

BARRETTERS

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In this article a study is made of the way in which the current regulating function of a regulator barretter is connected with the variation of the electrical resistance and the heat dissipation of a filament as functions of the temperature. The most satisfactory regulation curves can be obtained with an iron filament in an atmosphere of hydrogen at low pressure. Different forms of construction of Philips barretters are discussed. Finally several points are discussed which are important in the application of barretters to electrical installations. For the sake of illustration, the decrease in the current fluctuations in a tungsten lamp, a constant resistance and a carbon filament lamp are studied in connection with the loss of voltage in the preceding barretter.

Introduction

Barretters have been used in electrical engineering for many decades for the purpose of decreasing the current fluctuations which appear in electric circuits as a result of variations in the mains voltage or of changes in the load applied. An urgent need of such a current regulator was first experienced about 1900 when Nernst lamps were connected to power mains. The incandescent element of the Nernst lamp (thorium oxide) has a strongly negative temperature coefficient of the electrical resistance. If as a result of a small increase in voltage the current $I = V/R$ becomes somewhat larger, the resistance R decreases because of the corresponding increase of temperature, so that the current and the tem-

perature continue to rise. If there were no resistance at all in series with the lamp, the current would continue to grow because of this instability until the element fused.

In order to avoid this unstable behaviour a resistance is connected in series with the Nernst lamp, which resistance varies with the temperature in exactly the opposite way to that in which the resistance of the element of the Nernst lamp varies. As early as 1899 it was found that an iron filament in an atmosphere of hydrogen was very suitable for this purpose. Iron was used because it has the highest positive temperature coefficient of the resistance, while hydrogen was originally chosen to protect the iron from oxidation. It was found later also that the heat conduction of the gaseous hydrogen is of importance.

As an illustration of the action of a current regulator the current voltage characteristics of two different barretters are shown in *fig. 1*. In example *a*), which may be considered a normal case, the current remains practically constant with a threefold increase of the voltage. In example *b*) there is even a falling back of the characteristic over a definite voltage interval, thus a decrease in the current with increasing voltage, and at the end of the regulation range the voltage is five times as great as in the beginning of that range.

In the course of years the Nernst lamp has been displaced by better sources of light. Barretters on the above-described principle have, however, continued to be used, and are finding continually wider application for the most divergent purposes. The iron filament lamp, as has already been mentioned in this periodical, is used as the series resistance of gas discharge lamps, where it fulfils exactly the same function as in the Nernst lamp. A barretter is, however, some-

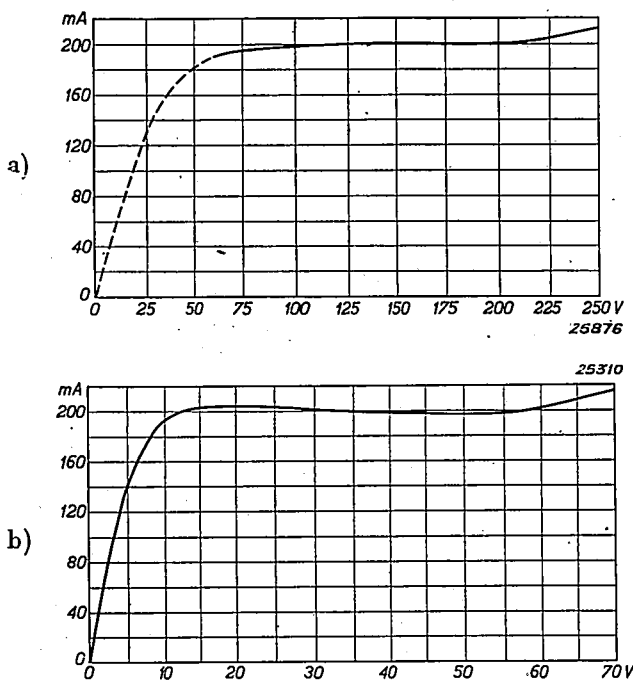


Fig. 1. Current through two barretters as a function of the voltage.

a) Normal type.

b) Type with exceptionally wide regulation range.

times also connected in series with ordinary incandescent lamps, where it is necessary to provide for large fluctuations of the mains voltage as on railways. There are, moreover, other applications in electrical engineering, such as for maintaining the constancy of the heating current of radio valves and of the charging current of batteries.

How is a flat current-voltage characteristic obtained?

If we assume that the filament has the same temperature over its whole length, we can easily calculate the relation between I and V , when the energy loss (radiation plus heat conduction plus convection) A , and the electrical resistance R as functions of the temperature T are known. We have the relations

$$\left. \begin{aligned} V \cdot I &= A(T) \\ V/I &= R(T) \end{aligned} \right\} \dots \dots \dots (1)$$

A depends upon the nature and pressure of the gas and upon the external temperature; R is a property of the material of the wire.

The first equation expresses the fact that the state is stationary; the energy supplied is equal to that given off. The second is simply Ohm's law.

From these two equations it follows that

$$\left. \begin{aligned} a) \quad V &= \sqrt{A \cdot R} \\ b) \quad I &= \sqrt{A/R} \end{aligned} \right\} \dots \dots \dots (2)$$

By calculating V and I for a number of temperatures we thus obtain an $I-V$ curve. The following calculations are based on measurements of the heat dissipation of very thin wires in hydrogen gas by Busch¹⁾ and on resistance measurements of very pure iron by Potter²⁾.

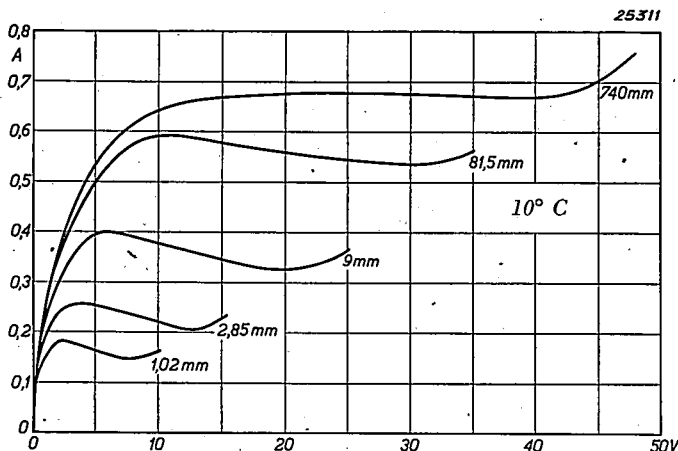


Fig. 2. Calculated $I-V$ curves for an iron filament in hydrogen at different pressures. In a certain voltage interval there is a decrease of the current with increasing voltage.

1) H. Busch, Ann. Physik 64, 401, 1925.
2) H. H. Potter, Proc. Phys. Soc. 49, 671, 1937.

The diagrams reproduced in fig. 2 refer to a constant external temperature of 10° C and various pressures of the hydrogen. In fig. 3 the characteris-

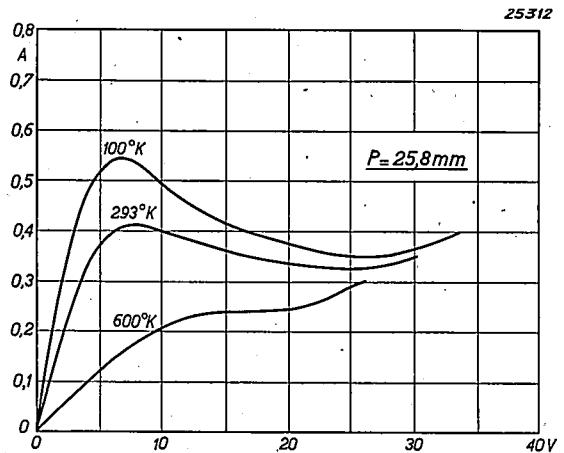


Fig. 3. Calculated $I-V$ curves for a hydrogen pressure of 25.8 mm Hg at three different temperatures. With increasing external temperature the fall of the characteristic is less pronounced.

tics are reproduced for a constant amount of hydrogen in the valve (25.8 mm Hg at 20° C) and three different external temperatures. The surprising result of these calculations is that the $I-V$ curve for a given voltage reaches a maximum and then exhibits a falling back over a long range of voltages. The falling back of the characteristic is more pronounced the lower the external temperature.

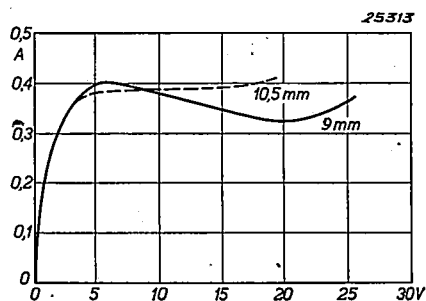


Fig. 4. Comparison of a calculated characteristic (fig. 2, 9 mm Hg) with a recorded characteristic under about the same conditions. The general shape is well confirmed. The descending portion, however, cannot be realized, because a uniform temperature is not established in this portion.

Fig. 4 shows, in addition to the curve for 9 mm pressure of fig. 2, an experimental curve for the same conditions. The general behaviour of the calculated curve is well confirmed; the falling back of the characteristic is, however, not present. The cause must be sought in the fact that a uniform distribution of temperature over the whole length of the wire, as was assumed in the calculation of the $I-V$ curve, is not stable in the descending portion of the characteristic.

If we allow the temperature of a given element of the wire to rise slightly, not only the heat dissipation increases, but also the resistance and the supply of heat. In the descending portion of the $I-V$ curve the supply of heat is found to increase more rapidly than the dissipation of heat, so that the temperature of the element continues to increase while the rest of the wire cools off when the voltage on the wire is kept constant.

The shape of the $I-V$ curve is very sensitive to accidental factors. The parts of the wire which will become hotter, and how much hotter they will become, and the parts which will become cooler depend upon very slight irregularities in the state of the surface of the wire. The heat conduction along the wire is also important in this connection since it works to decrease the irregularity in the distribution of temperature along the wire. We shall not go more deeply into this very complicated problem.

What kinds of wire and what gases are suitable for use in barretters?

We shall now examine the conditions which must be satisfied if the current is to remain constant over a certain interval of temperature. The answer is implicit in equation (2).

By setting the first differential of the current with respect to the temperature equal to zero, we obtain:

$$R \frac{dA}{dT} - A \frac{dR}{dT} = 0; \quad \dots \dots (3)$$

$$\text{and therefore} \quad \left. \begin{aligned} R \frac{dA}{dT} - A \frac{dR}{dT} &= 0; \\ \frac{T}{A} \frac{dA}{dT} &= \frac{T}{R} \frac{dR}{dT} \end{aligned} \right\}$$

In order to make the significance of this equation somewhat clearer, we can let A and R approach a certain working point T_0 by definite powers of the temperature:

$$A = A_0 \left(\frac{T}{T_0} \right)^\alpha,$$

$$R = R_0 \left(\frac{T}{T_0} \right)^\rho,$$

and therefore

$$I = \sqrt{A_0/R_0} \left(\frac{T}{T_0} \right)^{\frac{1}{2}(\alpha - \rho)}$$

The requirement of a constant current thus comes down to the condition that $\alpha = \rho$.

The exponent ρ of the resistance is approximately equal to unity for ordinary metals. α should be about 4 when the heat dissipation takes place by radiation.

With heat dissipation by convection, α may be smaller, but it always remains considerably greater than one. The result is that a constant current is only possible when care is taken that the resistance increases with an extraordinarily high power of the temperature, and the heat dissipation increases with an extraordinarily low power of the temperature.

The metals iron and nickel, which show exceptionally high temperature coefficients of the electrical resistance somewhat above the magnetic Curie points, may in the first place be considered as materials for the filament. The values of $T/R \, dR/dT$ lie in a suitable temperature range between 2 and 2.5.

In contrast to the heat radiation, which increases with the fourth power of the temperature, heat conduction and convection, especially with great differences in temperature between filament and gas, show a much slower increase with temperature. By using a light gas, such as hydrogen, the conduction can be made to dominate over the radiation and the lowest possible value of $T/A \, dA/dT$ is thus obtained.

In order to obtain some idea of the suitability of different materials and gases, the quantities $T/R \, dR/dT$ (continuous lines) and $T/A \, dA/dT$ (dotted lines) are shown for these materials and gases in fig. 5 as functions of the temperature.

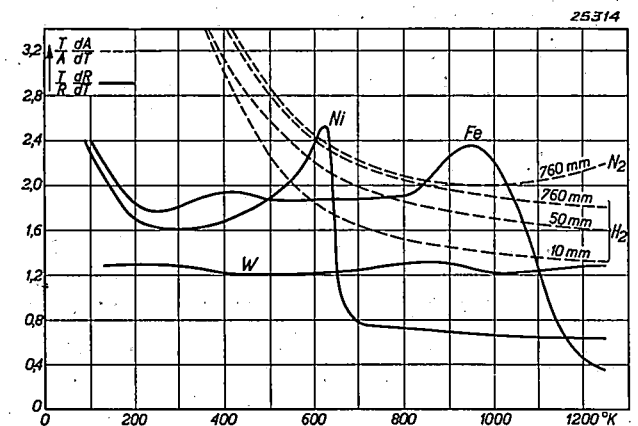


Fig. 5. Continuous lines: $T/R \, dR/dT$ values of different metals as a function of the temperature (R , electrical resistance, T absolute temperature). Dotted lines: $T/A \, dA/dT$ values of a very thin wire for different gases and pressures (A heat dissipation of a wire in this gas). In the range where a continuous line lies above a dotted one, the corresponding combination of metal and gas shows a descending characteristic. The greatest descending range is that of an iron wire in an atmosphere of hydrogen at a pressure of 10 mm.

If a continuous line and a dotted line intersect, the combination in question of filament material and gas produces a descending $I-V$ curve. In the temperature range between 850° K and 1100° K the $T/A \, dA/dT$ value for nitrogen lies relatively close to the $T/R \, dR/dT$ value of iron. In this range therefore an iron filament in nitrogen at ordinary pressure would be suitable as a current regulator. In the case of most metals the resistance is about proportional to the temperature

right just above the transitionpoint (906 °C). The left-hand filament is quite smooth and bright, the right-hand one is badly shrivelled.

With filaments of a nickel-iron alloy, which has no transition phase, these difficulties are not encountered, and current regulators with low regulation current can be made for alternating current also. The relation between the maximum and the minimum voltage of the regulation range need only be slightly less favourable with these barretters than with those having pure iron filaments.

Circuits containing barretters

Since the current in the regulation range of the barretter lamp is fixed, a separate type of lamp must be used for each current. There is in principle no limitation of the current. It is, however, advisable to use several lamps in parallel for currents greater than 6A, because the heating up time of 6A barretters is several seconds, and increases approximately with the square of the current.

For different regulation ranges of the voltage a separate type of valve is also necessary. The voltage, however, need not be adjusted so accurately as the current; it is only necessary that the variations in voltage occurring fall within the regulation range of the valve. Barretters are made with voltages up to 240 volts in the middle of the regulation range. The connection of several lamps in series is not immediately possible. If the barretters do not have exactly the same current in the regulation range, then, when *I* is the current through both, the barretter lamp with characteristic *a* (fig. 9) will

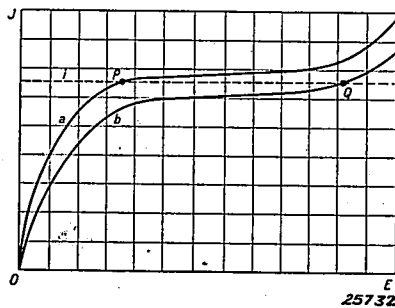


Fig. 9. Two barretter lamps of the same type, with slightly differing characteristics may have quite different working points *P* and *Q* at the same current. Because of this regulator lamps may not be connected in series.

adjust itself to the working point *P*, and the tube with the characteristic *b* to point *Q*. This destroys any possibility of regulation, because at the moment when lamp *a* assumes its regulatory function, *b* is already fully loaded and every further increase in the load damages barretter tube *b*.

Two applications of Barretters

As an example³⁾ of the application of barretters let us try to decrease the current fluctuation of a tungsten lamp, a carbon filament lamp or a constant resistance on a variable mains voltage. To do this, we represent the *V-I* characteristic of the regulator at the working point by the equation

$$\frac{\Delta V_r}{V_r} = q \frac{\Delta I}{I} \dots \dots \dots (4)$$

For a constant resistance *q* = 1; for an absolutely flat characteristic *q* = ∞. We shall take the rather low value of *q* = 10 for the resistance tube, which is therefore not a very flat *I-V* characteristic. For the voltage *V_{gl}* on the load, for example an electric lamp, a similar equation holds

$$\frac{\Delta V_{gl}}{V_{gl}} = p \frac{\Delta I}{I}, \dots \dots \dots (5)$$

where *p*, for tungsten filaments for instance, is about equal to 2, and for carbon filament lamps is about 0.7. From (4) and (5) it follows that

$$\frac{1}{p} \frac{\Delta V_{gl}}{V_{gl}} = \frac{1}{q} \frac{\Delta V_r}{V_r} \dots \dots \dots (6)$$

Now the total variation in the voltage of the mains is

$$\Delta V = \Delta V_{gl} + \Delta V_r, \text{ or according to (6)}$$

$$\Delta V = \Delta V_{gl} + \frac{q}{p} \frac{V_r}{V_{gl}} \Delta V_{gl},$$

from which it follows that

$$\frac{\Delta V_{gl}}{V_{gl}} = \frac{\Delta V}{V} \frac{p V}{p V_{gl} + q V_r}$$

$$\frac{\Delta V_{gl}}{V_{gl}} = \frac{\Delta V}{V} \frac{1}{1 + \left(\frac{q}{p} - 1\right) \frac{V_r}{V}} \dots \dots (7)$$

The relative voltage fluctuations on the lamp are thus decreased more, the greater the portion *V_r/V* of the mains voltage destroyed by the regulator. In *Table I* are given several numerical values for *q* = 10; *p* = 2, *p* = 1 and *p* = 0.7.

If a barretter is used which takes up half of the voltage (*V_r/V* = 0.5), the voltage fluctuations of an ordinary electric lamp, a constant resistance and a carbon filament lamp are reduced to 33, 18 and 13 per cent respectively.

³⁾ N. A. Halbertsma, Elektrotechn. Z. 48, 512, 1927.

Table I.

V_r/V	$\frac{\Delta V_{gt}}{V_{gt}} : \frac{\Delta V}{V}$		
	$p = 2$	$p = 1$	$p = 0,7$
0.0	1.000	1.000	1.000
0.1	0.714	0.526	0.429
0.2	0.556	0.357	0.273
0.3	0.455	0.270	0.200
0.4	0.384	0.218	0.158
0.5	0.333	0.182	0.131
0.6	0.294	0.156	0.111
0.7	0.263	0.137	0.097
0.8	0.238	0.122	0.086
0.9	0.217	0.110	0.077
1.0	0.200	0.100	0.070

The considerations above refer only to stationary working states. When a starting current surge occurs, it is usually not decreased by the current regulator, and in some cases it is even reinforced, since the cold resistance of the barretter is very small.

In the stabilization of the heating current in some radio sets it is necessary to take precautions against these starting surges. In these sets there is a small lamp for lighting the tuning scale connected in series with the heating filament of the indirectly heated cathodes. This lamp has a much smaller heat capacity and might burn through in the time necessary for the indirectly heated cathodes to heat up. For the stabilization of this heating current a special stabilizing resistor has been constructed which has a semi-conductor as limiting resistance in series with the filament. The size of this resistance is about 2000 ohms at room temperature; when, however, it is raised to 300° C by the heat of the current, only 100 ohms of the resistance remain⁴⁾.

⁴⁾ Resistors of this material are also used as starting resistances for motors, and have already been described in this periodical by P. C. van der Willigen, Philips techn. Rev. 1, 205, 1936.

Upon switching on the set the current is limited by the resistance of the semi-conductor to a small portion of its running value. During the heating up of this resistance the iron filament also becomes warm and assumes its regulatory function so that the current never reaches too high a value.

The action of a semi-conductor in series with the regulator valve is made clear in *fig. 10*. The upper

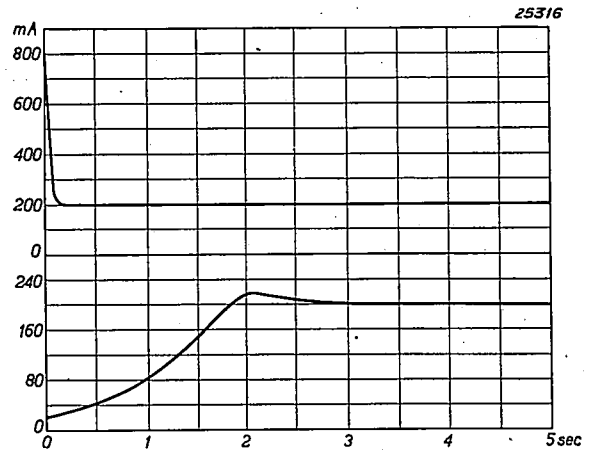


Fig. 10. Variation of the heating current in a radio receiver with receiver valves heated in series as a function of the time after switching on. Above: an ordinary barretter is in series with the filaments. Below: a regulator with a semi-conductor incorporated in it is in series with the filaments. The resistance of the semi-conductor has a very high value in the cold state, and therefore limits the starting surge of the current.

curve gives the variation of the current upon switching on the heating current without a limiting resistance, the lower curve shows the variation of the same when a starting resistance is used. In the first case the starting surge is about four times the running current, while the current reaches 10 per cent more than the running value at its maximum when a starting resistance is used, and reaches its stationary value only after several seconds. In this final state the greater part of the resistance of the valve is due to the iron filament, and only a small part is due to the semi-conductor, so that the regulatory action of the iron filament is manifested, and the current remains constant within narrow limits when the mains voltage fluctuates.