An Automatic Voltage Regulator

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III. *An Automatic Voltage Regulator.* *By* F. G. H. LEWIS.

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ABSTRACT.

The Paper describes a method by which automatic voltage regulation to 0·15 per cent. may be obtained for such purposes as the operation of photometric standard lamps on an ordinary outside supply varying by as much as 10 per cent. The lamp is placed across an unbalanced Wheatstone bridge of which two opposite arms are composed of tungsten filament lamps. The increase of resistance of these lamps, due to the extra current passing through them when the outside voltage rises, causes a shift in the balance of the bridge such that the voltage across the photometer lamp remains unaltered if the values of the resistances in the arms be properly proportioned. The power taken is about 40 times that used in the regulated circuit.

THE object of the scheme described in what follows is to find a simple method by which the fluctuations of voltage of an ordinary electric current supply may be overcome, and a steady voltage obtained for the purpose of running a glow-lamp photometer standard or any other purpose for which a steady voltage is required.

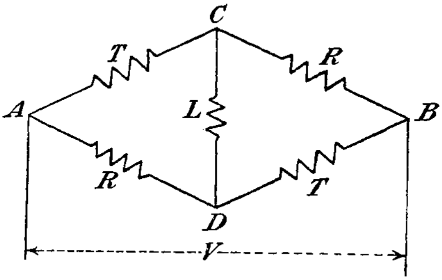

FIG. 1.—DIAGRAM OF CONNECTIONS.

The method depends on the fact that the resistance of a tungsten filament lamp rises with increase of temperature of the filament in such a way that the percentage increase in resistance is proportional to the percentage increase of current. This has been found experimentally by determining the change of current through a lamp due to change of voltage. The following experimental results show the values of current at various voltages for tungsten filament lamps of two different ratings :—

TABLE I.

100-volt Lamp.		200-volt Lamp.	
Voltage	Current	Voltage	Current
60	0·632	120	0·169
70	0·693	140	0·185
80	0·750	160	0·201
90	0·804	180	0·215
100	0·856	200	0·230
110	0·905	220	0·243

$dI/dV=0{\cdot}60(I/V)$ so that $dR/R=0{\cdot}67(dI/I)$

$dI/dV=0{\cdot}61(I/V)$ so that $dR/R=0{\cdot}64(dI/I)$

Now suppose an unbalanced Wheatstone Bridge be set up as in Fig. 1, where

T,T are resistances composed of tungsten filament lamps in parallel, while R,R are constant resistances of any ordinary type. L is a standard lamp, the current through which it is desired to maintain constant, and V is a fluctuating supply voltage. It will be seen most clearly by means of a numerical example, how a constant voltage may be maintained at L when V varies.

As an example, suppose that the outside voltage, which may vary from 220 to 260 volts, be applied at AB, and that it is desired to have 40 volts constant across CD when the current flowing from C to D is 0·3 amperes. Then, when the voltage across AB is 220 volts, the voltage from A to C is 90 volts and that from C to B is 130 volts if the resistances in these two arms are respectively equal to the resistances in BD and DA. If, then, i_1 is the current in CB, the current in AC is $(i_1+0{\cdot}3)$.

Hence $90=T_1(i_1+0{\cdot}3)$ where T_1 is the resistance of T when the current through it is $(i_1+0{\cdot}3)$.

Also $130=R\,i_1$.

Similarly when the outside voltage is 260, the voltage between A and C must be 110 and that between C and B must be 150, in order to maintain 40 volts across CD.

Hence $110=T_2(i_2+0{\cdot}3)$ where T_2 is the resistance of T when the current through it is $(i_2+0{\cdot}3)$, for if the resistances of the arms AC and DB be equal at the lower value of current, they will also be equal at the higher current, since both are composed of lamps having the same current-resistance characteristic.

Also $$150=Ri_2$$

Hence $$T_2/T_1=11(i_1+0{\cdot}3)/9(i_2+0{\cdot}3)$$

and $$i_1/i_2=130/150$$

But since for a tungsten lamp $dR/R=a\ (dI/I)$ where a is about $2/3$, it follows that

$$(T_2-T_1)/T_1=\frac{2}{3}\{(i_2+0{\cdot}3)-(i_1+0{\cdot}3)\}/(i_1+0{\cdot}3)$$

whence $$T_2/T_1=\frac{2}{3}(i_2+0{\cdot}3)/(i_1+0{\cdot}3)+\frac{1}{3}$$

Thus from the two expressions for T_2/T_1

$$\frac{2}{3}x^2+\frac{1}{3}x-\frac{11}{9}=0$$

where $$x\equiv(i_2+0{\cdot}3)/(i_1+0{\cdot}3)$$

This equation gives $$x=1{\cdot}127$$

and from this result, since $i_1/i_2=13/15$, we get $i_1=1{\cdot}43$, and hence $T=52$ and $R=91$ ohms.

Thus a regulated voltage of 40 volts with a current of 0·3 amps. may be obtained with a total current of approximately 3 amps. on a variable circuit of nominally 240 volts.

This result may be somewhat improved by using, instead of constant resistances in the arms CB and AD of the bridge, carbon filament lamps which have a small negative temperature coefficient of resistance.

The device has been tried in this form with the following values of resistances :—

Arm *AC*—2 120-volt, 60-watt tungsten filament lamps, and 2 105-volt, 25-watt t.f. lamps in parallel.

DB—3 120-volt, 60-watt and 1 110-volt, 30-watt t.f. lamps in parallel.

AD and *CB*, each 5 200-volt, 16-c.p. carbon-filament lamps in parallel.

The voltages measured across the lamp terminals in *CD* with various voltages across *AB* are given in Table II.

TABLE II.

Voltage across *AB*.	Voltage across *CD*.
260	68·0
250	68·2
240	68·2
230	68·1
220	67·9

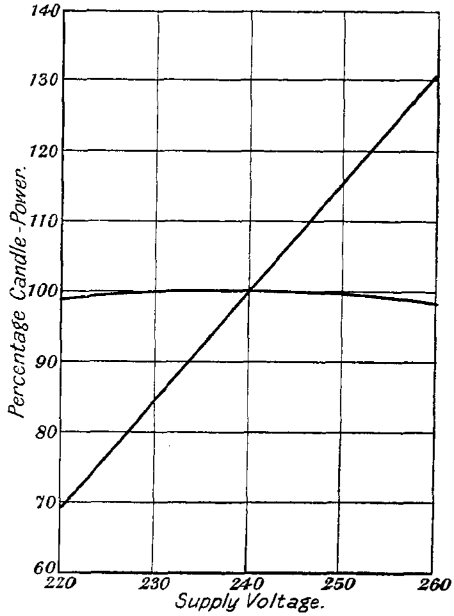

FIG. 2.—GRAPH OF RESULTS OBTAINED WITH REGULATOR.

Total current through circuit, 2·26 amps. ; current in *CD*, 0·20 amps.

It is suggested that this device should prove useful for a small photometric laboratory where the expense of upkeep of a storage battery is excessive for the amount of photometric work to be done. As will be seen from the table above, a voltage regulation to within 0·2 per cent. can be obtained on a supply fluctuating by as much as 5 per cent. from the mean, with a circuit in which the total power used is 40 times that needed for the photometer lamp.

The curves in Fig. 2 show the variation in the candle-power of a lamp operating (*a*) on the outside voltage as it varies from 220 to 260 volts, and (*b*) on the regulated voltage (over the same range of variation of supply voltage). In these curves the value 3·7 has been used for the percentage variation of candle-power due to 1 per cent. change of voltage.

The circuit is very easy and cheap to set up, and it can be readily adjusted by trial and error to give the required result. It is desirable to have a switch or series resistance in the regulated circuit, as the low resistance of the tungsten lamps when cold causes a rush of current in this arm when the main current is first switched on. The device might also find application in meter testing, or in other cases where a small current at a steady voltage is required.

DISCUSSION.

Dr. **Rayner** suggested that the apparatus described might afford a new type of standard E.M.F.

Mr. F. E. **Smith** dissented from the view of the previous speaker, and showed that the voltage which is to be kept constant is in fact a function of the resistance of the non-incandescent arms of the bridge. It can thus never be possible in such an arrangement to secure an absolutely constant voltage, such as would be required for the purposes of a standard.

Prof. **Fortescue** said that the method produced a distinct gain in steadiness of voltage and would undoubtedly be appreciated in testing work.

Mr. J. W. T. **Walsh**, who read the Paper on behalf of Mr. Lewis, referred, in reply, to Fig. 2 of the Paper, which shows candle-power plotted against supply-voltage. The curve is very flat-topped, thus permitting of steadiness within very close limits, even for variations of supply voltage which would be considered as very large.

Communicated Remarks.

From Mr. T. **Smith**: Mr. Lewis' problem can be treated theoretically by considering only algebraic forms. Taking the resistances of the outer arms of the bridge in cyclic order as P, Q, R, S, and the resistance on the regulated circuit to be G, the currents in these arms are evidently proportional to $S(Q+R)+G(R+S)$, $R(P+S)+G(R+S)$, $Q(P+S)+G(P+Q)$, $P(Q+R)+G(P+Q)$ and $PR-QS$ respectively. If then a constant current C is to be maintained in the regulated circuit the resistance in the first arm must be P when the current in this arm is

$$\frac{S(Q+R)+G(S+R)}{PR-QS}C$$

and similarly in the other cases. If P is the only variable resistance the regulation can only be exact if the law followed by the filament is of the form

$$\text{Voltage}=\alpha\times\text{current}+\beta\times\text{resistance},$$

where α and β are constants. When these constants are known the proper resistances for the bridge can be set up at once. The extension to the case when the resistance of more than one arm depends upon the current is obvious from the above expressions. The external voltage is

$$\frac{PQRS\left(\frac{1}{P}+\frac{1}{Q}+\frac{1}{R}+\frac{1}{S}\right)+G(P+Q)\ (R+S)}{PR-QS}C$$

and the battery current is

$$\frac{(P+S)(Q+R)+G(P+Q+R+S)}{PR-QS}C$$

From these expressions it is evident that the power efficiency of the regulation will be low unless the control can be effected by the use of a material having a large value for the coefficient β. If such a material were available it would evidently be desirable to employ it in the lamp of the regulated circuit, and with a suitable coefficient the need for the bridge would disappear. The condition would be exactly met if the resistance were proportional to the square of the voltage, or

$$\frac{dR}{R}=2\frac{dV}{V}=-2\frac{dC}{C}$$

which may be compared with the author's experimental results. It is difficult to imagine a material with the property that the current decreases continuously over a certain range in consequence of a continuous increase in the applied voltage, but the author's scheme may enable the construction of standard lamps with a self-contained automatic voltage steadier.

From Mr. A. CAMPBELL: The thermal system of voltage regulation used by Mr. Lewis is not novel, except in so far as tungsten is employed as the heated material. The general system was described by the writer many years ago (Proc. Inst. El. Engs., Vol. XXX., p. 889, 1901), and the mathematical conditions were investigated for one case. The hot wires actually used were of nickel, platinum or copper, and very exact automatic regulation was obtained. A 40-volt lamp was exhibited regulated on a variable circuit of about 150 volts. In the discussion on the Paper referred to, Professor Callendar described his use of the system for potentiometer purposes; he was probably the first to employ the method. Mr. Lewis has made the method more easily available by putting ordinary tungsten filament lamps in place of specially constructed resistances.

From the AUTHOR: I feel that Mr. T. Smith's mathematical treatment of the problem adds much to the value of the Paper, but I would emphasise the fact that in any particular case the final adjustments are always more conveniently made by trial and error, since the resistances of the opposite arms of the bridge need not necessarily be exactly equal. As Mr. Smith says, the efficiency of the device depends upon the quantity he calls β, and if β be so large compared with α that the latter may be neglected, the need for the device would disappear. Unfortunately, as he remarks, the substance in which the current decreases as the applied voltage increases is one somewhat difficult to imagine.

I regret very much that I was not aware of Mr. Campbell's previous description of the device before the Institution of Electrical Engineers, or of Professor Callendar's use of it. It clearly appears that the principle of the method was first employed by Professor Callendar, but I would point out that the use of tungsten lamps instead of nickel resistances not only simplifies the setting up of the device, as Mr. Campbell remarks, but it also has another more important result, viz., that of making the regulation independent of external temperature. Mr. Campbell achieved this by the use of compensating resistances placed in the same enclosures as the nickel arms of his bridge, but any such arrangement is unnecessary in the case of tungsten lamps where the conductor operates at a temperature of something like 2000 deg. in a vacuum. It can be shown both theoretically and practically that the effect of even a 100-deg. change in the temperature of the surroundings is quite inappreciable in its effect on the temperature, *i.e.*, the resistance of the filament.

It thus seems that Dr. Rayner's suggestion is one well worth investigating further, and a small form of the bridge, to be used on a circuit regulated to the nearest volt (as it might easily be), could be made very handy and suitable for use with a potentiometer or for similar standardising purposes, and should give a voltage which remains constant and unaltered by temperature to at least 0·01 per cent., and it is possible that a very much greater constancy than this might prove to be obtainable.