lamps is on roads outside the built-up areas, where they are usually connected to branch lines of the electric mains and thus exposed to the worst voltage fluctuations. The relative insensitivity of sodium lamps to voltage fluctuations means that the voltage fluctuations along the supply cables may be larger while the difference in luminous flux between the various lamps fed by a given cable will still be within the prescribed limits. It is therefore possible to cut cable costs by reducing the copper cross-sections of the cables.

It is evident from the foregoing that, for lighting traffic routes, sodium lamps deserve preference over other light sources in all cases where colour rendering is a minor consideration. Sodium light offers better visibility and more visual comfort than other kinds of light. Moreover sodium lamps possess properties that make them particularly attractive for large lighting installations: they have a high luminous efficiency, making economic operation possible; their shape and dimensions facilitate the optical design of street lanterns; and they are relatively little affected by temperature and voltage fluctuations. Where their poor colour rendering is an insuperable objection, high-pressure mercury lamps with fluorescent bulbs (HPL lamps) are preferable to fluorescent and tungsten lamps, chiefly because—compared with fluorescent lamps—their shape and dimensions are more advantageous and they are less sensitive to temperature variations.

Summary. If a traffic route is to be lighted so that motorized vehicles can proceed safely without using headlights, the lighting installation must create conditions that offer acceptable visual comfort and perceptibility. The extent to which it does so is determined by the average luminance of the road surface, the glare caused by the lanterns of the installation and the uniformity of the surface luminance. Experiments in Philips' lighting laboratories, and elsewhere, indicate that 2 cd/m² (0.6 footlambert) is a reasonable average road-surface luminance. A recommendation is made as to what constitutes admissible glare; the effects of irregular surface luminance (bright and dark patches) have not yet been sufficiently investigated for a recommendation to be given.

Four commonly used kinds of light source—tungsten lamps, sodium lamps, high-pressure mercury lamps with fluorescent bulbs (HPL lamps) and tubular fluorescent lamps—are compared in regard to the influence of the kind of light on visual comfort and perceptibility, to the significance of their dimensions, shape and luminance, and to their sensitivity to temperature and voltage fluctuations. Sodium lamps compare favourably on all counts. The conclusion is that, where their poor colour rendering is a minor consideration, sodium lamps deserve preference for road lighting. Where colour discrimination is important, the use of HPL lamps is recommended.

DC/AC CONVERTERS USING SILICON CONTROLLED RECTIFIERS FOR FLUORESCENT LIGHTING

by J. J. WILTING *).

In lighting practice today there is a general trend towards higher levels of illumination. The lighting in public transport vehicles, such as railway carriages and buses, is no exception. The power in these vehicles is usually obtained from a dynamo of limited capacity, together with a buffer battery. It is therefore necessary to use very economical light sources, for which purpose tubular fluorescent lamps are particularly suitable.

Since the power source delivers direct current, two systems are possible:

1) Special fluorescent lamps may be used (e.g. Philips "TL" C type) which are fed in series with a ballast resistor directly from the DC source 1). This system is restricted to voltages of at least 72 V.

2) Standard fluorescent lamps may be used in conjunction with a DC/AC converter.

The second system has the advantage over the first that the loss in the ballasts is very much lower. The converters originally used were almost invariably robust rotary types, like centrifugal converters employing a rotating mercury jet 2). Nowadays electronic converters are gaining ground as a result of the development of semiconductor devices, such as the transistor 2) and the silicon controlled rectifier.

The electrical behaviour of the silicon controlled rectifier resembles that of thyristors and ignitrons, hence the name "solid-state thyatron" by which it is sometimes known 3). Compared with these two


3) F. W. Gutwinder, Power-controlling kilowatts with silicon semiconductors, Control Engng 6, 113-119, 1959. — This rectifier is available commercially under various names, such as SCR (silicon controlled rectifier), "Thyristor" and "Triac." The I.E.C. recently recommended the general name "Triac" (Interlaken, June 1961; see Bull. Schweizer Elektrot. Ver., 52, 934, 1961). This name is derived from πύλη = gate, which is roughly synonymous with πύλα = door, from which the names thyatron and "Thyristor" were formed.

*) Philips Lighting Division, Eindhoven.

1) L. P. M. ten Dam and D. Kolkman, Lighting in trains and other transport vehicles with fluorescent lamps, Philips tech. Rev. 18, 11-18, 1956/57.
Electronic switching or commutating devices — to which we may add the triode — the silicon controlled rectifier has the advantage of a much smaller voltage loss (only 1 to 1.5 V) and consequently a higher efficiency. It is particularly compact and rugged and requires no heating of the cathode. Although its switching speed is lower than that of a triode, it is greater than that of a thyratron or ignitron. The maximum permissible voltage is at present lower than for thyrratrons and ignitrons but much higher than for transistors. Silicon controlled rectifiers are now commercially available 4) for operation at a rated peak voltage of 400 V and a mean current of 70 A, and can be used for building converters for tens of kilowatts. It has been reported 5) that further development is expected to raise these values to 1000 V and 1000 A, giving a power-handling rating of 1 MW per rectifier.

Silicon controlled rectifiers are still very expensive. Even so, as an investment for a lighting installation converters using these devices are already comparable with rotary converters, and are expected to compare even more favourably in the near future. Among their present advantages are their considerably higher efficiency, their smaller weight and volume, and the fact that they need no maintenance.

Advantages of operating fluorescent lamps from a converter

In the conversion of direct current into alternating current the choice of voltage and frequency is fairly wide. Where converters for fluorescent lighting are concerned, the voltage and frequency of the AC mains should preferably not be chosen, for neither have the optimum value for operating fluorescent lamps. A voltage of 220 V, for example, is inadequate for reliably starting long fluorescent lamps (types of 40 W and more) unless special measures have been taken, and at the usual low frequencies of 50 and 60 c/s the lamps are far from operating under the most favourable conditions. We shall now discuss both points briefly.

Most fluorescent lamps work in conjunction with a ballast and a starter, which delivers a high (and usually brief) voltage surge sufficient to initiate the discharge. Moreover, the electrodes of the lamp are preheated, which lowers the ignition voltage required. As a result, the ignition is always attended by some delay. In one type of lamp — Philips "TL" S lamp 6) — a conducting strip on the inside of the tube has so reduced the ignition voltage as to make the above measures unnecessary. This lamp is of course somewhat dearer in construction than a conventional fluorescent lamp, and the losses in the strip make the efficiency somewhat lower.

Using a converter the voltage can be chosen high enough to ignite the longest lamps reliably and without delay with a simple ballast. Preheating is unnecessary (the electrodes must then be accordingly dimensioned) and no conducting strip is needed. To comply with safety regulations the secondary of the transformer in the converter can be centrally earthed, so that the AC cables carry half the full potential with respect to earth.

As regards the frequency, there are several advantages in raising its value to between 5 and 10 kc/s for fluorescent lamps:

1) The weight and size of the ballasts, and the ballast losses, can be considerably reduced. Light weight and low heat generation are sometimes of decisive importance.
2) The luminous efficiency of fluorescent lamps rises with increasing frequency 3) 7). The efficiency of a 40 W "TL" lamp, for example, is about 10% higher between 5 and 10 kc/s than at 50 c/s.
3) The light is steadier, without any stroboscopic effect.
4) The lamps cause less radio interference.

The latter two advantages are due to the fact that at high frequencies the gas discharge is much more regular than at the usual mains frequencies 5): the ion concentration remains virtually constant, reignition effects are eliminated. This may also be assumed to benefit the life of the lamp, but life tests still have to confirm this assumption. *(The choice of frequencies higher than 10 kc/s does not add much to the above-mentioned advantages, whereas it considerably increases the losses, including radiation losses, entailing the risk of interfering with communication channels.)*

The conspicuous benefits of high frequencies are a strong argument in favour of using converters that deliver alternating current at these frequencies. The transistor converter is capable of doing so 7), but because of its low power and the inability of transistors to withstand high voltages, its applications are very limited (lighting in buses etc.). The con-

4) See e.g. Controlled-rectifier manual of the (American) General Electric Co.
5) E. J. Duckett, DC to AC power conversion by semiconductor converters, Westinghouse Engr 20, 170-174, 1960 (No. 6).
verter equipped with silicon controlled rectifiers, on the other hand, which is also capable of producing alternating current at frequencies up to 10 kc/s, can operate on a DC input of the order of 100 V and deliver a power in the region of 1 to 10 kW. This converter is therefore eminently suited for powering fluorescent lighting systems in trains and ships.

The latter type of converter can also be useful for operating fluorescent lamps in office buildings and factories which have been specially wired for the purpose: the converters are then operated from the ordinary electricity mains via rectifiers. The energy saving due to the lower losses in the ballasts and the higher luminous efficiency more than offset the losses in the rectifiers and converters. Once the prices of silicon controlled rectifiers have dropped, the net saving in itself will justify the investment in an installation of this kind, which at present is still rather high. Plans for a test installation at Eindhoven are now being worked out.

Converters using silicon controlled rectifiers

We shall confine ourselves in this article to a concise description of a converter developed in the electrical laboratory of Philips' Lighting Division, primarily for train lighting. First of all we shall deal briefly with the properties of the silicon controlled rectifier.

The silicon controlled rectifier

The silicon controlled rectifier consists of four alternate layers of P-type and N-type silicon (Fig. 1). There are two principal electrodes: the anode a and the cathode b, and one control electrode c. Provided the voltage between a and b does not exceed a specific value, the rectifier in the quiescent state passes no current (apart from a leakage current of no more than a few milliamperes); this holds for both polarities of the voltage between a and b. To make the rectifier conductive — which, without causing damage, is possible only in the forward direction (a positive with respect to b) — a momentary current injection in the control electrode is sufficient. A very high current is permissible in the forward direction (up to several tens of amperes, depending on the type). The voltage drop is only 1 to 1.5 V, i.e. an order of magnitude smaller than in gas discharge tubes such as thyatrons and ignitrons. The non-conductive state returns only when the main current has dropped below a certain lower limit, called the holding current, below which insufficient charge carriers are generated in the P-N junctions. For certain types of silicon controlled rectifiers a peak voltage of 400 V (500 V for short periods) of both polarities is permissible in the non-conductive state, but in the forward direction not before the concentration of residual charge carriers after the passage of current has dropped to a level such that the leakage current is lower than the minimum value of the control current. Nor must the voltage in the forward direction rise so rapidly as to cause the resultant capacitive current in the P-N junctions to exceed the minimum value of the control current. The limiting value of the various quantities is dependent on the temperature inside the rectifier and on the nature and dimensioning of the circuit. Breakdown in the reverse direction causes irreversible damage.

Fig. 2 shows a family of characteristics of a silicon controlled rectifier. It can be seen that the "breakdown voltage in the forward direction" decreases in value as the control current increases.

As a commutating device the silicon controlled rectifier can often advantageously replace triodes.

---

thyratrons, ignitrons and transistors. In common with ignitrons and transistors this rectifier has no cathode that needs a certain time to heat up and that must be kept up to temperature. As mentioned, the voltage drop is lower than in thyratrons and ignitrons, and hence much lower than in triodes.

A drawback of converters using the new rectifiers, as opposed to mechanical converters, is their greater sensitivity to overloads. Overloading can easily cause permanent damage to the rectifying elements. To meet this difficulty the design should allow for a wide safety margin, and/or the converter should be provided with overload protection, preferably electronic.

A converter using silicon controlled rectifiers for train lighting

In order to bring silicon controlled rectifiers in a generator circuit recurrently from the non-conductive into the conductive state, periodic control pulses are needed. These are no problem to generate. A matter of more difficulty is the method of returning the rectifiers periodically to the non-conductive state at the high switching frequency which, for fluorescent lighting, is so advantageous.

![Fig. 3. Simplified circuit diagram (control circuit omitted) of a converter using silicon controlled rectifiers (P1, P2) in push-pull arrangement. T1, transformer. C1, commutating capacitor. L, choke. Vb, battery voltage. R', load resistance.](image)

The simplest and most reliable method consists in using a series resonance circuit. The current then tends to have an oscillating character, but after the first half-cycle the rectifying element automatically becomes non-conductive.

**Fig. 3** shows a simplified circuit diagram of a converter with silicon controlled rectifiers for train lighting. The two rectifying elements P1 and P2 are in a push-pull arrangement. The capacitor C1 shunted across the primary of the transformer T1 is called the commutating capacitor. The load on the transformer secondary is drawn here as a resistance R'. The situation when the first control pulse makes P1 conductive can be represented by the equivalent circuit of **Fig. 4**. Here R and C are the transformed values of R' and C1 in **Fig. 3** in respect of one half of the transformer primary. The above-mentioned series resonant circuit is formed by C and the choke L. When P1 becomes conductive, the battery voltage Vb suddenly appears across terminals 1 and 2. If the circuit is properly dimensioned, the current i1 which now starts flowing will tend to have the waveform represented in **Fig. 5**, i.e. a damped oscillation superposed on an exponentially rising current. However, at the moment t = t1, at which i1 drops to zero, the rectifying element becomes non-conductive so that i1 remains for a while at zero. If we now apply the next control pulse to P2 — some time after t1 to give the charge carriers in P1 an opportunity to recombine sufficiently — the process will be repeated, except that some quantities change}

![Fig. 4. Equivalent circuit for the moment at which the rectifying element P1 in fig. 3 is made conductive. The DC voltage Vb then appears suddenly across terminals 1 and 2. C and R are the transformed values of C1 and R' in fig. 3 with respect to one half of the transformer primary.](image)

![Fig. 5. The full line shows the variation of the current i1 in the circuit of fig. 4: damped oscillation superposed on a current variation approximately of the form Vb(1-e^-at)/R (dashed line). Since the rectifying element prevents the current from changing direction, in the circuit of fig. 3 the current i1 remains zero from point t1 onwards, so that only the thickly drawn portion of the waveform is obtained.](image)
their sign and that, since $C$ retains a certain charge, the initial conditions are different. The current $i_2$, which now starts to flow through $P_2$, will also remain at zero after the first half cycle. A moment later, $P_1$ is again made conductive, and so on. Periodic repetition of the control pulses produces a certain steady state, resulting in an alternating voltage across the transformer (fig. 3).

**Brief analysis**

The voltages in fig. 3 satisfy the following equation:

$$u_{P_1} = V_b + u_L + \frac{1}{2}u_C. \quad \ldots \ldots (1)$$

We distinguish two states of the circuit: 1) one of the two rectifying elements is conductive and the other not, and 2) neither is conductive.

1) **One rectifying element ($P_1$) is conductive and the other not.**

As an approximation, then, $u_{P_1} = 0$, so that from (1):

$$\frac{1}{2}u_C = -(V_b + u_L). \quad \ldots \ldots (2)$$

The current $i_1$, which flows from $t_0$ to $t_1$ through $P_1$, can be shown to have the value:

$$i_1 = \frac{V_b}{R} \frac{V_b}{R \sin \varphi} e^{-\omega t} \sin (\omega t + \varphi) + \frac{V_b + \frac{1}{2}u_C}{\omega L} e^{-\omega t} \sin \omega t,$$

where

$$\omega = \frac{1}{\sqrt{LC - \alpha^2}},$$

$$\varphi = \tan^{-1} \frac{\omega}{\alpha};$$

$$u_C = \text{voltage across } C \text{ at the time } t = t_0 \quad (U_C \text{ can be found from a further calculation, not given here.)}$$

For the voltage $u_L$ during the interval $t_0-t_1$, we find:

$$u_L = -\frac{V_b}{\omega CR} e^{-\omega t} \sin \omega t + \frac{V_b + \frac{1}{2}u_C}{\sin \varphi} e^{-\omega t} \sin (\omega t - \varphi). \quad (4)$$

The waveforms of $i_1$ and $u_L$ during the interval $t_0-t_1$ are roughly illustrated in fig. 6a and b. Assuming that $U_C$ is known, the waveforms of $u_C$ and $u_{P_1}$ can be constructed with the aid of (1) and (2) (see fig. 6c and d).

2) **Both rectifying elements are non-conductive.** After the moment $t_0$ no current passes through $P_1$. Up to the moment $t_0$ at which $P_2$ receives a control pulse, the $R-C$ circuit is left to itself, so that $C$ discharges exponentially with the time constant $RC$. Since $i_1$ and $i_2$ are now zero, so too is $u_L$, and the waveforms of the various voltages during the interval $t_1-t_2$ are easily found; see fig. 6b, c and d. The variation from the moment $t_2$ can also be found without much difficulty. For a more detailed analysis, reference may be made to the literature 10.

It can be seen from fig. 6d that the peak voltage across the rectifying elements can considerably exceed $V_b$, the precise value depending on the dimensioning of the circuit and the load. This should be taken into account when choosing the value of $V_b$ and the type of rectifying element.

It follows from (3) that the choice of $L$ and $C$ determines the duration $t_2-t_3$ of the conduction in every half cycle $T$. It is therefore possible after every pulse to give the rectifying elements a certain "recovery time", from $t_2$ to $t_3$ ($t_3 = t_0 + \frac{1}{2}T$) as needed to ensure proper operation.

The complete circuit diagram of the converter is shown in fig. 7. The resistive load of fig. 3 is now replaced by a number of "TL" S lamps (chosen because they operate without a starter). Half the

---

number of lamps have a choke as ballast with an inductance $L_{o}$, the other half a small capacitor of capacitance $C_{o}$. The value $L_{o}C_{o}$ is chosen near to resonance at the frequency of the converter. Since the voltage is roughly sinusoidal (see fig. 6c), this load is not much different from a resistive load for the converter.

When the converter is switched on, it is set in operation by starting pulses from the transistorized pulse generator $I$. As soon as the converter starts oscillating, the pulse generator is automatically made inoperative (see caption to fig. 7). The control pulses are now delivered by the pulse transformer $T_{2}$, which has a ring-shaped ferrite core with a rectangular hysteresis loop. The primary of $T_{2}$ is fed from the converter itself via chokes $L_{1}$ and $L_{2}$ and the capacitor $C_{o}$. The pulse repetition frequency can be adjusted by varying $L_{2}$ and $C_{2}$.

Fig. 8 shows an experimental 1 kW converter designed on this principle, for operation from a 100 V DC supply. The load consists of 24 “TL” S 40 W lamps. Fig. 9 shows a later version of this converter, intended for an experimental lighting installation in a train of the Netherlands Railways.

---

Fig. 7. Basic circuit of a converter using silicon controlled rectifiers, designed for train lighting. $P_{1}$, $P_{2}$, $L$, $C_{1}$, $T_{1}$ and $V_{b}$ (here 100 V) as in fig. 3. $F$ fluorescent lamps of type “TL” S (one half in series with chokes $L_{o}$, the other half in series with capacitors $C_{o}$). $T_{2}$ pulse transformer with ferrite core (rectangular hysteresis loop) fed by the converter itself via network $L_{1}$-$L_{2}$-$C_{2}$.

$I$ starting-pulse generator. Capacitor $C_{3}$ discharges periodically through transistor $T_{r}$ and the control electrode and cathode of $P_{2}$. Once the converter is oscillating, the anode of $P_{2}$ becomes negative with respect to the cathode during a part of each cycle (see fig. 6c); this negative voltage discharges capacitor $C_{3}$ through diode $D$ and resistor $R_{1}$, which makes the starting-pulse generator inoperative.

Fig. 8. Experimental converter as in fig. 7, loaded with 24 “TL” S 40 W fluorescent lamps.
Fig. 9. Converter on the principle of fig. 7, designed for a fluorescent lighting system on trial in a train of the Netherlands Railways. Input voltage 100 V, power 1 kW, frequency 7 kc/s, efficiency better than 85%, weight approx. 10 kg. On the right, two standard lamp holders for a "TL" lamp, each fitted with a "ballast" (in one a choke, in the other a capacitor).

also gives an idea of how small the "ballasts" are, so small indeed that they can be accommodated in the standard covers of the lamp holders.

Summary. For operating fluorescent lamps from a DC source (as in trains) use has mainly been made hitherto of rotary DC/AC converters. Electronic converters are now gaining ground, and a new type is discussed here which is equipped with P-N-P-N silicon controlled rectifiers. These rectifiers can handle a considerably higher power than transistors and have a voltage drop of only 1 to 1.5 V, which is an order of magnitude smaller than in thyratrons and ignitrons. Converters with silicon controlled rectifiers have a much wider field of application than rotary converters, which they will largely supersede in the near future. They can operate in the frequency range from 5 to 10 kc/s. This has particular advantages for fluorescent lighting, enabling small, light-weight ballasts to be used which have extremely low losses, and giving a luminous efficiency about 10% higher than at 50 c/s. A description is given of a converter using silicon controlled rectifiers which has been designed for train lighting: the input voltage is 100 V, the power 1 kW, the frequency 7 kc/s. In conjunction with mains rectifiers the new converters will be useful for fluorescent lighting in offices and factories. It is expected that the present fairly high costs of such installations will be reduced in the not too distant future, to such an extent that the energy savings will make them a profitable proposition.

AN INSTRUMENT FOR AUTOMATICALLY RECORDING ISOCANDELA DIAGRAMS OF BEAMED LIGHT SOURCES

by W. BÄHLER *).

One of the problems facing the designer of beamed light sources is to produce a beam pattern that meets specific requirements. For lighting airfields, for example, beams are required that are fairly broad in the horizontal plane but very narrow in the vertical. For beacon lights, signalling lamps and car headlamps the requirements are complicated, and where beacons are concerned they differ from case to case. For flood-lighting, too, beams are often needed that are not simply radially symmetrical.

As an example we shall briefly discuss, with reference to fig. 1, the present specifications applicable in many European countries to the dipped beam or passing light of car headlamps 1). Broadly speaking, the beam should be such that a motorist driving on an unlighted road retains sufficient lighting to be able to see the road ahead without dazzling oncoming traffic. Fig. 1 gives a perspective drawing of a road 6 m wide as "seen" by a car headlamp at a height of 75 cm above the road surface, in the middle of the right half of the road. If we draw the system of lines in this figure, with the given dimensions, on a screen and set it up 25 m away from a headlamp, the light thrown by the headlamp on to the screen should meet the follow-

*) Philips Research Laboratories, Eindhoven.

1) A comparison of the properties of the (then) European and American dipped beam has been given by J. B. de Boer and D. Vermeulen, Philips tech. Rev. 12, 305, 1950/51.