts covered by Table 19 (of 2005/32/EC, not of 2000/55/EU, which it supersedes! See Table 8.4 here). Parallel with the old Directive, this implies that the ballast's efficiency shall match the requirements of class A3 when set to full power and shall use no more than 50% of its full power when set to 25% light output, as used to be the case in the old Directive.
- **Second stage requirements:** Three years after the entry into force there is no change to non-dimmable ballasts for fluorescent lamps. Limits for high-pressure discharge lamps are upgraded, and the stand-by consumption of dimmable ballast goes from 1 W down to 0.5 W maximum.
- **Third stage requirements:** Eight years after the entry into force the minimum efficiencies of ballasts are:
  η = 71% for ballasts up to 5 W (nominal power),
  η = 91% for ballasts from 100 W upwards,

$$\eta = \frac{P_{Lamp}}{2 * \sqrt{\frac{P_{Lamp}}{36}} + \frac{38}{36} P_{Lamp} + 1}$$

for ballasts between 5 W and 100 W.

This calculation of η is called EB_{bFL} in 2005/32/EC. As described above, this approach yields different efficiency values for the same lamp, depending on whether it is being operated with a magnetic or an electronic ballast if different power ratings are given for either of these. The required efficiencies turn out to be a little bit lower for electronic ballasts, which is obvious when one enters slightly lower values of P_{Lamp} into the formula.

Table 17 of Directive 2005/32/EC – Energy efficiency index requirements for non-dimmable ballasts for fluorescent lamps

Lamp data				Ballast efficiency ($P_{\text{Lamp}}/P_{\text{input}}$) – non-dimmable						
Lamp type	Nominal wattage	Rated / typical wattage		EEI class (for stages 1 and 2)					EBb_{FL}	
		50Hz	HF	A2 BAT	A2	A3	B1	B2	50Hz	HF
T8	15W	15.0W	13.5W	87.8%	84.4%	75.0%	67.9%	62.0%	82.8%	81.9%
T8	18W	18.0W	16.0W	87.7%	84.2%	76.2%	71.3%	65.8%	84.1%	83.2%
T8	30W	30.0W	24.0W	82.1%	77.4%	72.7%	79.2%	75.0%	87.0%	85.8%
T8	36W	36.0W	32.0W	91.4%	88.9%	84.2%	83.4%	79.5%	87.8%	87.3%
T8	38W	38.5W	32.0W	87.7%	84.2%	80.0%	84.1%	80.4%	88.1%	87.3%
T8	58W	58.0W	50.0W	93.0%	90.9%	84.7%	86.1%	82.2%	89.6%	89.1%
T8	70W	69.5W	60.0W	90.9%	88.2%	83.3%	86.3%	83.1%	90.1%	89.7%
T5-E	14W	—	13.7W	84.7%	80.6%	72.1%	0.0%	0.0%	—	82.1%
T5-E	21W	—	20.7W	89.3%	86.3%	79.6%	0.0%	0.0%	—	85.0%
T5-E	24W	—	22.5W	89.6%	86.5%	80.4%	0.0%	0.0%	—	85.5%
T5-E	28W	—	27.8W	89.8%	86.9%	81.8%	0.0%	0.0%	—	86.6%
T5-E	35W	—	34.7W	91.5%	89.0%	82.6%	0.0%	0.0%	—	87.6%
T5-E	39W	—	38.0W	91.0%	88.4%	82.6%	0.0%	0.0%	—	88.0%
T5-E	49W	—	49.3W	91.6%	89.2%	84.6%	0.0%	0.0%	—	89.0%
T5-E	54W	—	53.8W	92.0%	89.7%	85.4%	0.0%	0.0%	—	89.3%
T5-E	80W	—	80.0W	93.0%	90.9%	87.0%	0.0%	0.0%	—	90.5%
T5-E	95W	—	95.0W	92.7%	90.5%	84.1%	0.0%	0.0%	—	90.9%
T5-E	120W	—	120.0W	92.5%	90.2%	84.5%	0.0%	0.0%	—	91.0%
T5-C	22W	—	22.3W	88.1%	84.8%	78.8%	0.0%	0.0%	—	85.4%
T5-C	40W	—	39.9W	91.4%	88.9%	83.3%	0.0%	0.0%	—	88.2%
T5-C	55W	—	55.0W	92.4%	90.2%	84.6%	0.0%	0.0%	—	89.4%
T5-C	60W	—	60.0W	93.0%	90.9%	85.7%	0.0%	0.0%	—	89.7%
TC-TE	120W	—	122.0W	92.6%	90.4%	84.7%	0.0%	0.0%	—	91.0%
TC-DD	55W	—	55.0W	92.4%	90.2%	84.6%	0.0%	0.0%	—	89.4%

Table 8.4: Excerpt from Table 17 of Directive 2005/32/EC

So also this new document makes no statement whatsoever about any prohibition of magnetic ballasts. Otherwise what sense would there be in defining new values for classes B1 and B2? Rather, there used to be quite an imbalance to the advantage of electronic ballasts in the old scheme according to Directive 2000/55/EU, which will now have to go in the foreseeable future. While it is always argued among experts that one of the advantages of electronic ballasts was the lower internal power loss, even the old Directive 2000/55/EU stated the very opposite! For instance, it says there referring to a 58 W T8 lamp:

- Lamp power with **magnetic** ballast: 58 W,
- systems power with **magnetic** ballast (class B1 – old): ≤ 64 W.
- This allows for a power loss of ≤ 6 W inside the magnetic ballast.
- Converted to the new calculation method, this yields a minimum efficiency requirement of $\eta \geq 58\text{ W} / 64\text{ W} \approx 91\%$, matching the new class A2, rather than B2, which would already satisfy stage 1 of the new regulation! The EBb_{FL} requirement of stage 3 is only $\eta = EBb_{\text{FL}} \geq 89.6\%$, so it is also easily fulfilled by the good old magnetic ballast!

But at the same time it also says in the old 2000/55/EU document:

- Lamp power with **electronic** ballast: 50 W,
- systems power with **electronic** ballast (class A3 – old): ≤ 59 W.

- This allows for a power loss of ≤ 9 W inside the electronic ballast!
- Converted to the new calculation method, this yields a minimum efficiency requirement of $\eta \geq 50\ \text{W} / 59\ \text{W} \approx 85\%$ – passing B2 (new) but failing B1 (new), therefore just about compliant with stage 1. The EBb_{FL} requirement of stage 3 is $\eta = EBb_{FL} \geq 89.1\%$ here, hence also failed! In other words: The old Directive allocates a higher class to a poorer ballast and vice versa!

The **new** classification requires the energy efficiency of a 58 W ballast for a T8 lamp to be 84.7% in class A3 or 86.1% in class B1, respectively. It is a bit confusing why the new class B1 requires a higher efficiency than class A3. In fact it also allocates a higher class to a poorer ballast here. This is the case not with all, but with a number of ballasts and may be a remnant of the old definitions for classes B1 and A3, whenever it is better concealed there (see above). After all this is nothing to worry too much about because these requirements are only a transition to the continuously calculated method of the final stage No. 3. However, it does become evident that a **magnetic** ballast of class B1 according to the **present (old)** classification has far lower losses than required by the **present (old)** class A3; moreover, it even **complies with the new A2 requirements!** An electronic ballast according to the old class A3, however, just about manages to comply with the new class A3. This does not really look like a prohibition of magnetic ballasts but rather the opposite!

8.4 Avoiding avoidable losses in small fluorescent lamps

Advertisements in favour of electronic ballasts occasionally claim that in magnetic ballasts »up to 30%« of the luminaire's total power intake is absorbed as losses. First of all, it remains to be noted that a statement like »up to«, very popular though it may be, is also totally inappropriate to make any statement at all, unless simultaneously complemented by indicating the mean and the maximum values [2, p. 289]. The same here: The greatest relative losses occur with the smallest lamps. This can be traced back to a law of nature once called »Paradox of the Big Machine«[17]. In a 58 W lamp, for instance, it is only 13% (see Section 8.5). Moreover, the piece numbers of smaller lamps are also smaller, and so their overall contribution to the total losses is all the smaller. So the indication »up to 30%« tells nothing at all.

While, on the other hand, it is even disexaggerating. For instance, when measuring the power shares on a TC-S lamp rated 5 W and operated with a conventional magnetic ballast, a lamp power magnitude of 5.6 W may be found, along with once again the same magnitude of ballast losses, so in this case you may very well speak of 50% losses.

Generally, however, the lamp voltage across smaller, i. e. shorter fluorescent lamps of the same type family is lower than with the longer types of the same series. Thereby, for longer lamps a larger share of the voltage drops across the lamp and a smaller share across the ballast. At the same time the current rating is a bit lower with the longer lamps, while the ballast remains the same (Fig. 8.3, Fig. 8.4). However, the ballast losses are approximately proportional to the square of the current. So if you replace the 5 W lamp in one and the same luminaire with a 7 W lamp, which is not a problem at all if only the greater lamp length can be accommodated, under the bottom line you receive more lamp power at lower power loss.

But this is still not the full story, since the lamp voltage across the TC-S lamps rated 5 W, 7 W and 9 W is so low that the common mains voltage of 230 V allows two of these lamps to be operated in series on one ballast. In effect, this doubles the lamp voltage again, of course. Since the same ballast is used for this so-called tandem connection as for the single operation, the actual current and thereby the resulting lamp power when operated in tandem lie slightly below the ratings. In order to minimize the deviation, the magnetic ballasts are designed in a way so that in single mode the current and power magnitudes are slightly above the ratings. In total, the effect is that the ballast is always less loaded, the more lamp power rating is connected to it. More lamp load leads to an absolute drop in losses and thus, in relative terms, saves duplicate (Fig. 8.6).

Fig. 8.3: 4 different single lamps and 3 possible tandem configurations can be operated on one and the same ballast

Simultaneously, the lamp efficiencies improve when the lamps are not operated at full power, and inversely efficiencies drop when lamps are operated at overload (more about this in Section 8.5). This was revealed during a measurement carried out by a well respected and independent lighting institute[18], recording not only the electrical values but along with these the light output (Table 8.5). In this test the 9 W lamp turned out at the end of the scale, since the 5 W and 7 W lamps had already disqualified themselves to participate at all according to the results of a pre-test displayed in Fig. 8.6.

Fig. 8.4: One and the same ballast is designed for 4 different single lamps and (for reasons of space not listed here) 3 possible tandem configurations

Fig. 8.5: TC-D lamp 18 W, energy efficient magnetic ballast and electronic ballast for this (top) and energy efficient magnetic ballast for a commonplace T8 lamp of equal power rating (bottom)

Albeit, the light output efficiency with a tandem connection of two 9 W lamps on one magnetic ballast – and even an old, less efficient one – turned out equal to that of a high-end CFL and 20% better than a cheap CFL from the DIY supermarket! It remains to be stated here that the operation of a CFL is always an operation with an (integrated) electronic ballast! So much about the better lamp efficiency with electronic ballasts. Compared to the single-mode operation of one 9 W TC-S lamp the 2*9 W tandem configuration turned out 25% more efficient – with the same ballast, after all! However, the light output is a bit less than double that of the single lamp. This remains to be considered when designing a lighting installation.

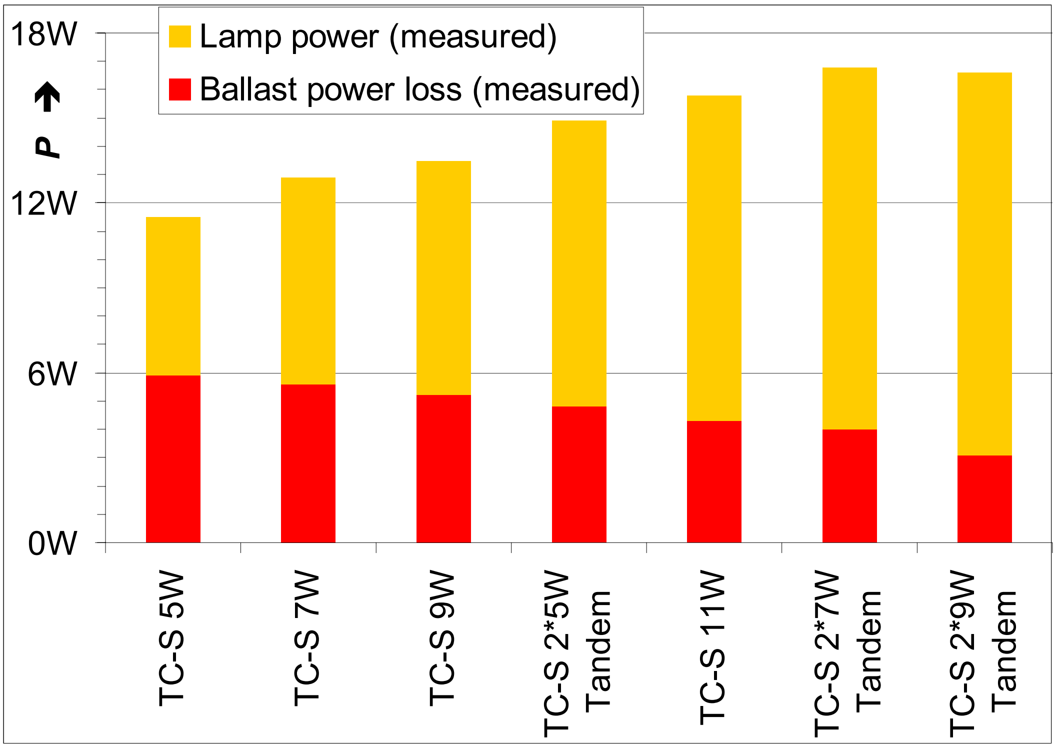

Fig. 8.6: Split of total luminaire power intake for different TC-S lamp configurations with the same ballast

But the tandem connection is also applicable to T8 lamps with a power rating of 18 W. Although in this case different ballasts are meant to be used for single and tandem configuration, the results are similarly profitable. Here, too, the finding is that the power loss in the class B1 ballast attributable to two lamps is even lower than that in the class B1 ballast for only one lamp (Fig. 8.7).

Type (device under test)	**Metering conditions**	**Measurements DIAL**						**Calculated values**			
		U V	**P_{tot}** W	**P_{Ball}** W	**P_{Lamp}** W	**I** mA	**Φ** lm	**η_{Lamp}** lm/W	**η_{tot}** lm/W	**P_{Loss} / P_{tot}**	**P_{tot} / P_N**
CFL Megaman 4W		**207.2**	3.43	---	---	29.7	159.1	---	**46.39**	---	---
	Rated voltage →	**230.0**	3.86	---	---	30.6	172.9	---	**44.79**	---	---
		253.1	4.30	---	---	31.5	183.8	---	**42.75**	---	---
CFL Action Sunlight 11W		**207.1**	9.59	---	---	98.7	479.6	---	**50.01**	---	---
	Rated voltage →	**230.0**	10.82	---	---	102.6	504.8	---	**46.66**	---	---
		252.9	12.04	---	---	106.5	529.0	---	**43.93**	---	---
CFL Osram Dulux EL 11W		**207.4**	10.52	---	---	78.0	593.3	---	**56.40**	---	---
	Rated voltage →	**230.3**	11.80	---	---	80.1	657.9	---	**55.75**	---	---
		253.3	13.02	---	---	81.9	706.4	---	**54.26**	---	---
Osram Dulux S 9W		**207.0**	11.05	3.70	7.40	150.0	509.0	68.79	**46.07**	33.5%	100.0%
	Rated voltage →	**230.0**	13.29	5.10	8.20	176.0	559.9	68.28	**42.13**	38.4%	100.0%
		253.0	16.47	7.30	9.20	212.0	612.6	66.59	**37.20**	44.3%	100.0%
2*Dulux S	Rated voltage →	**230.0**	16.64	3.20	13.50	136.6	928.4	68.77	**55.79**	19.2%	100.0%

Table 8.5: Comparison of electrical data and light outputs with small fluorescent lamps

Now there are some more lamp types with a rating of 18 W available on the market, e. g. the TC-D lamp. But this one has a much higher operational voltage drop and can therefore not be operated in tandem mode. But since the voltage drop across the lamp under normal operating conditions is greater, the voltage drop across the ballast is smaller. So the required reactive power rating of the ballast is also selected accordingly smaller – and thereby the whole ballast is.

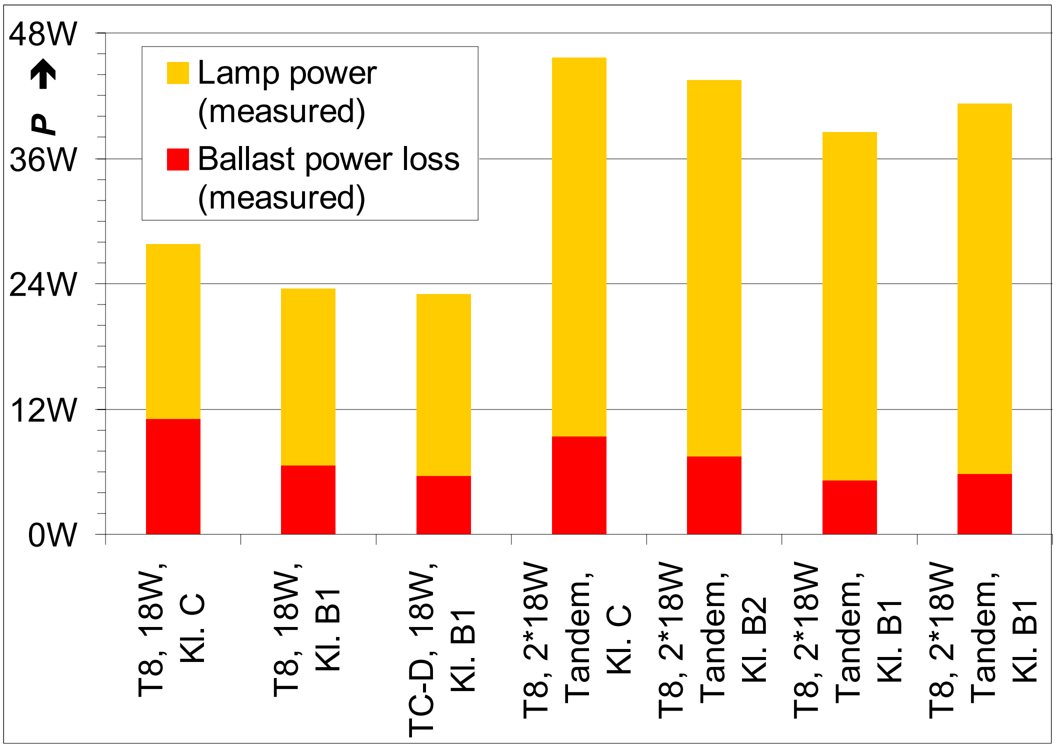

Fig. 8.7: 18 W fluorescent lamps in single and tandem mode comparison

But this is not yet all. When the lamp voltage is greater, the lamp current is also smaller and reduces the required reactive power level again (see Section 5.2). Therefore a magnetic ballast for a TC-D lamp can be built extremely small, also when designed according to efficiency class B1 – even smaller than a commensurate electronic ballast (Fig. 8.5)! So especially a luminaire with a TC-D lamp and a high-efficiency magnetic ballast saves space, production costs and energy in one go.

The latter finds its confirmation when you add another light output measurement. For this reason the single and tandem operation modes of class B1 magnetic ballasts for 18 W and 2*18 W, respectively, were compared to a single and twin operation mode on an electronic class A2 ballast rated 18 W or 2*18 W, respectively. The result is compiled in 3 blocks of 7 measurements of the light flux Φ each, displayed in Table 8.6:

- One single T8 lamp,
- two T8 lamps in tandem or twin mode, respectively,
- one TC-D lamp,

with the following ballasts and data:

- Electronic ballast at the lower voltage tolerance limit 90% (207 V),
- electronic ballast at rated voltage (230 V),
- electronic ballast at the upper voltage tolerance limit 110% (253 V),
- magnetic ballast at the lower voltage tolerance limit 90% (207 V),
- magnetic ballast at rated voltage (230 V),
- magnetic ballast at the upper voltage tolerance limit 110% (253 V)
- magnetic ballast at the voltage magnitude where the light output equals that of the same lamp with electronic ballast at 230 V.

Type (device under test)	Metering conditions	Measurements DIAL						Calculated values			
		U	P_{tot}	P_{Ball}	P_{Lamp}	I	Φ	η_{Lamp}	η_{tot}	P_{Loss}	P_{tot}
		V	W	W	W	mA	lm	lm/W	lm/W	P_{tot}	P_N
T8 lamp 18W with electronic ballast EEI=A2		**207.0**	19.10			98.4	1382		**72.34**		
	Rated voltage →	**230.0**	19.13			90.6	**1381**		**72.19**		
		253.0	19.10			85.0	1383		**72.41**		
T8 lamp 18W with magnetic ballast EEI=B1		**207.0**	20.96	4.70	16.23	304.7	1195	73.65	**57.03**	22.4%	85.7%
	Rated voltage →	**230.0**	24.47	6.24	18.21	354.6	1320	72.50	**53.95**	25.5%	100.0%
	Φmag=Φelec →	**241.7**	26.18	7.21	18.94	382.2	**1381**	72.91	**52.75**	27.5%	107.0%
		253.0	28.19	8.22	19.94	410.6	1438	72.13	**51.02**	29.2%	115.2%
T8 lamps 2*18W with electronic ballast EEI=A2		**207.0**	36.59			181.0	2816		**76.96**		
	Rated voltage →	**230.0**	36.58			164.2	**2817**		**77.00**		
		253.0	36.53			149.7	2815		**77.07**		
T8 lamps 2*18W with magnetic ballast EEI=B1		**207.0**	33.70	3.33	30.37	296.0	2330	76.72	**69.14**	9.9%	79.8%
	Rated voltage →	**230.0**	42.24	5.34	36.90	379.0	2809	76.12	**66.50**	12.6%	100.0%
	Φmag=Φelec →	**230.8**	42.70	5.58	37.12	387.0	**2817**	75.90	**65.98**	13.1%	101.1%
		253.0	50.48	8.20	42.28	473.0	3169	74.95	**62.77**	16.2%	119.5%
TC-D lamp 18W with electronic ballast EEI=A2		**207.0**	16.09			78.5	1064		**66.13**		
	Rated voltage →	**230.0**	17.75			78.2	**1173**		**66.11**		
		253.0	19.84			79.8	1276		**64.34**		
TC-D lamp 18W with magnetic ballast EEI=A2		**207.0**	17.71	3.33	14.40	165.7	982	68.19	**55.44**	18.8%	81.7%
	Rated voltage →	**230.0**	21.69	4.96	16.70	204.7	1117	66.87	**51.48**	22.9%	100.0%
	Φmag=Φelec →	**241.4**	23.86	6.01	17.80	225.7	**1173**	65.93	**49.18**	25.2%	110.0%
		253.0	26.53	7.48	19.05	250.5	1229	64.51	**46.32**	28.2%	122.3%

Table 8.6: Compilation of measuremets on 18 W fluorescent lamps with magnetic and electronic ballasts

For measuring the T8 lamp in single-mode, a single-lamp electronic ballast was used instead of using the twin-mode one and connecting only one lamp, which would have been possible but would have yielded wrong results. The most crucial results can be found in Table 8.6, represented as the light efficiency η_{tot} in lumens per watt electrical power intake of the whole lamp and ballast system. The light efficiency cannot be given in per cent because regarding brightness the human eye is differently receptive to light of different colours. Therefore the sensitivity of a standardised average eye is already integrated into the unit for brightness. This unit is called lumen (simply the Latin word for light). So the efficiency of lamps and lumiaires has to be given in lumens per watt. So this and only this unit is adequate to assess which technical device provides the greatest brightness per power intake. Of course the share of ballast losses in the total power intake can be given as a percentage – as done in the last column of the table. However, with the electronic ballasts the required measurement of the lamp power, the ballast output power to the lamp so to say, was not possible due to the high output frequency. Therefore the efficiency η_{Lamp} of the lamp alone could not be calculated. Nevertheless, the following results can be read and conclusions drawn from the table:

1. The advantages of the tandem configuration and of the TC-D lamp already found in the pre-measurement with respect to reactive power find their confirmation.
2. The magnetic ballast power loss increases highly over-proportionally to the systems operating voltage. At 253 V the power loss is usually double as high as at 207 V. Together with the slight increase of lamp efficiency η_{Lamp} the voltage reduction practice results as an efficient means of loss reduction for all magnetic ballast configurations.
3. Inversely as with 58 W lamps (see Section 8.5), the lamps are about 4% brighter with electronic than with magnetic ballasts. With the twin electronic ballast compared to the magnetic tandem configuration the difference is even 8%. The operating voltage on the tandem has to be turned nearly up to the upper tolerance limit of 244 V before the same brightness as with the electronic twin ballast is achieved.

Therefore when assessing the light efficiency two different approaches have to be considered:

4. Either the luminaires are operated at rated voltage in either case. The comparison will then be closer to what will usually happen in practice, though it is not objective. We are then talking about a systems power of 19.13 W with electronic ballast versus a systems power of 24.47 W with magnetic ballast. A payback time for the well over 5 W saved cannot be given, as the impact of the price premium for an electronic ballast upon the price for a complete lighting installation is subject to substantial variances. However, with an energy price of 10 c/kWh it takes 1872 operating hours to save the first Euro. This cornerstone can be used for the according conversions: At 5 c/kWh it takes 3744 hours, at 20 c/kWh it takes 936 hours to save 1 Euro.
5. Or you calculate objectively. Nobody will increase the line voltage in order to achieve precisely the same brightness with the used / planned magnetic ballast as with the electronic ballast not used, but the lighting planner might include a few more lamps if the decision for magnetic ballasts has been taken. This would have practically the same effect as if the same number of lamps were connected to a line voltage of 241.7 V, which would be equivalent to the difference between 19.13 W and 26.18 W systems power, say 7 W. So the real, effective »savings cornerstone« is then 1418 operating hours per Euro saved at 10 c/kWh.
6. Moreover, it becomes obvious that the limits of the EU directive, which is 24 W systems power in class B1 and 19 W in class A2, are in principle not complied with, neither by the magnetic nor by the electronic ballast. Only by being rather lenient accounting to metering inaccuracy the EEI classes can still be seen as just about fulfilled.

But by all means this mode of operation does not represent the optimal combination. The power loss in a 36 W ballast is not double the loss in an 18 W ballast (»Paradox of the Big Ballast«), about the triple advantage of the tandem mode not even to speak. Rather, the respective conclusions to above items 4 to 6 for the twin or tandem modes of two 18 W lamps will be:

7. Comparing the operation at rated voltage in either case, the difference between magnetic and electronic ballast operation is now only more 2 W per system, whereas a system now comprises two lamps and one ballast (and two starters in the case of magnetic the ballast). So with an electricity price of 10 c/kWh it takes 5000 operating hours to save one Euro. Or, selecting a different example: At uninterrupted permanent duty with 8760 h/a and an electricity price which is usually quite inexpensive for such use, e. g. 5.7 c/kWh, the electronic ballast saves precisely one Euro per year.
8. With equivalent brightness, that is, assuming corrected voltage for the magnetic ballast (although, as mentioned earlier, hardly anybody will ever do this in practice) the difference is 6.6 W per system. With an electricity price of 10 c/kWh one saves one Euro in about 1500 operating hours.
9. Although the directive provides a separate line with limits for two lamps being operated on one ballast, the values per lamp are identical to those for the single-mode operations as under item 6. Very much unlike with the configuration described under item 6, however, the limits are by far kept here: The electronic ballast remains well over 1.5 W below the class A2 limit, the magnetic ballast even falls 3.5 W below the B1 limit.

On the TC-D lamp the following can be observed:

10. The efficiency is about 5% to 10% poorer than that of the T8 lamp. This may be due to the compact design which leads to a part of the light generated hitting the lamp itself.
11. Here the use of the electronic ballast results in an uncommonly high saving of 28% on equal voltage or 34% at equal light output, respectively. It by far fulfils the requirements for class A2, while the magnetic one does not really match the limit for class B1. The magnetic one may have been designed a bit too small in favour of facilitating the design of

very small luminaires (Fig. 8.5 top right), and in electrical engineering skimping on active material (magnetic steel and copper) always comes at the price of reduced efficiency. It has to be considered, however, that these two measurements possibly cannot really be compared because they could not be carried out on the same lamp. The TC-D lamp for magnetic ballast operation is equipped with an integrated starter and therefore has only two connections (Fig. 8.5). The starter is wired internally. The version for electronic ballast operation requires four pins.

12. Unlike the other electronic ballasts used in this test, the one for this lamp is not equipped with an electronic power stabilisation to offset variances of the input voltage.

8.5 How to make magnetic ballasts **more** efficient than electronic ones

It is not so sure whether the uncontested, measurable rest of the efficiency improvement beyond the 4% difference of light output with electronic ballasts really bases on the high frequency – or perhaps rather on the current waveshape fed into the lamp? It was tried to find this out by means of another measurement at a special independent lighting institute.[18] The idea behind this was another statement found in an already mentioned source[10] that the efficiency of a fluorescent lamp is not optimal at rated current but better at lower current, as is the case with a lot of electrical equipment, incandescent lamps exempted. If this is valid for the TRMS or arithmetic mean value of same current, then it also goes for each and every instantaneous value along the curve. So, with sine current, efficiency drops within the range around the peak, since most of the light is generated during this time span. If the output current of an electronic ballast were rectangular, then there would be no efficiency drop at any point of the curve – and energy efficiency would be better, because this constant value would be considerably lower than the peak value of a sine wave. Indeed the output current of an electronic ballast looks more like a rectangle than like a sinus (Fig. 8.8).

If this is so, then it should be possible to achieve the same efficiency improvement by lowering the overall current. The generalizing conclusion may be justified that higher power intensity is bad for efficiency.

The values in the Directive refer only to rated power, but what happens at reduced power, e. g. when a lamp with magnetic ballast is fed only with the power rated for operation with an electronic ballast (Table 8.1) or even substantially less? To find out, 5 different ballasts for a 58 W lamp were taken under test (Fig. 8.9):

- One stone-old ballast from an installation that had already been knocked down in 1987, still being rated 220 V and of course not efficiency classified and thereby falling into class D according to Table 8.1.
- One new »superslim« magnetic ballast, inevitably falling into class C, since in electrical engineering restrictions of space nearly always come at the price of restricted efficiencies.
- One new magnetic ballast efficiency class B2.
- One new magnetic ballast efficiency class B1.
- One mint condition electronic ballast rated efficiency class A3.

Now on each of these 5 samples all required parameters were measured, always using the same lamp: Active and reactive power across the whole system, active power (loss) across the ballast, and of course the light output of the lamp. All of the results have been compiled in Table 8.7) but, the graphic evaluation of this verbose table (Fig. 8.10) provides much more ease of interpretation. Unfortunately, on account of the high output frequency at the terminals of the electronic ballast, it was not possible to measure its output power. This is not a tragedy, though, since the most important data, system input power and light output, could be measured. The following can be concluded from the results:

- Neither system input power nor light output vary with varying voltage. So the device under test fully compensates variances of the supply voltage within the tested range, which is usually seen as an advantage – and one commonly expected from electronic ballasts. A deliberate variation of power input and thereby of light output via the feeding voltage, however, is therefore not feasible.

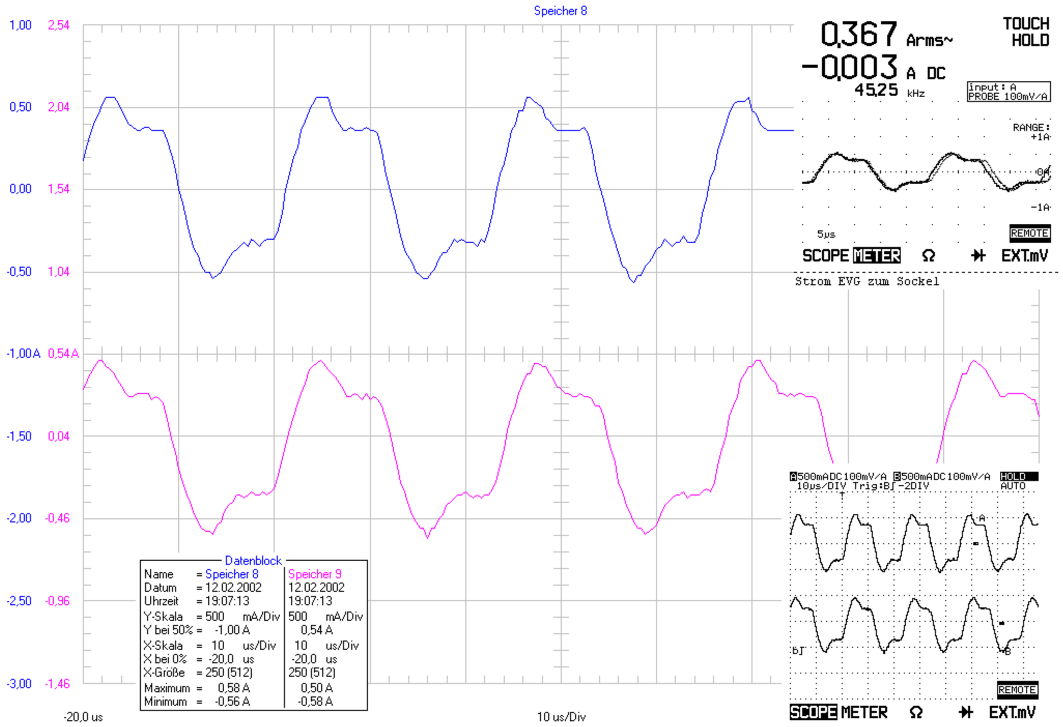

Fig. 8.8: Output current curve of an electronic ballast (H.-G. Hergesell, Paderborn Airport), recorded with 3 different power analyzers

- Of course the energy efficiency comparison turns out best for the electronic ballast at 230 V, but at 200 V the A3 electronic one is only more about the same as the class B1 and even the class B2 magnetic ballasts, and at 190 V the electronic one performs poorer! So at 190 V supply voltage the B1 and even the B2 should be classified as A3, since the efficiency of the A3 model has not altered, while those of both the B1 and the B2 models have exceeded it!
- The information of the light output with electronic ballasts being about 4% reduced against that of efficient magnetic ballasts at rated input **voltage** (not necessarily rated input power – see next bullet point) finds its confirmation.
- The rated lamp power is not always reached precisely at rated voltage. Other than the old ballast, the later magnetic ballast models of all classes reach their rated power only considerably above the rated system voltage. At 230 V, however, the electric lamp input power still falls considerably below the 58 W rating. After all that has been said so far, such design, e. g. deliberate utilisation of the permitted minus tolerance, must be seen as a reasonable approach.
- Still, this does not yet mean that the electric values are now totally comparable to those of an electronic ballast! With classes C, B2 and B1, the light output is around 5000 lm, while the electronic ballast tested here provided only 4720 lm.
- So the improved magnetic ballast models under test only feed about **53.5 W** into the lamp instead of the rated 58 W, and still, the lamp shines **4% brighter** than with the electronic ballast! Hence, for reasons of objectivity, in order not to compare apples with pares, the electronic ballasts' light output at 230 V would rather need to be compared to those values metered on the improved magnetic models at about **220 V** actual voltage.

- At **this** point of operation the actual lamp inputs were only more around 50 W – matching the rating given for an electronic ballast. This makes the deviating lamp ratings for operation with magnetic versus electronic ballast operation appear relative and raises doubts about the improvement of efficiency at high frequencies. The confinement to this statement is the lack of measured electric output power at the electronic ballast. However, the systems' power intakes with electronic A3 and magnetic B1 ballasts **at the points of equal light outputs** deviated from each other only more by exactly **2.1 W**, interpolating between the two measured points at 220 V (4662 lm) and 230 V (4952 lm) to the 4720 lm the lamp performs with electronic ballast.

Fig. 8.9: Test samples for the measurements documented in Table 8.7 and Fig. 8.10

- By switching from a poor class C magnetic ballast to a class B1 model the efficiency at rated lamp power is improved by 10% from 70.3 lm/W to 77.4 lm/W, since the share of ballast losses among the total input power drops from 22.9% to 15.0%. The price premium for the more efficient magnetic ballast therefore pays off in nearly all applications, short payback periods guaranteed.
- Contrary to this, the persistent use of very old poor efficiency ballasts – especially if still designed for 220 V line voltage rating – leads to a significant lamp overload with highly overproportional increase of losses and reduced lamp life but only little increase of light output.
- By reducing the operating voltage from 230 V to 190 V, the efficiency e. g. of a lamp with a class C ballast is improved from 73.0 lm/W to 84.1 lm/W, that is by well over 15%. When a class B1 ballast is used, the light efficiency still rises from 80.6 lm/W to 89.1 lm/W and hence still by about 10.6%. So the reduction of the feeding voltage also pays off, especially in cases where poor magnetic ballasts are not replaced with better ones. However, this shall not be an excuse for further operating »old scrap« any longer, for also with high-efficiency magnetic ballasts the fairly simple and usually rather inexpensive voltage reduction technique provides pretty short payback periods. The upgrade from anything to a B1 ballast really is the bargain, and some greater or smaller voltage reduction may come on top of it as a perfection.

Type (device under test)	Metering conditions	Measurements DIAL						Calculated values			
		U	P_{tot}	P_{Ball}	P_{Lamp}	I	Φ	η_{Lamp}	η_{tot}	P_{Loss}	P_{tot}
		V	W	W	W	mA	lm	lm/W	lm/W	P_{tot}	P_N
T8 lamp 58W with magnetic ballast EEI=D	R_{20}= 19.73 Ω	**190.0**	49.13	6.18	43.10	447	4039	93.71	**82.21**	12.6%	61.4%
	m= 1.60 kg	**200.0**	58.99	8.97	49.92	544	4624	92.62	**78.38**	15.2%	73.7%
		210.0	67.10	11.80	54.87	624	5010	91.31	**74.67**	17.6%	83.9%
	Rated power →	**218.0**	72.10	14.20	**58.00**	679	5311	91.56	**73.66**	19.7%	90.1%
	Rated voltage →	**220.0**	73.90	14.80	58.97	695	5301	89.89	**71.73**	20.0%	92.4%
		230.0	80.00	18.10	62.60	765	5543	88.55	**69.29**	22.6%	100.0%
		240.0	88.00	21.90	65.93	839	5756	87.30	**65.41**	24.9%	110.0%
		250.0	96.30	26.50	69.62	918	5954	85.53	**61.83**	27.5%	120.4%
T8 lamp 58W with standard magnetic ballast EEI=C	R_{20}= 23.30 Ω	**190.0**	38.02	4.28	33.71	328	3197	94.83	**84.08**	11.3%	55.1%
	m= 1.02 kg	**200.0**	47.61	6.56	41.04	415	3895	94.90	**81.81**	13.8%	69.0%
		210.0	55.46	9.00	46.41	490	4365	94.06	**78.71**	16.2%	80.4%
		220.0	62.32	11.55	50.89	555	4722	92.80	**75.78**	18.5%	90.3%
	Rated voltage →	**230.0**	68.98	14.36	54.67	622	5033	92.06	**72.96**	20.8%	100.0%
	Rated power →	**240.0**	75.40	17.30	**58.00**	686	5301	91.40	**70.31**	22.9%	109.3%
		250.0	82.28	20.88	61.30	753	5504	89.79	**66.90**	25.4%	119.3%
T8 lamp 58W with low-loss magnetic ballast EEI=B2	R_{20}= 17.90 Ω	**190.0**	36.71	2.90	33.85	325	3233	95.51	**88.07**	7.9%	57.9%
	m= 1.10 kg	**200.0**	45.41	4.54	40.84	410	3894	95.36	**85.76**	10.0%	71.6%
		210.0	51.92	6.15	45.93	478	4349	94.68	**83.76**	11.8%	81.9%
		220.0	57.92	7.73	50.07	541	4692	93.71	**81.01**	13.3%	91.3%
	Rated voltage →	**230.0**	63.41	9.66	53.73	602	4979	92.66	**78.52**	15.2%	100.0%
		240.0	68.60	11.40	57.07	656	5228	91.60	**76.20**	16.6%	108.2%
	Rated power →	**243.5**	70.50	12.40	**58.00**	681	5306	91.48	**75.26**	17.6%	111.2%
		250.0	73.80	13.80	59.94	718	5417	90.38	**73.41**	18.7%	116.4%
T8 lamp 58W with low-loss magnetic ballast EEI=B1	R_{20}= 13.80 Ω	**190.0**	35.42	2.44	32.94	314	3157	95.85	**89.14**	6.9%	57.7%
	m= 1.32 kg	**200.0**	43.78	3.82	40.03	397	3813	95.25	**87.09**	8.7%	71.3%
		210.0	50.57	5.14	45.38	470	4295	94.65	**84.94**	10.2%	82.3%
		220.0	56.24	6.57	49.70	537	4662	93.80	**82.89**	11.7%	91.6%
	Rated voltage →	**230.0**	61.42	8.01	53.36	596	4952	92.80	**80.62**	13.0%	100.0%
		240.0	66.40	9.60	56.72	659	5198	91.64	**78.28**	14.5%	108.1%
	Rated power →	**244.0**	68.53	10.31	**58.00**	683	5306	91.48	**77.42**	15.0%	111.6%
		250.0	71.60	11.50	59.91	724	5420	90.47	**75.70**	16.1%	116.6%
T8 lamp 58W with electronic ballast EEI=A3		**190.0**	54.92			297	4722		**85.98**		100.2%
	m= 0.22 kg	**200.0**	54.75			285	4723		**86.27**		99.9%
		210.0	54.90			275	4724		**86.06**		100.2%
		220.0	54.85			263	4723		**86.12**		100.1%
	Rated voltage →	**230.0**	54.80			256	4718		**86.10**		100.0%
		240.0	54.86			248	4724		**86.11**		100.1%
		250.0	54.72			242	4723		**86.32**		99.9%

Table 8.7: Measurements on 5 different ballasts at different line voltages with the same lamp

The high variance of efficiency even with moderate voltage reduction on a lamp circuit with whatever type of magnetic ballasts has three main reasons:

- Copper loss and approximately also iron loss in the ballast rise by the square of the current. Therefore the power lost in the ballast drops over-proportionally when current is reduced (see Table 8.7).
- Lamp voltage increases when lamp current decreases (Fig. 2.1). Therefore electrical lamp power decreases under-proportionally with decreasing supply voltage, while lamp efficiency moderately increases and simultaneously ballast losses dramatically drop.
- On account of this, current drops over-proportionally to the voltage reduction and accelerates the former effects.

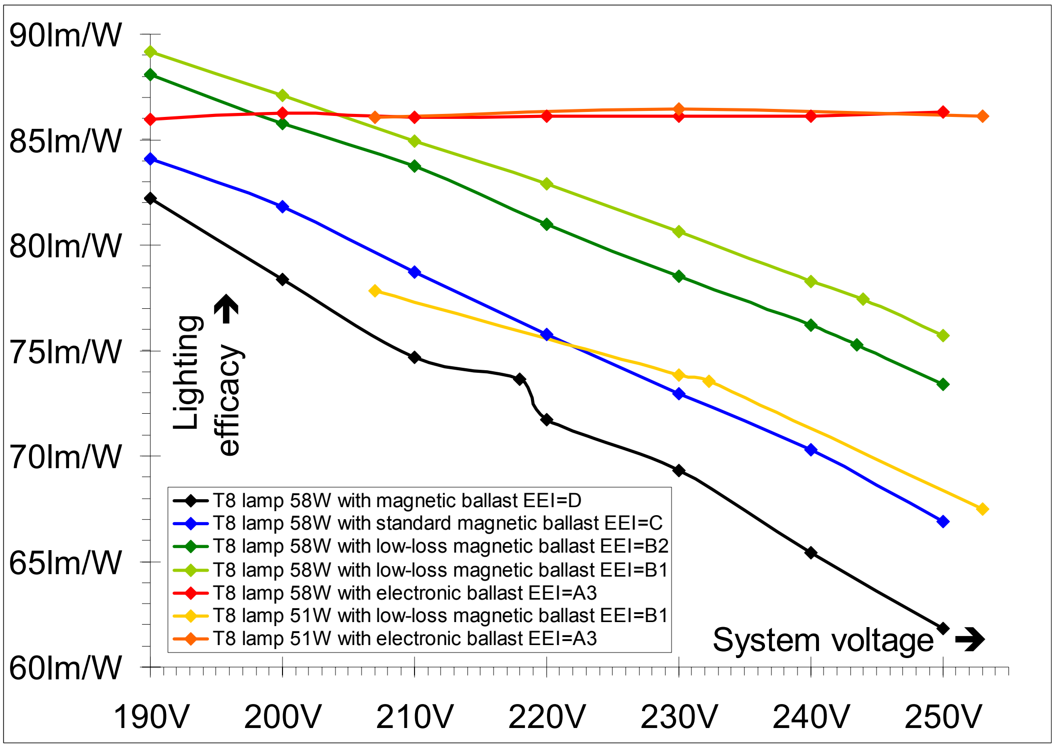

Fig. 8.10: Graphs of Table 8.7

To offset the lower absolute light output, about 150 magnetic ballast luminaires operated at 190 V would have to be used to replace 100 electronic ballast luminaires. Now since the 150 magnetic ballast luminaires are simultaneously the more energy efficient solution, a cost premium would be acceptable in replacing the electronic with magnetic ballasts in order to save energy, inverting the usual approach. Still, this need not necessarily be any more expensive. Cases have been reported where the solution with 100 electronic ballasts has been bid higher. So the payback time may assume a negative value! Adding the cost for voltage reduction, it is still very short. In two example cases from Switzerland 50 open longitudinal 58 W luminaires were bid alternatively with electronic ballasts at 2575 SFr and 50 commensurate luminaires with magnetic ballasts, regardless of efficiency class, at 1700 SFr.[19] So no premium was charged at all for a better efficiency class of the magnetic ballast, but it was very well possible to get 150 lamps equipped with these at a lower price than 100 luminaires with electronic ballasts. Whether the price premium in such cases really improves the electrical contractors’ businesses or whether the electronic ballast merely adds to the turnover but cuts revenues is yet another question to be critically scrutinized in each individual case.

In May 2000, being informed about this, the EU made an amendment to their document that any other measure judged appropriate to improve the inherent energy efficiency of ballasts and to encourage the use of energy-saving lighting control systems should be considered.

Indeed, in Germany there are at least 10 producers of dedicated voltage reduction plant that is meant to operate fluorescent lighting at reduced voltages.[20] Refurbishment in existing installations is easy as long as dedicated power lines for the lighting have been installed. Occasionally voltage reducers are also offered for the general supply but these have to be treated with care. Many power consuming devices have the inverse behaviour as fluorescent lamps with magnetic ballasts. Incandescent lamps, whenever living a lot longer, yield a dramatic loss of energy efficiency. Induction motors as well as practically all electronic devices, including decent electronic ballasts with constant light output regulation, have an increased instead of decreased current intake with reduced line voltage. Ohmic losses in the mains and especially inside the motor increase instead of decreasing. Also electronic ballasts of the type tested here, with constant regulated light output, react in this way and therefore cannot be influenced by varying the line voltage. With fluorescent lighting, however, the loss of luminous density can be offset by installing additional lamps – or simply taken for granted, which often is acceptable.

In some cases the reduction uses only the permissible ±10% mains voltage tolerance range at the junction box, which would bring it to 207 V. Some use another 3% permissible drop within the installation, coming down to 199 V. Others go as low as 185 V. A further reduction is not feasible, since lamps – at least those without serial compensation – just cease to work then. This is an energy saving function, no dimming technique, since the brightness regulation range is not very wide. Various additional functions are available, control in steps or continuous, day time and temperature dependent (for street lighting) and others. Lamps are always started at full voltage and stepped down only when they have reached their normal operating temperature. The technique could also be used to operate old luminaires still equipped with ballasts rated 220 V on the new uniform European 230 V line voltage, especially since lamp efficiency drops and ballast loss rises dramatically at overvoltage and lamp life is shortened. But normally the old ballasts will have a very poor efficiency anyway and will be worthwhile replacing.

On the other hand, the undervoltage extends the lamp life by about 33% ... 50%, the voltage reduction plant producers claim. However, ZVEI, the trade association of German lamp and ballast producers, points out that also the opposite can happen because the optimum filament temperature is not reached.[21] So far it can only be concluded from the conflicting statements that this issue has not yet been experimentally investigated. Life time tests of longlife devices take a long time by definition.

Moreover, ZVEI point out that undervoltage operation, as far as it falls below the permitted tolerance limit of 207 V, represents an operation outside the producer's specification and therefore voids warranty. This is correct but rather relates to the fact that the affected ratings, also those for the compensation capacitors, as explained in Section 5, have not been revised any more for decades. However, if the saving technique saves just 5 W all together through improved lamp efficiency and reduced ballast losses, then the lamp saves its own price within 10,000 hours of operation. If the lamps at average live as long as this, you may very well lose your warranty, and you still do make a bargain. Your warranty does under no circumstances include more than the purchase cost of a failed lamp, if any, or a ballast, respectively, but to assume a magnetic ballast might fail on account of undervoltage is as absurd as believing your car might fail because you don't always drive full speed.

A few other solutions may in certain situations achieve the same effect with an even lower or no price premium at all:

- In some luminaires, 2 smaller fluorescent lamps may be connected in series on 1 magnetic ballast (and 2 starters), as described in Sections 5.2 and 8.3.
- Magnetic ballasts are also available with 240 V rating. Using these on a 230 V supply will normally not cause any problems, even less if electronic starters are used. The current is slightly reduced, accompanied by the over-proportional saving effects as described for lower input voltage, but with an even better stability of light because the full voltage is applied. As described earlier in this section, the operation of the modern magnetic ballasts at rated voltage did not match the point of operation with the electronic ballast in the test. Rather, although the electric lamp input power already fell 4% below the rating with the tested magnetic ballasts, the light output was still 4% above that of the electronic one. So the operation of these magnetic ballasts at 4% undervoltage provides a much closer equivalence to the electronic ballast than at rated voltage.

For a concise insight into the economic potentials, here comes a review of all the saving quotes. By reducing the voltage from 230 V to 190 V (by 17.4%) the following reductions are achieved:

With	magnetic ballast Class D	magnetic ballast Class C	magnetic ballast Class B2	magnetic ballast Class B1	electronic ballast Class A3

ballast losses drop by	65.9%	70.2%	70.0%	69.5%	≈ 0%.
electrical lamp power drops by	31.2%	38.3%	37.0%	38.3%	≈ 0%.
whereby system power intake drops by	38.6%	44.9%	42.1%	46.7%	≈ 0%
light output drops by	27.1%	36.5%	35.1%	36.2%	≈ 0%.
Subsequently, the overall efficiency improves by:	**18.6%**	**15.2%**	**12.2%**	**10.6%**	**≈ 0%.**

Table 8.8: Power savings and light losses at reduced operating voltage

Fig. 8.11: Demonstration model for a direct comparison

Fig. 8.13: Brighter or not brighter, that is hardly a question any more here: On the left 20520 lx at 111 W, on the right 21560 lx at 145 W

Fig. 8.12: This unobtrusive little box effects the remarkable change – shown here is the smallest available unit (900 VA) for up to 7 lamps of 58 W each when not compensated or up to 13 lamps of 58 W each, respectively, when compensation is provided right inside the luminaire (behind the reducer) ➔

It has to be borne in mind, though, that at 230 V and with the class B1 magnetic ballast the lamp already supplied 4.7% more light than was the case with the electronic ballast (at any voltage between 190 V and 230 V). Therefore the true light loss is not 36.2% but only 31.5%. So, to be precise, 46% more lamps would need to be installed to obtain the same light flux. Their costs need to be balanced against the savings with energy and lamp replacement. Final customers or their contractors will need to calculate this in each individual case. In general you may select to install some 20% to 30% more lamps as a compromise, alone because with the more even distribution of light a lower total light level may suffice. To calculate this in each individual case is the lighting planners' task.

It is remarkable in this context that the human sensitivity for brightness, as is the case for noise level, is logarithmic. Differently from noise, however, the applied assessment dimensions are linear, so a measured enhancement of luminous density by a factor 10 is perceived as a doubling of brightness, 100 times more light is felt to be triple, 1000 times more seems just 4 times brighter and so on. In the end of a day a number of test persons were not able to say whether certain lamps were operated at 190 V or at full line voltage. One company[19] constructed a demonstration panel for this purpose (Fig. 8.11), in which 2 luminaires, each with 2 fluorescent lighting tubes rated 58 W (in lead-lag circuit) are operated, one luminaire at full line voltage and one at 190 V or even just 185 V. So visitors can convince themselves: You actually see no difference in brightness even here where both variants are inevitably viewed simultaneously side by side (Fig. 8.12)! A power saving of 23.5% costs only 4.8% loss of light. What remains to be subtracted from this saving is the power loss inside the voltage reducer (Fig. 8.13) but which is only 13 W in the case of this small unit, i. e. 1 W per each of the maximum 13 lamps that could be connected.

What you do see is a difference between the leading and the lagging lamp in each luminaire. They seem to have a slightly different colour. This basically should not be the case, so if anything then **this** shouts for an adjustment of the serial capacitance rating (see Section 5).

What you do very well see is a difference between the lead and the lag circuit in the lead-lag configuration of each luminaire. The lighting tubes seem to have a slightly different colour shade. **If** anything looks like need for action, then it is this, namely an adequate adaptation of the capacitance ratings for the lead-lag compensation (see Section 5).

After all, when the EU Directive was finally published in September 2000 it read:

»This Directive aims at reducing energy consumption … by moving gradually from the less efficient ballasts, and to the more efficient ballasts which may also offer extensive energy saving functions.«

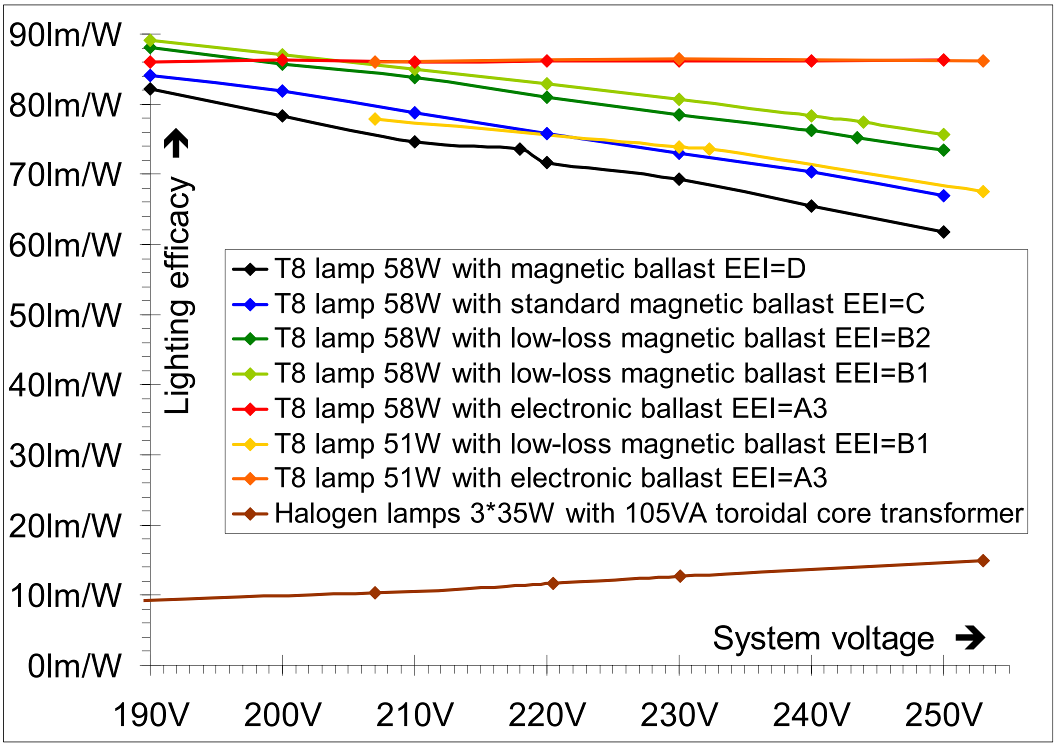

Fig. 8.14: Repetition of Fig. 8.10, but without zero base suppression – and suddenly the incandescent lamps shows up at the very bottom of all lighting techniques

No more talk of reducing, let alone phasing out the market share of magnetic ballasts – and this is what it should be like, otherwise a prohibition of incandescent lamps would have to be considered first in order to come from 10 lm/W to 80 lm/W. After this we might continue discussing whether a further increase to 86 lm/W pays off, whether it should perhaps be even 90 lm/W and how much this may cost. It is common practice within the lighting industry to compare the best electronic ballast to the poorest magnetic model when they come to talk about the efficiency of lighting. Now doing it the other way round and comparing the class A3 electronic to the B1 magnetic model, and doing so at the operation points of equal light outputs, revealed that the difference in electric input is **2.1 W** for a lamp rated 58 W. Hence, it takes about 3000 hours of operation to save 1 €. After all, more attention should be paid to the lamp itself, since there is quite a wealth of more efficient and of less efficient types available on the market. Well, and all of this is to be seen on the background that fluorescent lamps are a very efficient light source under all circumstances, whatever way they are being operated (Fig. 8.14).

8.6 Are the new T8 lamps with reduced power ratings more efficient?

A new series of T8 lamps was recently released that comes with reduced power ratings at the same sizes, e. g. just 51 W instead of 58 W for the 1.5 m lamp. The manufacturer claims these lamps could be used as a fully compatible replacement for the existing lamps without replacing a ballast, be there magnetic or electronic ones installed in an existing luminaire. Now customers start to wonder and to ask whether these lamps can actually save energy. Well, this depends on what you mean by that and what you expect.

In order to reduce the lamp input power with a given ballast you need to vary the lamp impedance. Assuming as a first approach the lamp were an ohmic load, which is far from true, it still remains acceptable to view it as a greatly active load, while the ballast is approximately inductive. The serial interconnection of these two elements, the lamp and the ballast, theoretically yields two values of lamp impedance (here assumed to be resistive – Fig. 8.15) where the lamp power matches its rating. In the case of the traditional 58 W lamp the lower one is the one used. In order to shift to 51 W the lamp impedance needs to be further reduced. Unfortunately this yields a higher current, while the losses in a magnetic ballast increase with the square of the current. So a slight reduction in lamp power comes at the price of a steep increase in losses and hence gnaws on the system efficiency from both sides. While it would have been attractive to use the upper one of the two theoretically possible points of operation, this is practically impossible. A fluorescent lamp with a voltage drop of more than something around half of the line voltage will not start on same line voltage.

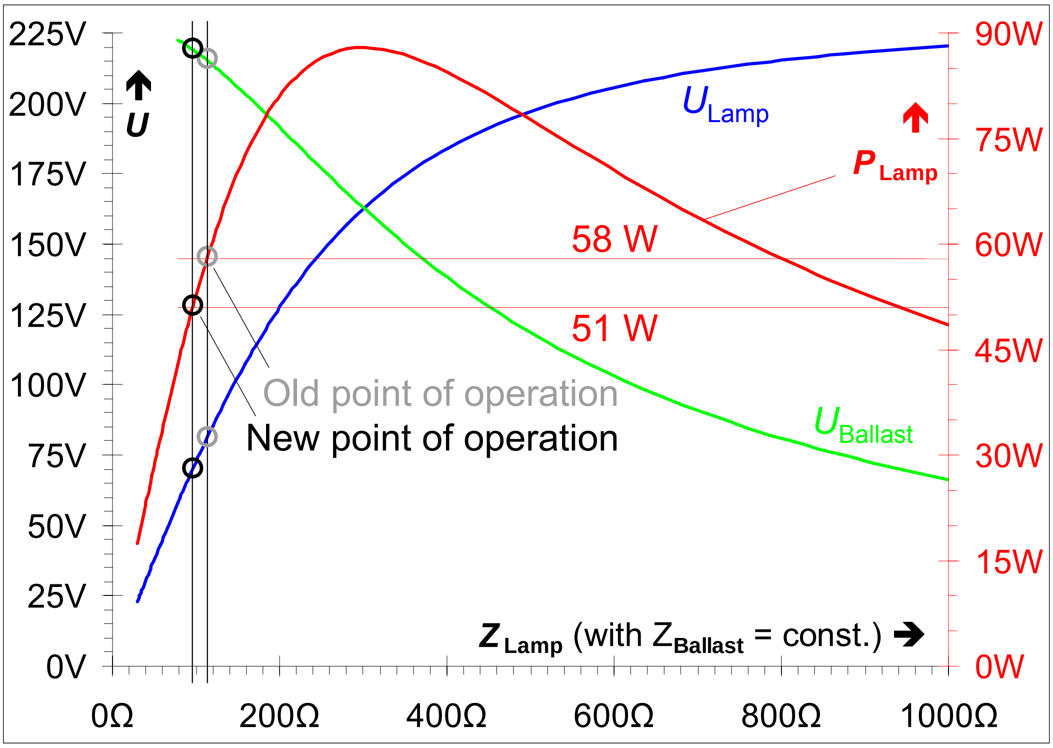

Fig. 8.15: In order to reduce the lamp input power with a given ballast the lamp impedance has to be reduced

It would have been fine if the lamp alone performed a significantly higher efficiency to offset the higher ballast losses, but another measurement (Table 8.9) revealed that this is unfortunately not the case. In fact the lamp efficacy is even poorer, and all the more is the system efficacy. Sure the absolute power intake is lower, but you receive a minor electrical energy saving at the price of a major loss of brightness.

With an electronic ballast the balance looks considerably better. The system efficiency is then at least the same. So when using this type of lamp the difference between magnetic and electronic mode of operation is considerably greater than with the ordinary type. Still, the morals is: If you can afford to sacrifice some light the best approach is to use good magnetic ballasts, regular T8 lamps and a voltage reduction unit. Then and only then you receive a major electrical energy saving at the price of a minor loss of light output.

Type (device under test)	**Metering conditions**	**Measurements DIAL**						**Calculated values**			
		U **V**	**P_{tot}** **W**	**P_{Ball}** **W**	**P_{Lamp}** **W**	**I** **mA**	**Φ** **lm**	**η_{Lamp}** **lm/W**	**η_{tot}** **lm/W**	**P_{Loss} / P_{tot}**	**P_{tot} / P_N**
T8 lamp 51W with low-loss magnetic ballast EEI=B1		**207.0**	44.73	5.88	38.82	502	3481	89.66	**77.82**	13.1%	80.4%
	Rated voltage →	**230.0**	55.64	8.95	46.38	627	4109	88.59	**73.84**	16.1%	100.0%
	Φmag=Φelec →	**232.3**	56.50	9.19	47.12	640	**4156**	88.20	**73.56**	16.3%	101.5%
		253.0	66.08	13.66	52.56	775	4459	84.84	**67.48**	20.7%	118.8%
T8 lamp 51W with electronic ballast EEI=A3		**207.0**	48.16			245	4145		**86.07**		100.2%
	Rated voltage →	**230.0**	48.04			226	**4153**		**86.44**		100.0%
		253.0	47.84			213	4120		**86.12**		99.6%

Table 8.9: Measurements on a T8 lamp 51 W with a magnetic and an electronic ballast

8.7 Are T5 lamps more efficient?

Reports about new lighting systems and renovations of lighting installations regularly quote the »new more efficient T5 lamps«, as if it went without saying that the efficiency of a T5 lamp is by default higher than that of a T8 lamp. Albeit, a look at the catalogue data already reveals that this, if at all, only applies to the so-called T5HE lamps optimized for High Efficiency. Those classified T5HO, optimized for High Output, perform significantly poorer than a commonplace triphosphor T8 lamp (Table 8.10).

Comparison of T5 and T8 fluorescent lamps						
Lamp	**T5 »HE«**	**T8 (measured values)**			**T5 »HO« (catalogue data)**	
Length	1449mm	1500mm			1449mm	
Power rating	35W	58W			49W	80W
operated with	Electronic	Magnetic ballast (50Hz)			Electronic ballast (HF)	
Rated system power	42W (A3) 39W (A2)	---	67W (B2) 64W (B1)	---	58W (A3) 55W (A2)	92W (A3) 88W (A2)
Measured lamp power	---	49W	53W	58W	---	---
Measured system power	37W (A1)	55W	61W	69W	---	---
System voltage	207V…253V	217V	230V	244V	207V…253V	207V…253V
Light flux	3300lm	4596lm	4951lm	5305lm	4300lm	6150lm
System light efficacy	**79lm/W (A3)** **85lm/W (A2)**	**84lm/W (B1, measured)**	**81lm/W (B1, measured)**	**77lm/W (B1, measured)**	**74lm/W (A3)** **78lm/W (A2)**	**67lm/W (A3)** **70lm/W (A2)**

Table 8.10: Catalogue data of T5 HE and T5 HO lamps with electronic ballasts compared to the measured data of T8 lamps with magnetic ballasts described in detail in Section 8.5

In the cases of electronic ballasts the input power and light output remains stable independently of the input voltage, while the input power to a magnetic ballast system of course varies greatly with input voltage. So a point can be found (at 217 V) where the measured lamp power in a 58 W T8 lamp driven by a magnetic ballast is exactly 49 W and thereby matches the rating of an existing T5 lamp with a light output of 4300 lm. But at this point, namely of equal power inputs to the T5 and T8 lamps, the light output of the T8 lamp is already ≈4600 lm – even though it was operated at mains frequency here and the T5 lamp, of course, at high frequency, as specified. This casts serious doubts over the practical effect of the theoretical efficiency improvement at high frequency operation. Or over the »more efficient T5 lamps«. Or both.

Lamp power rating		**Maximum input power of ballast and lamp circuits (ratings according to 2000/55/EU)**						
50Hz (mag-netic)	**HF (elec-tronic)**	**Class D**	**Class C**	**Class B2**	**Class B1**	**Class A3**	**Class A2**	**Class A1**
	14W					19W	17W	9.5W
	21W					26W	24W	13.0W
	24W					28W	26W	14.0W
	28W					34W	32W	17.0W
	35W					42W	39W	21.0W
	39W					46W	43W	23.0W
	49W					58W	55W	29.0W
	54W					63W	60W	31.5W
	80W					92W	88W	46.0W

Table 8.11: Values and classes of linear fluorescent T5 lamps with ballasts (values for B, C, D classes missing because these lamps are specified for use with electronic ballasts only)

Due to the curious fact mentioned earlier that the Directive allows higher losses in an electronic ballast than in a magnetic one, e. g. a 54 W T5 lamp with a class A3 ballast may have a systems power of 63 W (Table 8.11), yielding a ballast loss share of 14.3%, while the magnetic B1 system with a 58 W lamp – formally and officially – must not exceed 64 W and is thereby limited to a loss share of 9.4% (Table 8.1). But it was also mentioned there that in practice the lamp power with a magnetic ballast is found to be only between 53.5 W and 54.5 W, and that in the end of a day the systems power is crucial and not its split across lamp and ballast. Howsoever, through the theoretical or the practical approach, the T5 lamp hits a tough challenge to match the expectation to provide a better efficiency than a good T8 magnetic system has. On top of this, the unfortunate fact that in one system the rated light output is reached more or less around the rated power intake and in the other one even far below, both catalogue data and the Directive yield unrealistic payback times. Unfortunately this will never ever be discovered, since the electricity consumption of the lighting installation is not registered separately and because during a renovation a new system will always replace an over-aged one which is insufficient in all respects. Never ever will e. g. an optimized modern magnetic system be replaced with an optimized modern electronic system. So the energy savings remain a matter of belief and trust in what the specifier specifies.

8.8 Energy savings with dimmable ballasts

So if you want to save energy you will try to reduce the lighting level automatically, dependent on the level of available daylight. As you have learned in Section 8.5, the reduction of the voltage fed into magnetic ballasts, although it does save energy, does not reach far enough to call it a »dimming technique«, so you will try with dimmable electronic ballasts. But again, the question was how far the savings potential would go. Measurements were commissioned with an independent certified lighting laboratory[18] by the German Copper Institute DKI[22] and the company M&R Multitronik[23] to complement the existing measurements on magnetic ballasts. In order to obtain objective, comparable results compliant with the existing measurements reported in Section 8.5, a twin electronic ballast together with two commonplace, readily available T5 lamps (triphosphor, colour rendering index 840) were used, since it has turned out in Section 8.3 that a twin electronic ballast usually has lower losses than two single-lamp ones. As for the lamps, the lowest wattage of the biggest available size (1449 mm) was chosen because the greatest efficiency could be expected from these. This led to a rating of 2*35 W.

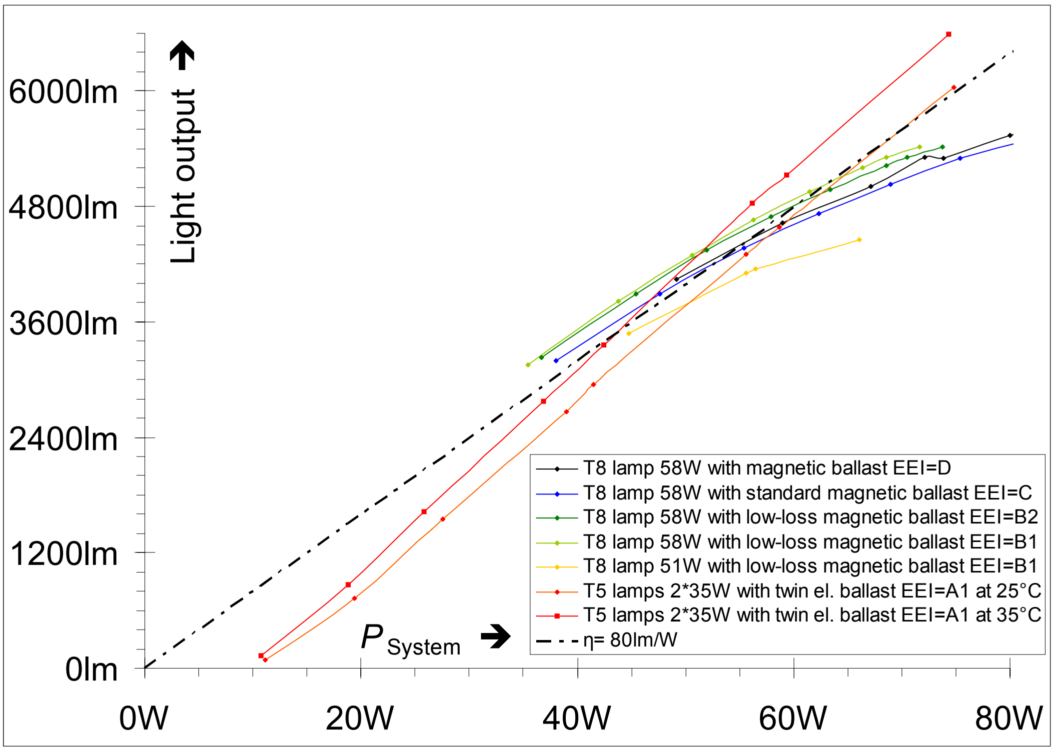

Fig. 8.16: Light outputs of different systems employing T5 and T8 fluorescent lamps, plotted against the absolute electrical systems power input

The T8 lamps had been tested before with an ambient temperature of 25°C according to the standard[24] where they usually perform their best efficacy. The T5 lamps were additionally measured with an ambient temperature of 35°C, deviating from the standard, since for some good reasons they are optimized to this ambient temperature.

The results were summarized in Fig. 8.16, where the systems' light outputs were plotted against the respective electrical power intake. Further, a line was included in the plot, representing a constant efficacy of η = 80 lm/W, which should represent a guideline for the efficiency in today's lighting installations. In this way the following becomes evident:

- The efficacy of any T8 system increases during input power reduction. Generally speaking, the values in the lower segment lie above the 80 lm/W »guideline«, while in the upper half they lie below, and especially in the overload range they strongly tend to flatten out.
- The T5 lamps exhibit the inverse behaviour: Efficiency decreases during dimming. Values in the upper range tend to lie above the »guideline«, while values in the lower range will rather lie below.
- The improved efficiencies of the T5 lamps at 35°C against the values measured at 25°C become quite obvious.

But unfortunately this type of plot is not very adequate for a direct comparison of either system against the other one because there are not any two lamps T5 and T8 with equal electrical power ratings available. It was therefore successfully tried to find a different method to compare both of the systems to each other by plotting the light efficacy against the **relative** system power (Fig. 8.17). In this type of graph a direct comparison of different systems should be possible when keeping the following remarks in mind:

- For the T8 systems, what is meant by relative systems power is the ratio of the measured systems power at the respective voltage divided by the systems power measured at rated voltage of the same system (for instance, with the old magnetic ballast class EEI=C the reference point representing 100% is 69 W, that of an improved magnetic ballast class EEI=B1 is 61.4 W, which represent the respective systems values measured at 230 V).

- For the T5 system, what is meant by relative systems power is the ratio of the measured systems power at the respective dimming level divided by the systems power measured when set to full light output (100%, i. e. same system with dimmer set to full power).
- For ease of orientation, the minimum requirements for class A1 are plotted in the chart in stroke-dotted lines once for a reference ambient temperature of 25°C and once for 35°C.
- The non-dimmable electronic ballast also included in the measurements could not reasonably be displayed in this format, since its power intake, along with the light output, is invariable and would have yielded only a dot.

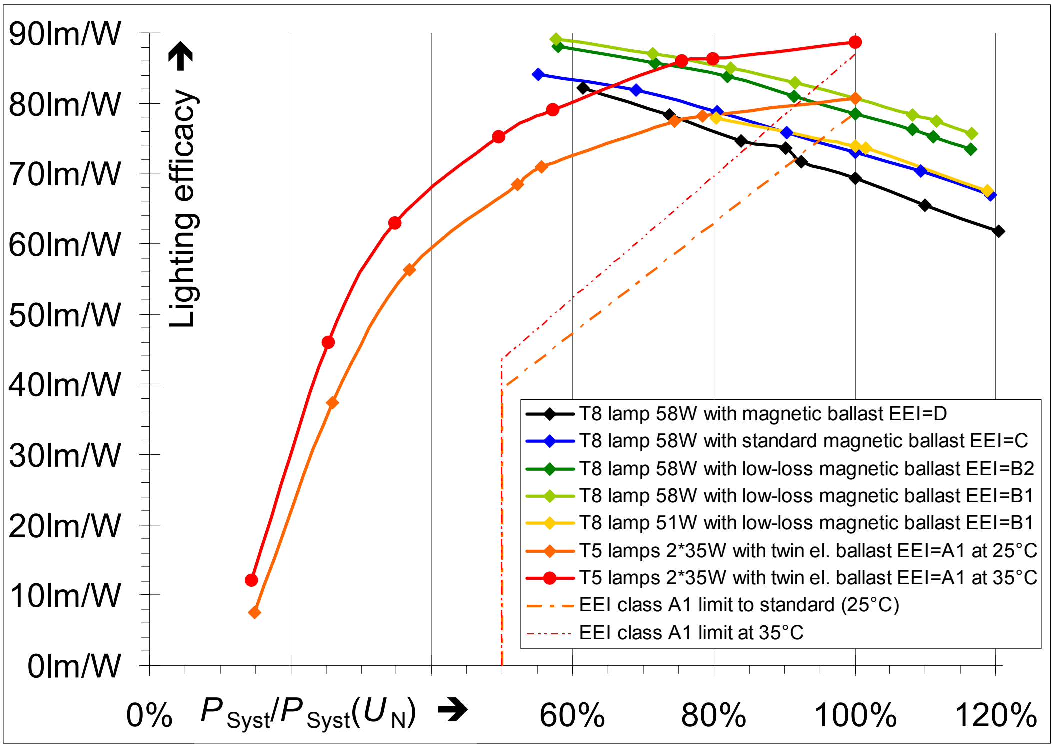

Fig. 8.17: Light efficacies of different systems employing T5 and T8 fluorescent lamps, plotted against the relative electrical systems power input

Hence, the above description facilitates the following observations:

- The T5 system under test by far exceeds the minimum requirements.
- It becomes even clearer now that the efficacy of the T8 system increases due to power reduction (and accordingly drops inadequately in the overload range), while the efficacy of the T5 system is best at full power and drops during dimming.
- At full load and 25°C ambient temperature the T5 system is about equally efficient as the best T8 magnetic system (EEI=B1).
- At full load and 35°C ambient temperature the T5 system is ≈10% more efficient than the best T8 magnetic system is at 25°C.
- At ≈75% of their respective electrical power input measured at 230 V or, respectively, of the undimmed lamp, the efficacy of the best T8 magnetic system is about equal to that of the T5 system at 35°C.
- When reducing, respectively dimming, the systems power to ≈60%, the efficacy of the T5 system even drops below that of a T8 system with an ancient class D magnetic ballast which was rescued from a scrap metal container back around 1986.

- When reducing to ≈50% input power the possible range of application for the voltage reduction technique ends. Otherwise the lamps will go out completely. A greater dimming range can be implemented with dimmable electronic ballasts only.

This facilitates the following conclusions:

- Dimmable ballasts provide only a rather limited energy savings potential. Who wants to save energy should reasonably employ a combination of voltage reduction and subsequent grouped automatic switching (e. g. from the aisle side to the window side in an office) after exploiting the (limited) »dimming« potential of voltage reduction – optionally, wherever possible, applying a technique which comes without any need for stand-by consumption[25] and using electronic starters[7], which spare on the lamp life as well as on the employees' nerves wherever switching occurs more frequently than once a day.
- The voltage reduction technique is no replacement for dimming. Who wants to dim has to use dimmable electronic ballasts. On the background of today's knowledge all techniques for dimming magnetic ballasts that have ever been around are makeshift solutions and do not satisfy modern needs. They should therefore not be considered any longer.

8.9 Make sure not to replace losses with losses

Still, these considerations do not yet include the following circumstance:

Dimmed operation of fluorescent lamps represents permanent cathode heating operation. The position »Lights off« is usually identical with the position »Dimmed down to 0«. Unless care is taken that the supply voltage to the lighting installation is shut off after work and on weekends, the lamps continue to be operated in a »Dimmed down to 0« state. This sabotages the underlying endeavours to save energy. E. g. with the following assumptions:

- On a T8 lamp rated 58 W (whose systems power is 59 W in class A3 or A1, respectively) a power saving of 55.8 W be possible (»Dimmed down to 0« with a residual consumption of 3.2 W – see Fig. 8.18),
- an average office be in operation for 3000 h/a,
- the light be in operation for about $^2/_3$ of this time, yielding 2000 h/a,
- during half of this time, say, 1000 h/a,
- half of this power level be enough, i. e. 500 h/a savings potential, converted to full-load hours,
- the stand-by consumption, however, remaining active during all of the 8760 h/a

yield the following calculation for the energy saved:

$$W = 500\frac{h}{a} * 55.8W = 28\frac{kWh}{a}.$$

The basically useless additional consumption calculates as:

$$W_0 = 8760\frac{h}{a} * 3.2W = 28\frac{kWh}{a}$$

Thereby a savings potential does no longer exist. In some favourable exceptions this is taken into regard and installed accordingly[26], so that the user does not deplete the daily savings at night, but it remains to be doubted that this practical approach is the rule among specifiers and designers. On top of this, the above calculation does not even take the drop of efficiency due to dimming into account but instead assumes the efficiency of a dimmed system were equal to that of same system at full power, which is not the case.

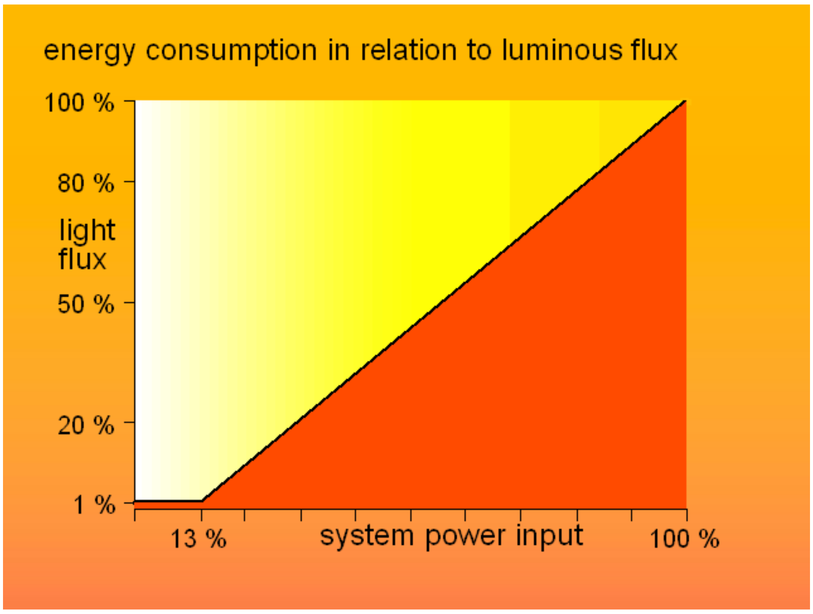

Fig. 8.18: Behaviour of a dimmable electronic ballast according to manufacturer's documents

Further, if installed as a refurbishment, each sensor and each actuator of such a monitoring system will need its own power supply from the mains. The net DC requirement may be as low as some very few milliwatts each, but each single one of them employs a mains adaptor including a small transformer. However, the smallest commercially feasible transformer is a unit rated around 1 VA and has about 1 W of no-load loss. Load loss may be negligible on account of a very low loading factor – but the multitude of such power supply units form the major constituent of the standby consumption in the entire lighting arrangement. Advanced control systems like EIB, which are easy and not too costly to install if the cabling has been prewired right during the construction phase of a building, employ one central AC adaptor for all connected units. Signals and the SELV DC supply share a common line. This technique provides the potential to cut the gross standby consumption down to a fraction. Therefore it remains to be considered in each individual case whether the use of high-efficiency magnetic ballasts plus some less sophisticated control technique, simply shutting off parts or all of the lamps completely while not needed, could be both the cheaper and the more effective approach.

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