United States Patent [19]

Nolan et al.

[11] **3,718,849**

[45] **Feb. 27, 1973**

[54] **VOLTAGE REGULATORS FOR USE IN BATTERY CHARGING SYSTEMS**

[75] Inventors: **Roger William Nolan**, Redditch; **Maurice James Wright**, Quinton, both of England

[73] Assignee: **Joseph Lucas (Industries) Limited**, Birmingham, England

[22] Filed: **June 3, 1971**

[21] Appl. No.: **149,585**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 93,876, Nov. 30, 1970, abandoned, which is a continuation of Ser. No. 701,892, Jan. 31, 1968, abandoned.

[30] **Foreign Application Priority Data**

Feb. 6, 1967 Great Britain........................5,566/67

[52] **U.S. Cl.** **320/61**, 322/28, 323/38

[51] **Int. Cl.** **H02j 7/10**

[58] **Field of Search**......322;28/; 323/38; 320/61, 38, 320/68, 39, 32

[56] **References Cited**

UNITED STATES PATENTS

3,373,333	3/1968	Eckard..................................320/32
3,538,421	11/1970	Young...................................323/38
3,201,681	8/1965	Van Wilgren et al...............320/68 X

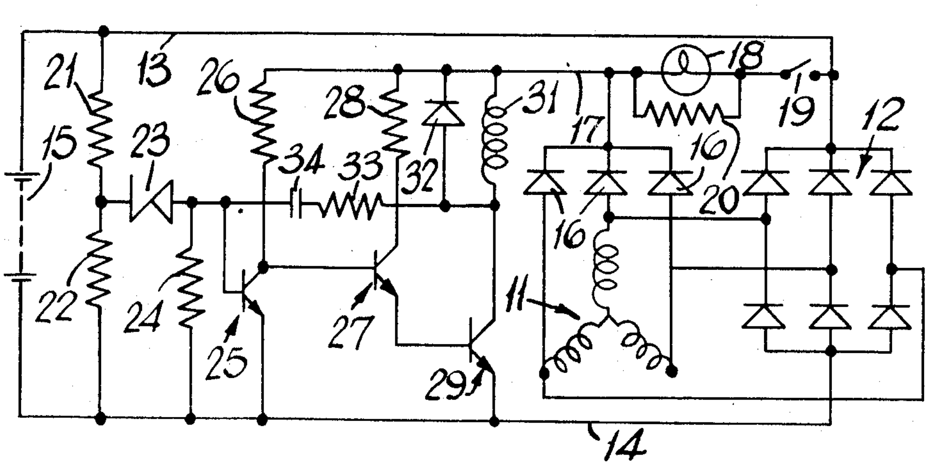
Primary Examiner—J. D. Miller
Assistant Examiner—Robert J. Hickey
Attorney—Holman & Stern

[57] **ABSTRACT**

A voltage regulator is disclosed for varying the output of a generator of a road vehicle by changing the current flow in its field winding. The voltage regulator device includes, as is common, a Zener diode or equivalent break-down device which, as known, conducts at a predetermined battery voltage, and serves to render a transistor conductive, which transistor, when rendered conductive, acts through further components to reduce the current flow in the field winding.

In systems of this type it is commonplace to provide for temperature compensation by providing a thermistor or equivalent device in the circuit. Such device, in a known manner, serves to compensate for changes in battery temperature, as well as for the changes in temperature coefficient of the Zener diode and the transistor so utilized. However, in accordance with the instant invention, such temperature compensation is achieved by means of a simple impedance network interconnecting the Zener diode or equivalent device and the transistor, such impedance network, in effect, serving to multiply the net negative inherent temperature characteristics of the transistor by a selected amount to compensate for the net positive temperature coefficient of the Zener diode, the resultant characteristics of the voltage regulator circuit with respect to temperature being desirably negative or, at least, zero. In the specific preferred embodiment, a resistor is disposed across the base-emitter of the transistor, and another resistor is disposed in series circuit with the Zener diode. The ratio of these two resistors substantially defines a multiplication factor which enhances the net negative temperature coefficient of the transistor and serves to overcome the net positive temperature coefficient of the Zener diode.

4 Claims, 6 Drawing Figures



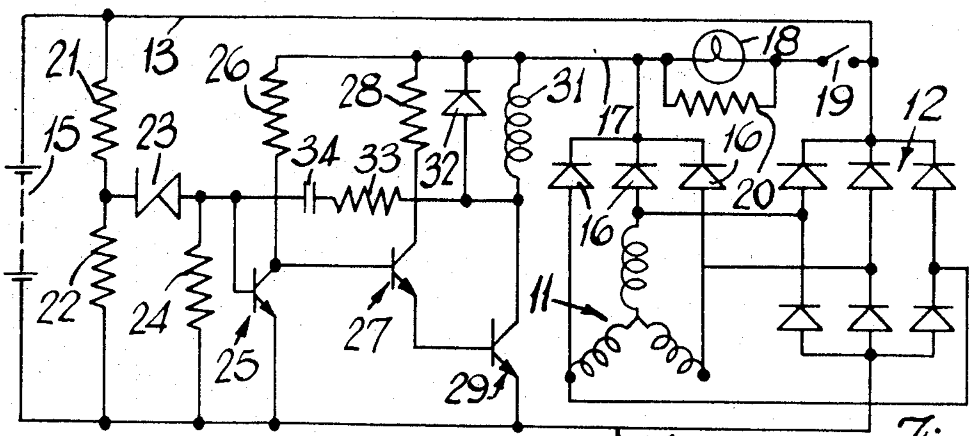


Fig. 1.

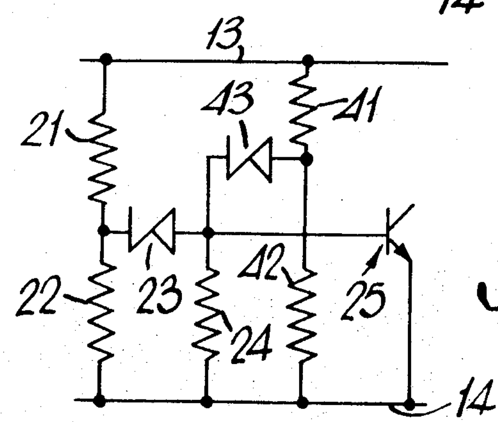


Fig. 2.

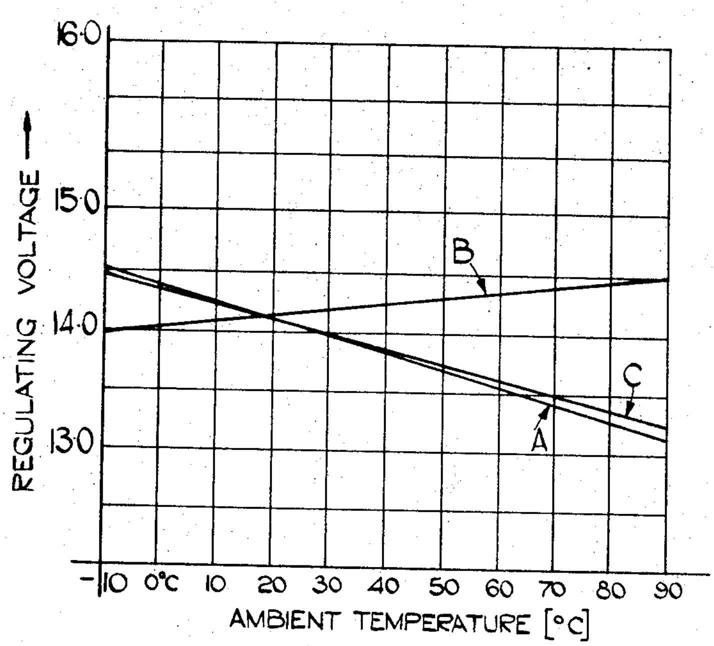


Fig. 3.

INVENTOR
Roger William Nolan & Maurice James Wright

ATTORNEYS

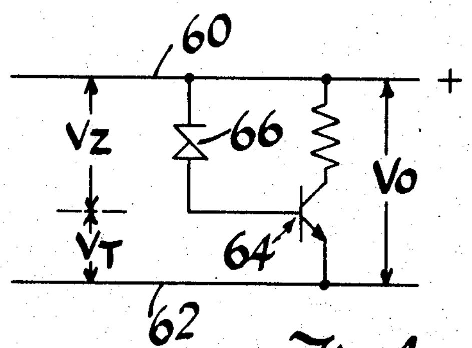


Fig. 4.

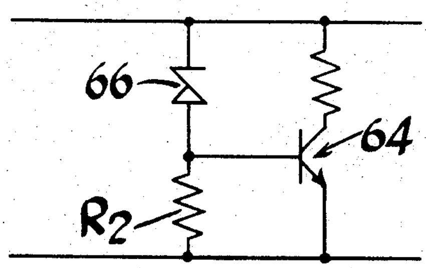


Fig. 5.

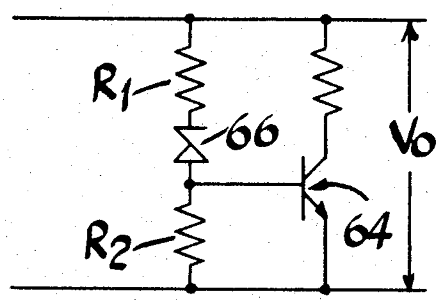


Fig. 6.

INVENTOR
Roger William Nolan & Maurice James Wright

ATTORNEYS

VOLTAGE REGULATORS FOR USE IN BATTERY CHARGING SYSTEMS

This application is a continuation-in-part application of co-pending Application Ser. No. 93,876, filed Nov. 30, 1970 now abandoned which in turn is a continuation of Application Ser. No. 701,892, filed Jan. 31, 1968 now abandoned.

The invention disclosed herein relates to voltage regulators for use in battery charging systems on road vehicles, and particularly concerns a novel voltage regulator circuit which achieves temperature compensation in a unique manner.

Voltage regulator circuits and devices for use in vehicular battery charging systems have long been known in the art and are generally seen to comprise a pair of terminals adapted for connection to the vehicle battery with a series circuit coupled across the terminal pair and including a voltage sensitive device such as a Zener diode and a resistor, the voltage sensing device being adapted to conduct at some predetermined battery voltage so as to develop an output signal across the resistor. A transistor device is normally also provided with the device having its base-emitter junction connected across the resistor. The collector output circuit of the transistor is normally coupled to the field winding of a generator, for example, such that the collector current of the transistor effectively varies the output of the generator which charges the battery. In known manner, the overall regulator circuit is such that regulation will commence at some predetermined transistor collector current.

Problems arise, however, with circuits of this type, such problems being specifically related to temperature compensation. As is known, in practice, the temperature of the vehicular battery inevitably varies and it thus becomes necessary to provide some type of temperature compensation. In addition, as the temperature of the ambient environment varies, the particular characteristics of the individual components, such as the Zener diode and the transistor, likewise vary, this variation in and of itself being deleterious to proper operation of the regulator circuit. For example, it is known that the normal type of Zener diode used in such a regulator has what can be termed a net positive temperature coefficient such that, as the temperature increases, the breakdown for conduction voltage of the Zener diode likewise increases. Even though the transistor devices utilized in such circuits have inherently negative temperature coefficients in that, for a given output collector current, the input base voltage needed decreases at increasing temperatures, the net positive temperature coefficient of the Zener diode will be seen to effectively swamp or override the negative transistor characteristics such that the overall temperature coefficient of the regulator circuit is positive. Again, such positive characteristics are inappropriate to proper regulation techniques as will be apparent from a consideration of a paper entitled "The Battery, The Voltage Regulator and the need for System Concept", delivered by R.W. MacKay, of Prestolite Corporation, at the International Automobile Engineering Congress held at Detroit on January 11–15, 1963.

In an effort to overcome these disadvantages of the typical and basic regulation circuit above-described the prior art has gone to the utilization of a thermistor device, for example, coupled in the Zener diode-transistor circuit, the thermistor device functioning in known manner to compensate for the otherwise deleterious temperature coefficient of the regulator circuit. Yet, even the provision of such a thermistor device has its disadvantages in that such devices are, for one, expensive and, further, cannot easily be manufactured with micro-circuitry techniques and the like. Additionally, it is difficult, when one considers the manufacture of a large number of regulator circuits, to find a correspondingly large number of thermistors having suitable tolerances.

As one of its primary objectives, the instant invention contemplates the provision of a regulator circuit of the above basic type, but wherein the thermistor so prevalent in prior art constructions is eliminated while an overall advantageous temperature coefficient of the circuit is retained. In this respect, the novel invention contemplates the provision of an impedance network, such as resistors, in circuit with the Zener diode or other breakdown device and the transistor, this impedance circuit being such that the net inherently negative temperature coefficient of the transistor is effectively multiplied by a predetermined amount sufficient to overcome the net positive temperature coefficient of the Zener diode as above discussed.

Specifically, the instant invention contemplates the provision of a regulator device which, in standard fashion, includes a pair of terminals for connection to the battery. A series circuit is likewise coupled across the pair of terminals and includes a voltage sensitive device such as a Zener diode and resistors, one such resistor being coupled across the base-emitter junction of a transistor likewise coupled across the pair of terminals. A further resistor likewise is coupled in series circuit arrangement with the breakdown device.

In the usual fashion, means are provided which are sensitive to the collector current of the transistor for varying the output of the generator which charges the battery. However, temperature compensation is achieved in a unique manner in that the value of the resistor coupled across the base-emitter junction is so chosen in relation to the characteristics of the transistor and the other circuit value such that the battery voltage at which regulation commences varies with temperature in a desired, predetermined manner. In the preferred inventive embodiment, the ratio of the resistor disposed in series circuit with the Zener diode and the resistor coupled across the base-emitter circuit of the transistor substantially defines a multiplication factor, which factor serves to inherently multiply the net negative temperature coefficient of the transistor by an amount sufficient to overcome the net positive temperature coefficient of the Zener diode so as to render an overall regulator circuit temperature coefficient that is negative or is at least zero as is desirable in this art.

As a more detailed, though still exemplary embodiment of the instant invention, let it be assumed that the transistor selected has a known given negative temperature coefficient of $-t_x$. Let it further be assumed that the Zener diode so utilized has a positive net temperature coefficient of $+t_y$. As further definition, let the resistor coupled to and disposed in series circuit with the Zener diode be termed R_1 and let the resistor coupled across the base-emitter circuit of the transistor be termed R_2. Now, and as will be shown herein below, suitable selection of these resistor values can serve to effect a resultant net negative or at least zero temperature coefficient of the overall circuit. Specifically, the ratio of resistors or impedances in the manner of R_1/R_2 or, more precisely, $(R_1+R_2)/R_2$ substantially defines a multiplication factor F. In the circuit as described, this multiplication factor F will be seen to multiply the negative net temperature coefficient of the transistor in the manner $(F) \cdot (-t_x)$ so that this value equals or exceeds the absolute value of the net positive temperature coefficient of the Zener diode, (ty), whereby an overall negative or a substantially zero temperature coefficient is achieved.

As should be apparent, merely through the selection of suitable impedance values as set forth above, temperature compensation in a regulator circuit of the type above-described is achieved and, as should be appreciated, this in and of itself represents a marked advance in the art. By virtue of this technique, those of ordinary skill in the art can apply these teachings to other similar circuitry and, by merely utilizing impedance values in accordance with the above concept, select the overall temperature coefficient of the circuit.

The invention itself will be better understood and other advantages and objectives thereof will become apparent when reference is given to the following detailed description thereof, such description making reference to the appended drawings, wherein:

FIG. 1 is a circuit diagram illustrating one example of the instant invention as applied to a battery charging system which employs an alternator;

FIG. 2 is a fragmentary view of a portion of FIG. 1 illustrating a modification of the instant invention;

FIG. 3 is a graph of regulating voltage against ambient temperature for various regulator types useful in explaining the overall result of the instant invention; and

FIGS. 4, 5 and 6 are schematic diagrams of basic regulator circuits useful in teaching the principles of the instant invention.

As background of the instant invention and so as to better understand and appreciate the principles thereof, attention is initially directed to FIG. 4 of the drawings. In FIG. 4, the basic regulation circuit is depicted and will be seen to comprise a terminal pair **60** and **62** across which terminal pair is connected a transistor **64** in so-called "grounded emitter" configuration. A voltage break-down element such as Zener diode **66** is coupled to the base circuit of the transistor **64**. Such a circuit is, as stated, typical of regulation circuits and, per se, is well known in the art.

Now, considering the basic operation of this circuit, if the voltage of V_Z is below a desired or predetermined value, depending upon the transistor characteristics, then no current would flow into the transistor base, and therefore no collector current would flow from the transistor. As referred to above, such collector current is normally utilized in such circuits to control the alternator or generator of the regulation system. Thus, with this condition, the alternator would receive maximum field amperage since no regulation would be present.

If the circuit conditions were such that the system voltage V_O rises above some desired level, then the voltage V_Z would exceed the given break-down voltage of the Zener diode **66** and the Zener diode would conduct providing current to the emitter base circuit base of the transistor, and thus output collector current from the transistor utilized for regulation control. Accordingly, the amount of current flowing in the field winding of the system alternator or generator would decrease reducing the system output so as to maintain the system output at its desired value.

However, due to some practical as well as theoretical considerations, the basic regulation network above-described is seldom left in this simple form. For one, such a simple circuit requires the provision of a Zener diode of very close tolerances and quite precise values. Such diodes are difficult to obtain in quantity. Furthermore, the above-discussed basic circuit suffers a disadvantage with respect to its overall temperature coefficient and characteristic.

Specifically, the temperature coefficient of the circuit voltage is directly dependent upon the break-down voltage of the Zener diode **66**. For a nominal 5-volt Zener diode, the temperature coefficient approximates zero as is known in the art. However, this temperature coefficient increases in a positive manner for increasing voltages above 5-volts across the Zener diodes. As a typical example, and assuming that the Zener diode **66** is a nominal 13-volt diode manufactured by Texas Instruments 1S2130A, such a diode will be seen to have a positive temperature coefficient of +0.07 percent per degree Centigrade. Such a positive temperature coefficient is unfortunately high for battery charging circuits since it results in a net rise of system voltage with increasing temperature. As is known, such a positive temperature coefficient circuit is highly undesirable in this environment.

To prove this net positive temperature coefficient with more mathematical particularity let us look at what occurs at a 25° C. ambient temperature. The voltage V_Z across the Zener diode **66** will nominally be 13.00 volts whereas the voltage V_T across the base-emitter path of transistor **64** would nominally be 0.70 volts which is typical of silicon transistors of the specific type enumerated above, for example. Thus, the overall system voltage V_Z at 25° C. would be approximately 13.7 volts.

At 75° C. ambient temperature, different results follow due to the temperature coefficient of the Zener diode **66** and the transistor **64**. For example, and assuming the element types above discussed, at this temperature the voltage across the Zener diode V_Z would rise by the positive temperature coefficient multiplied by the temperature rise, that is by 0.07 percent of 13×50, which equals 0.455 volts, giving a total of 13.455 volts across the Zener diode V_Z. As is also known, for a silicon or germanium transistor, the temperature coefficient of the base-emitter voltage V_T is approximately minus 2.5 millivolts per degree Centigrade. Thus, at the 50° C. increase in temperature contemplated here, the voltage V_T would be reduced by 0.125 volts to form a new value of 0.575 volts. Adding together the voltages across the Zener diode and across the base-emitter path of the transistor, a new system V_O would be found to approximate 14.03 volts. As can be seen, an increase in ambient temperature has resulted in a net positive increase in system voltage and thus a net positive temperature coefficient of the circuit exists.

With the above now firmly in mind, the further development of the art in this area will be discussed and here attention is specifically directed at FIG. 5. Generally speaking, Zener diodes render rather poor operation due to their leakage currents at low current values. In such circuits, it is usual to have at least 1 to 5 milliamps in the Zener diode during regulation and, in the circuit described in FIG. 4 as well as now shown in FIG. 5, in order to have a final control current of zero to 1 milliamp through the transistor collector, the current flowing through the Zener diode **66** would be any where in the range from zero to 50 microamps. This calculation assumes a nominal and typical transistor gain of 20. In order to enable the Zener diode to conduct this current before actual base current slows into the transistor **64**, a resistor R_2 is provided across the base-emitter path of the transistor. Such resistor is necessary to complete a circuit path through the Zener diode **66** at the time when the transistor **64** still is not conducting since its base-emitter voltage V_t is not sufficiently high.

Furthermore, and referring here specifically to FIG. 6, the Zener diode **66** is easily damaged by ripple voltages as well as voltage excursions of the system voltage V_z due to the high currents which can be drawn through the Zener diode **66** and the transistor **64** which has a relatively low slope resistance. Accordingly, it is therefore desirable to provide some resistance in series with the Zener diode, such as resistor R_1 so as to limit the current and power surges to safe values which can easily be handled by the semi-conductor components. Thus, though normal development, regulatory circuits of the prior art are thus generally of the type shown in FIG. 6.

Yet, the circuit shown in FIG. 6, and assuming normal or prior art values of resistances R_1 and R_2, still suffers from temperature compensation problems in that the net or overall temperature coefficient of the circuit undesirably remains positive much as was indicated with respect to the circuit of FIG. 4.

To show this undesirable result, typical prior art values can be substituted for the resistors R_1 and R_2 such as 10 ohms, and 560 ohms, respectively. The remaining components will be assumed to be standard as discussed above. With these substituted values, the following results can be seen with respect to temperature compensation.

The system will commence regulation when the transistor **64** is brought into conduction to an extent where it causes a reduction of field current. That is, V_o increases until R_2 is passing sufficient current to develop 0.7 volts across it, since transistor **64** cannot conduct until this situation exists. Thus, the current in R_2 is given by

$$I_{R_2} = 0.7/560 = 1.2\text{mA}$$

However, the 0.7 volt is only true at one particular temperature and, in fact, the 0.7 volt decreases by 2.5 millivolts per degree Centigrade. Since it is the voltage of the base-emitter which determines the current in R_2 we have more strictly

$$I_{R_2} = (0.7\text{v} - 2.5\text{mV/°C})/560 = 1.20\text{mA} - 4.46\ \text{microamps/°C}$$

This current passes also through the Zener diode and the resistor R_1. In this analysis we shall ignore the current required between base and emitter of the input transistor. This is legitimate since in a practical circuit it can be kept small by suitable design, and this is done anyway in order to predict accurately what the temperature coefficient of a circuit will be.

The voltage of regulation is then given by the sum of the voltages across R_2, the Zener diode, and R_1. With a typical 13 volt Zener diode in a 12 volt system, the Zener diode having a + 0.07 percent per degrees Centigrade temperature coefficient, this gives +9.1 millivolts per degrees Centigrade for the 13 volt diode.

$$V_z = 13\ \text{V} + 9.1\ \text{millivolts /°C}$$

It is assumed here that the current of 1.2 milliamps is sufficient to bring the Zener into the avalanche voltage region which would be the case in any sensible design.

Lastly, the voltage drop across R_1 is given by its value multiplied by the current flowing through it. This current is the same as I_{R2}.

$$V_{R_1} = 10\,(1.2\text{mA} - 4.46\text{microamps/°C}) = 12\text{mV} - 44.6\text{microvolts/°C}$$

Adding the three voltages together, the voltage V_o at regulation is given by

V_o = 0.7 volts − 2.5 millivolts per degree Centigrade.
+13.0 volts + 9.1 millivolts per degree Centigrade.
+ 12 millivolts − 44.6 microvolts per degree Centigrade.
= 13.712 volts + (6.6 − 0.0446) millivolts per degree Centigrade.

It will be seen that the voltages contributed by the values of R_1 and R_2 are completely negligible since they give a voltage drop of only 12 millivolts with a −44.6 microvolt per degree Centigrade variation to add to the Zener and base emitter. In other words, the circuit quite clearly possesses an overall undesirable net positive temperature coefficient.

Yet, such a net positive temperature coefficient does not necessarily have to result with a circuit similar to that shown in FIG. **6** provided that a proper selection of resistors R_1 and R_2 is made. In this respect, applicants have discovered that if these resistors are properly chosen, a net negative overall temperature coefficient or at least a zero temperature coefficient can result. It is this discovery which lies at the very heart of applicants invention. In the foregoing calculations, it has been seen that the positive temperature coefficient of the Zener diode effectively "swamps" the inherently negative temperature coefficient of the transistor rendering the resultant or overall temperature coefficient of the regulatory circuit undesirably positive. By proper selection of the value of resistor R_1 and R_2, this inherently negative temperature coefficient of the transistor can effectively be multiplied to overcome the positive temperature coefficient of the Zener diode.

From a conceptual point of view, the novel invention will be seen to have the following general characteristics as concerns the selection of resistance values. In a circuit of this general type such as discussed in FIG. **6**, the positive temperature coefficient of the

Zener diode **66** is known upon selection of the particular element. Likewise, the inherent negative temperature coefficient of the transistor is known once a particular transistor type has been selected. Applicants have found that a ratio of the resistors R_1/R_2 or, more precisely, $(R_1 + R_2)/R_2$, in fact, substantially defines a multiplication factor F which, in circuit, will multiply the negative temperature coefficient of the transistor **64**, which coefficient will be termed $-t_x$. Again from a conceptual point of view, one need merely select values of resistance of the resistors R_1 and R_2 such that the multiplication factor is high enough so that this multiplication factor acting upon the negative temperature coefficient of $-t_x$ of the transistor **64** overcomes, i.e., equals or exceeds, the absolute value of the positive temperature coefficient of the Zener diode **66**, which temperature coefficient for purposes of illustration will be termed $+t_y$.

Applicants have therefore discovered that one may select any value of resistances R_1 and R_2 to satisfy the following equation:

$$\left(\frac{R_1+R_2}{R_2}\right) t_x \geq |t_y|$$

whereby a net negative or at least zero overall circuit temperature coefficient will result.

At this point, attention is directed to FIG. **1** of the drawings wherein the actual preferred and exemplary circuit of the instant invention is disclosed. Following this description, it will be seen that the values selected for the resistors corresponding to resistors of R_1 and R_2, or their equivalents, in FIG. **6**, fall within the above equation, and that this circuit, merely through suitable selection of resistance values in accordance with the instant invention, exhibits a net negative temperature coefficient.

Referring to FIG. **1** an alternator **11** supplies power to a full wave rectifier **12** to positive and negative supply lines **13, 14** between which the battery **15** of a road vehicle is connected. The alternator also supplies power through three additional diodes **16** to a positive supply line **17**, which in use will be at substantially the same potential as the positive line **13**. The lines **17, 13** are interconnected by a warning lamp **18** in series with the ignition switch **19** of the vehicle, a resistor **20** being connected across the lamp **18**.

Connected across the lines **13, 14** are a pair of resistors **21, 22** in series, the values of these resistors being such that the current drain when the vehicle is not in use is negligible. A point intermediate the resistors **21, 22** is connected to the cathode of a Zener diode **23**, the anode of which is connected to the line **14** through a resistor **24**, and is further connected to the base of an n-p-n transistor **25**, the emitter of which is connected to the line **14**. The collector of the transistor **25** is connected to the line **17** through a resistor **26**, and is further connected to the base of an n-p-n transistor **27**, the collector of which is connected to the line **17** through a resistor **28**, and the emitter of which is connected to the base of an n-p-n transistor **29**. The transistor **29** has its emitter connected to the line **14**, and its collector connected to the line **17** through the field winding **31** of the alternator, a diode **32** being connected in parallel with the winding **31**. The collector of the transistor **29** is also connected to the base of the transistor **25** through a feedback path including a resistor **33** and a capacitor **34** in series.

In operation, when the ignition switch **19** is closed, the transistors **27, 29** are turned on by current flow through the warning lamp **18**, which is illuminated. Field current now flows in the winding **31**. As soon as the alternator **11** produces an output, the potential of the line **17** rises to that of the line **13**, and so the warning lamp **18** is extinguished, although the transistors **27, 29** are still maintained conductive by power supplied through the diodes **16**. Maximum field current now flows.

When a predetermined voltage is obtained, the Zener diode **23** conducts and a voltage is developed across the resistor **24**. The resultant base emitter current in the transistor **25** causes collector current to flow in the transistor **25**, and when this collector current reaches a predetermined value, sufficient current flowing through the resistor **26** is diverted through the transistor **25** to cause a switching action to commence. The switching action causes the transistor **25** to become fully conductive and the transistors **27, 29** to be turned off. The field current circulates through rectifier **32** and commences to decay. The feedback path through the resistor **33** and capacitor **34** ensures that the circuit switches rapidly from one state with the transistor **25** on and the transistors **27, 29** off, and a second state in which the transistors **27, 29** are on and the transistor **25** is off. The mark-space ratio is determined by the current flowing through the Zener diode **23**, which in turn is dependent upon the voltage of the battery, and the arrangement is such that the mean current flow in the winding **31** maintains the battery voltage at a predetermined value.

As mentioned at the outset, if the battery temperature was constant, the circuit would be quite satisfactory as described above. However, in practice the temperature of the battery inevitably varies, and so it is necessary to provide temperature compensation. As remarked, such compensation is normally accomplished by utilizing a thermistor connected in parallel with the resistor **21**, and in FIG. **3** the curve marked A shows the relationship between temperature and regulating voltage for a known regulator using a thermistor. It will be seen that the characteristic which is preferable is a falling regulating voltage as the temperature increases. If the thermistor is omitted, curve B is obtained, and this curve is totally unsatisfactory. The curve C is obtained without a thermistor provided the values of the various components are correctly chosen in accordance with the invention, as discussed. The transistor **25** has an inherent characteristic such that for a predetermined collector current, the base-emitter voltage required decreases with temperature. Since regulation commences at a predetermined collector current, it can be arranged that the output voltage of the alternator is reduced as the temperature of the transistor **25** increases, and so regulation can be obtained provided that the transistor **25** experiences temperatures which are sufficiently closely related to the battery temperature. It must be noted that in order for this compensation to be effected, the value of the resistor **24** must be carefully chosen in relation to the value of the resistor **21**, because the effective compensation is multiplied by the ratio of these resistors. Circuits are known of the general form shown in FIG. 1 as per FIGS. 4 through 6 in which no temperature compensation is provided whatsoever. Such circuits are not suitable for use in a battery charging system, because of the problems mentioned above, and a circuit shown in FIG. 1 distinguishes from such circuits particularly in the way in which the relationship between the values of the resistors 21 and 24 is chosen. A typical, though exemplary set of values for FIG. 1 is given below:

component		component type	
21	1,000 ohms		
22	3,000 ohms	25	Lucas DT 16
24	200 ohms	27	Lucas DT 16
26	1,000 ohms	29	Lucas DT 32
28	150 ohms	23	8V Zener diode
33	1,000 ohms		
34	10,000 picofarads		

The actual nature of the variation of regulated voltage with temperature depends on the particular application, and so can take a variety of forms. Since the characteristics of the transistor 25 previously referred to is linear, the compensation will also be of a linear nature, but if desired the compensating law can be changed one or more times at various temperatures. FIG. 2 illustrates a modification which enables this to be done. The circuit is the same as FIG. 1 except that there is added a resistor 41 connected in series with a resistor 42 across the lines 13, 14 the junction of the resistors 41, 42 being connected through a second Zener diode 43 to the base of the transistor 25. It can easily be arranged for this circuit to ensure that the output voltage of the alternator is constant until a temperature of 20°C is reached, after which the output voltage of the alternator falls with further increase of temperature. In order to do this, the ratio of the resistance of resistors 21, 24 is chosen to give the constant voltage up to 20°C, and the ratio of the resistors 41,24 is chosen to give the required slope above 20°C. In order to set such a circuit, the resistors 22, 42 are first made with too high a value. The value of the resistor 22 is first set for operation below the temperature of 20°C, whereafter the value of the resistor 42 is set, with the circuit at an elevated temperature, to produce the required characteristics.

As mentioned, the circuit shown in FIG. 1, due to the selection of the values of resistances R_{21} and R_{24} in accordance with the general teachings of the instant invention as above-discussed, does, in fact, exhibit an overall negative temperature coefficient, and, in this manner, markedly differs form circuits of similar type in the prior art.

The operation of the impedance elements 21 and 24 to magnify the negative temperature coefficient of the transistor may be analyzed in terms of the voltages across the impedance elements to achieve a change in conduction of the transistor. For a silicon transistor, the base emitter voltage which is necessary to bring about a change of conduction is on the order of 0.7 volts. This voltage decreases with increasing temperature by 2 ½ millivolts per degree Centigrade. If resistor 24 has a typical value of 200 ohms, the current passed through this resistor by the circuit in order to bring about this change of transistor conduction is 3 ½ milliamps. This current decreases with increasing temperature by an amount proportional to the temperature coefficient of the transistor. With the given parameters this current decrease comes to 12 microamps per degree Centigrade.

All of the current which flows through resistor 24 also flows through resistor 21. Slightly more than 3 ½ milliamps minus 12 microamps per degree Centigrade must flow through resistor 21 in order to bring about a change in conduction of the transistor. Of course, some of the current which flows through resistor 21 also flows through the other divider resistor 22. The current through resistor 22 can be estimated at 2 ½ milliamps, with an 8 volt Zener in the circuit. Also, some of the current through the resistor 21 passes through the base emitter junction of the transistor. However, for the purposes of this conceptual analysis, we can neglect the base to emitter current since its value is kept small compared with the current in resistor 24.

We are now in a position to estimate the potential difference developed across resistor 21, which resistor has an exemplary value of 1,000 ohms, by a current which is sufficient to bring about a change in conduction of the transistor. This current will be 2 ½ milliamps plus 3 ½ milliamps, or 6 milliamps, and the effect of the temperature coefficient of the transistor is to reduce this by 12 microamps per degree Centigrade resulting in a voltage change of 1,000 × 12 or 12 millivolts per degree Centigrade. Thus, the voltage across resistor 21 at the point where the transistor changes conduction is 6 volts less 12 millivolts per degree Centigrade.

The voltage across the other divider resistor is the Zener reference potential plus the control voltage of the transistor. Given the present state of the art, Zener diodes have certain characteristics in common. It is known that above about 5 volts, Zeners have an increasing positive temperature coefficient. A 13 volt Zener INZ130A made by Texas Instruments Inc. has a temperature coefficient of about 0.07 percent per degree Centigrade. An 8 volt Zener will have less of a coefficient than that, but taking the 13 volt value as a worse case, the Zener reference potential will increase 5.6 millivolts per degree Centigrade. As we have said, the transistor control potential is about 0.7 volts minus 2 ½ millivolts per degree Centigrade. Therefore, the voltage across resistor 22 is 8.7 volts and increases with temperature at 5.6 minus 2.5 equals 3.1 millivolts per degree Centigrade.

It will be noted that the net increase of potential across resistance 22 with increased temperature is just what the prior art shows. Without the multiplying effect of resistors 21 and 24 the positive temperature coefficient of the Zener swamps the negative temperature coefficient of the transistor and the temperature coefficient of the circuit is positive.

Now, however, we are in a position to see the combined effects of resistors 21 and 24 and the rest of the circuit. The voltage across the voltage divider made up of resistors 21 and 22 when the conduction of the transistor changes will be the $VR_{21} + VR_{22}$.

$$VR_{21} = 6 \text{ volts} - 12 \text{ millivolts per degree Centigrade}$$

$$VR_{22} = 8.7 \text{ volts} + 3.1 \text{ millivolts per degree Centigrade.}$$

Clearly, the total circuit has a negative temperature coefficient of about minus 9 millivolts per degree.

As further examples and as additional proof of the reliability of applicants' equation and the novel inventive concepts herein expressed, one can substitute different values of resistance or impedance for the elements **21** and **24** and still arrive at a circuit having an overall negative temperature coefficient. In this respect, let it be assumed that resistances R_{21}, R_{22} and R_{24} have the following values, and a 10 volt Zener is used.

R_{21} = 300 ohms

R_{22} = 3,500 ohms

R_{24} = 100 ohms

Voltage across R_{24} = 0.7 volts − 2.5 millivolts per degree Centigrade.

Dividing by 100 gives the current flowing in R_{24} i.e.,

I_{R24} = 7 milliamps − 25 microamps per degree Centigrade

This current flows in R_{21} also developing a voltage across R_{21} which varies with temperature R_{21} also passes the current required by R_{22}. With a 10 volt Zener in circuit, this latter current is given by

$$I_{R22} = (10 + 0.7)/3,500 = 3.03 \text{ milliamps}$$

Total current in R_{21} = 10.03 milliamps − 25 microamps per degree Centigrade

Voltage across R_{21} = 3.01 − 7.5 millivolts per degree Centigrade.

The voltage of regulation is given by the sum of the three constituent voltages.

V_{R24} = 0.7 volts − 2.5 millivolts per degree Centigrade.

V_2 = 10 volts + 7.0 millivolts per degree Centigrade.

V_{R21} = 3.01 volts − 7.5 millivolts per degree Centigrade.

Sum = 13.71 volts − 3 millivolts per degree Centigrade.

Thus, this example gives negative coefficient but of rather lower magnitude.

As a further example, consider a case with R_{22} = infinity (i.e., open circuit) so that we revert effectively to FIG. **6**, but now with different resistance values, say R_{21} = 2,500 ohms and R_{24} = 300 ohms, so that as compared with FIG. **6** as analyzed above, R_{21} is high as compared with R_{24}.

As before, regulation cannot commence until 0.7 volts exists across R_{24}. for R_{24} = 300 ohms, 2⅓ milliamps is required through R_{24}. As before, the current in R_{24} varies with temperature because the base-emitter voltage varies with temperature. More strictly, the base-emitter voltage is 0.7 volts − 2½ millivolts per degree Centigrade. Therefore, the current in R_{24} is given by Ohms law as

$$I_{R24} = \frac{E}{R} = \frac{0.7 \text{ volts} - 2\tfrac{1}{2} \text{ millivolts per degree centigrade}}{300}$$

2⅓ milliamps − 8⅓ microamps per degree Centigrade.

All of the current flowing through R_{24} flows through R_{21}. Since in this example $R_{22} = \alpha$, no current is required for R_{22}. Also base-emitter current can be kept negligible by suitable values and characteristics of remaining circuit elements.

We can now state the potential across resistor **21** as

V_{R21} = 2,500 × (2⅓ milliamps − 8⅓ microamps per degree Centigrade)

= 5.83 volts − 20.8 millivolts per degree Centigrade.

The voltages across the Zener diode and base-emitter will be as before, i.e., a total of 8 volts + 0.7 volts plus 5.6 millivolts per degree Centigrade (for Zener) minus 2.5 millivolts per degree Centigrade (for V_{EB})

V_{R21} = 5.83 volts − 20.8 millivolts per degree Centigrade

V_Z = 8.0 volts + 5.6 millivolts per degree Centigrade

V_{EB} = 0.7 volts − 2.5 millivolts per degree Centigrade

Total volts = 14.53 − 17.7 millivolts per degree Centigrade.

The complete circuit thus has a negative temperature coefficient of minus 17.7 millivolts per degree Centigrade.

As should now be apparent, the objects initially set forth at the outset of the specification have been successfully achieved in that Applicants have clearly shown how a selection of resistance values in a circuit otherwise similar to the prior art, achieves a new, unobvious, and desirable result in that a regulatory circuit having a net negative temperature coefficient or at least a zero temperature coefficient is achieved without the use of thermistor elements. Accordingly

Having thus described our invention what we claim as new and desire to secure by Letters Patent is:

1. A voltage regulator for use in a battery charging system on a road vehicle, comprising in combination first and second supply lines for connection to the vehicle battery, a first resistor, a Zener diode and a second resistor connected in series between said supply lines, said Zener diode having a positive temperature coefficient, a third resistor connected across the series combination of the Zener diode and second resistor, an input transistor having its base-emitter circuit connected across said second resistor, the base-emitter circuit of said input transistor having a negative temperature coefficient substantially less than the positive temperature coefficient of said Zener diode, control means coupled to the collector of said input transistor for controlling charging of said battery in accordance with the conduction of said input transistor, and said negative temperature coefficient of said base-emitter circuit of the input transistor being multiplied by a factor dependent on the ratio of the resistance values of said first resistor and said second resistor, whereby said negative temperature coefficient is at least equal to the positive temperature coefficient of the Zener diode.

2. A battery charging system for a road vehicle, comprising in combination a battery, a generator incorporating a field winding, means coupling said generator to said battery whereby said generator charges said battery, a first resistor, a Zener diode and a second resistor connected in series across said battery, a third resistor connected across the series combination of said Zener diode and said second resistor, an input transistor having a base, a collector and an emitter, means connecting said base and emitter across said second resistor, an output transistor having said field winding in its collector circuit, means coupling the input transistor to the output transistor whereby conduction of the input transistor controls conduction of the output transistor, a positive feedback circuit between the output and input transistors whereby the circuit oscillates between one state with the output transistor fully on and the input transistor fully off, and another state with the output transistor off and the input transistor fully on, the

periods of conduction of the input and output transistors being determined by the current flow through said Zener diode, the base-emitter of said input transistor having a negative temperature coefficient and said Zener diode having a positive temperature coefficient which is substantially greater than the negative temperature coefficient of the base-emitter of said input transistor, and said first resistor having a substantially larger resistance than said second resistor, whereby the effective negative temperature coefficient of said base-emitter is increased by a factor determined by the ratio of the first and second resistors to a value at least equal to the positive temperature coefficient of said Zener diode.

3. A battery charging system for a road vehicle, comprising in combination a battery, a generator incorporating a field winding, means coupling said generator to said battery whereby said generator charges said battery, a first resistor, a Zener diode and a second resistor connected in series across said battery, a third resistor connected across the series combination of said Zener diode and said second resistor, an input transistor having a base, a collector and an emitter, means connecting said base and emitter across said second resistor, an output transistor having said field winding in its collector circuit, means coupling the input transistor to the output transistor whereby conduction of the input transistor controls conduction of the output transistor, a positive feedback circuit between the output and input transistors whereby the circuit oscillates between one state with the output transistor fully on and the input transistor fully off, and another state with the output transistor off and the input transistor fully on, the periods of conduction of the input and output transistors being determined by the current flow through said Zener diode, the base-emitter of said input transistor having a negative temperature coefficient and said Zener diode having a positive temperature coefficient which is substantially greater than the negative temperature coefficient of the base-emitter of said input transistor, and said first resistor having a substantially larger resistance than said second resistor, whereby the effective negative temperature coefficient of said base-emitter is increased by a factor determined by the ratio of the first and second resistors to a value at least equal to the positive temperature coefficient of said Zener diode, the system further including a fourth resistor and a second Zener diode connected in series across the series combination of said first resistor and first Zener diode, the ratio of said first resistor to said second resistor being chosen so that until a predetermined temperature is reached the overall circuit has a zero temperature coefficient, but said second Zener diode conducting at said predetermined temperature and the ratio of said fourth resistor to said second resistor being chosen so that above said predetermined temperature the overall circuit has a negative temperature coefficient.

4. A battery charging system for use in a road vehicle, comprising in combination first and second supply lines, a battery having its positive terminal connected to the first supply line and its negative terminal connected to the second supply line, an alternator, a full wave rectifier connected to the alternator and supplying power to the first and second supply lines, a third supply line, means connecting said third supply line to said first supply line through a warning lamp and an ignition switch of the vehicle in series, a plurality of diodes connected to the phase points of said alternator and supplying power to said third supply line, whereby when the alternator is operating the potential of said third supply line is equal to the potential of said first supply line so that said warning lamp is extinguished, a series circuit connected between said first and second supply lines and including a first resistor, a Zener diode and a second resistor, a third resistor connected across the series combination of said Zener diode and said second resistor, an input transistor having its base connected to the junction of the Zener diode and second resistor and its emitter connected to the second line, a fourth resistor coupling the collector of said input transistor to said third supply line, a second transistor having its base connected to the collector of the input transistor, its collector connected through a fifth resistor to the third supply line and its emitter connected to the base of an output transistor, said output transistor having its emitter connected to the second supply line and its collector connected to the third supply line through a field winding of said alternator, a diode bridging said field winding, said diode conducting energy stored in said field winding when said output transistor is off, and a positive feedback circuit coupling the collector of said output transistor to the base of said input transistor, the circuit incorporating the input transistor, second transistor and output transistor oscillating by virtue of said positive feedback circuit to establish a mean current flow in said field winding, said mean current flow depending on the current flow through said Zener diode, which depends on the voltage between the first and second supply lines, the base-emitter of said input transistor having a negative temperature coefficient, and said Zener diode having a positive temperature coefficient, and said first resistor being substantially greater in magnitude than said second resistor whereby the negative temperature coefficient of said base-emitter is multiplied by a factor determined by the ratio of the values of the first and second resistors, to a value at least equal to the positive temperature coefficient of said Zener diode.

* * * * *