

April 24, 1956

D. E. HOWES

2,743,409

PRECISION SPEED REGULATION OF ADJUSTABLE-SPEED D.C. MOTORS

Filed March 15, 1955

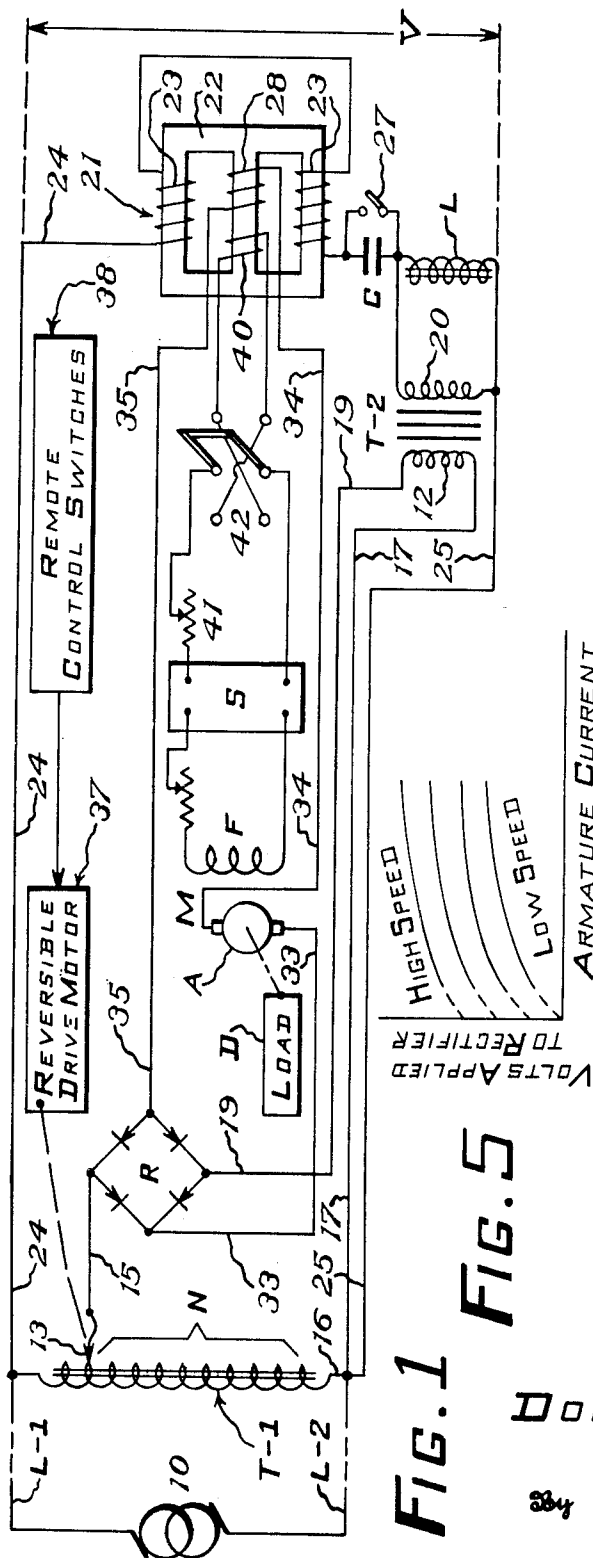


FIG. 1

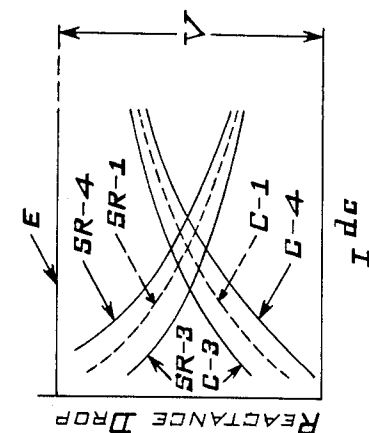


FIG. 4

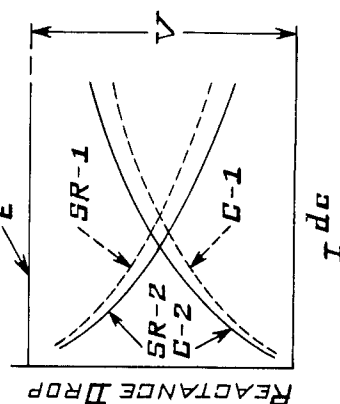


FIG. 3

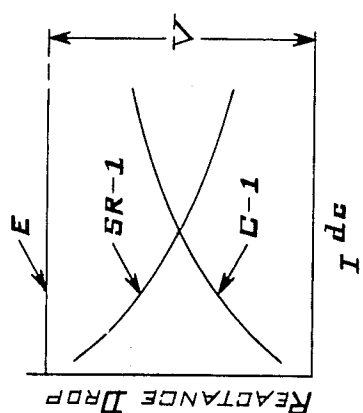


FIG. 2

Inventor

DOUGLAS E. HOWES

ସିଧା

William T. Kriener
Attorney

1

2,743,409

PRECISION SPEED REGULATION OF ADJUSTABLE-SPEED D. C. MOTORS

Douglas E. Howes, Worcester, Mass., assignor to Norton Company, Worcester, Mass., a corporation of Massachusetts

Application March 15, 1955, Serial No. 494,395

8 Claims. (Cl. 318—332)

This invention relates to electrical systems and apparatus for providing controllable or adjustable speed-changes in an electric motor whose armature is supplied, through rectifying means, with direct current from an alternating-current source.

One of the objects of this invention is to provide a system and apparatus of the above nature in which voltage drops in the armature supply circuit may be more readily compensated throughout their changes and thus wide range of motor-speed change achieved with better speed regulation at any selected speed within the desired range. Another object is to carry out this last-mentioned object in a manner, and preferably with static apparatus or devices, to readily suit such compensation to various characteristics of change in such voltage drop with change in armature current as load changes. Another object is to make practical and inexpensive provision for more readily substantially matching a particular curve or characteristic of change in voltage drop versus change of armature current as load varies and thus improve materially the operating characteristics, with good speed regulation, of a D. C. motor supplied with rectified electrical energy usually derived from usual or existing A. C. power supply circuits.

Another object is to provide better efficiency and superior speed regulation, in an adjustable or selectably controllable variable-speed D. C. motor-drive deriving its electrical energy by rectification from an A. C. source of supply, by coacting elements and features adapted, in a thoroughly practicable manner, to provide facility in compensating throughout the range of armature-current change with change in load. Another object is to structurally and functionally improve such A. C.-D. C. changeable-speed drive systems, more particularly with respect to voltage-drop compensation. Other objects will be in part obvious or in part pointed out hereinafter.

The invention accordingly consists in the features of construction, combinations of elements, and arrangements of parts as will be exemplified in the structure to be hereinafter described and the scope of the application of which will be indicated in the following claims.

In the accompanying drawing in which is shown an embodiment of my invention to illustrate several of various possible ways in which, severally, or collectively as to any two or more of them, my invention may be practiced,

Figure 1 is a diagrammatic representation of a system embodying an adjustable-speed direct-current drive motor deriving initial electrical energy from an A. C. source;

Figure 2 is a diagrammatic showing of two graphs or curves of voltage-drop compensating action, and

Figure 3 is a like showing of two other such graphs or curves, and

Figure 4 is a like showing of two sets of two other graphs or curves of voltage-drop compensating action.

Figure 5 is a small-scale diagrammatic representa-

2

tion of graphs for several different selected motor speeds, showing approximately the non-linear manner in which it is desired to overcome an illustrative non-linear IR drop rectifier characteristic.

Similar reference characters refer to similar parts throughout the several views of the drawing.

Referring first to Figure 1, conductors L-1 and L-2 represent an A. C. circuit such as a 220 volt, 60 cycle, power line in a factory or the like, supplied with electrical energy from any suitable source as indicated at 10. The voltage across line L-1, L-2 may be considered as substantially constant. At D is diagrammatically indicated a mechanical load to be driven at any selectable speed within the required or desired range of speeds, according to circumstances; the load D may take any form, such as a drive spindle of a machine tool, a machine tool feed-shaft, or the like. Load D is driven by a motor M which is desirably and preferably, in order to gain certain features or advantages thereof, a D. C. shunt motor having an armature A, which is in driving connection with load D, and a field winding F. The latter is energized by direct current in any suitable way, preferably at selectable fixed value, as is known in the art, as by way of a transformer and rectifier, and therefore need not be shown or described and is simply diagrammatically indicated at S.

It has heretofore been proposed to unidirectionally energize, at controllably variable voltage, the armature A by way of a variable-tap transformer and rectifier; such proposed arrangement is inherently defective and gravely inefficient. For example, it is plagued by detrimental effects of voltage-drops in the armature circuit in which the effective armature current, flowing in series through the transformer winding, rectifier, and armature, produces a total voltage drop considerably greater than that in the armature alone; since armature speed decreases directly with the voltage available or supplied to it, poor speed regulation at the intended or selected motor speed results and this is greatly accentuated at the lower available or selected speed settings because the increased armature currents at low speeds, particularly under normal or substantial mechanical loads, greatly increase the IR drops in the transformer winding and in the rectifier with the result that these IR drops, additive in their effects, can become a large fraction of the supply voltage setting on the variable-tap transformer. Not only is speed regulation poor, but also losses are substantial and efficiency is low. Moreover, prior attempts to effect appropriate compensation have been ineffective to cope, completely or with substantial precision, with the oftentimes different or varying conditions met with. Such and other disadvantages and detriments are overcome or greatly alleviated according to this invention in that, also, relative precision of compensation is achievable and at the same time the desirable features of A. C. power supply and of the D. C. shunt motor for adjustable or selectably changeable drive retained.

To unidirectionally energize armature A, I provide a full-wave rectifier R, which may also be of the selenium type; its input is supplied, for speed change of the armature A, with controllably variable A. C. energy which is derived from the power line L-1 and L-2 and which is modified automatically by means to compensate for the detrimental IR drop effects above noted but in a manner to substantially match the variability of the latter. Thus, I provide a transformer T-2 whose secondary winding 12 is in series, aiding, with a selectable transformer voltage as by a selectable number of turns N of an auto-transformer T-1, selectable by shiftable tap 13, and it is these two transformer secondaries that are additively connected to the input terminals of rectifier R; the rectifier-input

circuit, in the drawing, extends from one terminal of rectifier R, conductor 15, tap 13, through selected portion of the winding of transformer T-1, conductor 16, conductor 17, secondary winding 12 of transformer T-2, and then by conductor 19 to the other input terminal of rectifier R.

Transformer T-2 has its primary winding 20 energized, through a variable control, from the A. C. supply line L-1, L-2 via conductors 24, 25; the variable control preferably comprises a saturable core reactor 21 having a shell-type of core 22 on the outer legs of which are windings 23 connected in series with an iron-cored inductor L which is connected in parallel with the primary 20 of transformer T-2. The circuit extends from line L-1 via conductor 24, windings 23, parallel circuit 20-L, and then by conductor 25 to line L-2. In that circuit may be included a condenser C which may be shunted out of the circuit as by a short-circuiting switch 27 which, for the moment, may be considered closed and the condenser C left for later consideration.

On the middle leg of core 22 is a winding 28 which is unidirectionally energized proportionally to the current flowing to armature A of shunt motor M; thus, it may be in series with the armature A and in that case the circuit is from one D. C. output terminal of rectifier R, conductor 33, armature A, conductor 34, winding 28, and by conductor 35 to the other output terminal of rectifier R.

With this arrangement, transformer T-2 is preferably an insulation transformer and in transformation ratio is appropriately suited to the range of variation in IR drops, mentioned above, which are to be compensated for.

Tap 13 on transformer T-1 is controllable in any suitable manner; it may be manually shifted, automatically shifted, or shifted by any suitable means remotely controllable such as a reversible drive motor and gear schematically indicated at 37 which may be remotely controlled, as for start, stop and reverse, by any suitable means schematically indicated at 38. In such manner, the speed of drive of load D may be changed or selected throughout a wide range.

With the arrangement thus far described, disregarding the inductance L and condenser C, the intent is to add, by way of transformer T-2 and its secondary winding 12, a voltage V^{12} which it is sought to so vary (by the action of the saturable reactor impedance windings 23 on the primary of transformer T-2) as to be always proportional to armature current, to the voltage V^N selected at tap 13 of transformer T-1; thus the total A. C. voltage effective in the rectifier and armature circuit is V^N and V^{12} combined, preferably in phase with each other. At low armature currents, the D. C. energizing current of saturation winding 28 is correspondingly low and the impedance of A. C. reactor windings 23, in series with primary 20 of transformer T-2, is high, cutting down the applied primary voltage, so that the value of the added voltage V^{12} at the secondary winding 12 is low; at high armature currents, the reverse takes place, in that the impedance of A. C. reactor windings 23 is low and the applied primary voltage at transformer T-2 is higher so that the added voltage V^{12} supplied by the secondary 12 is high.

Ideally, for all loads at D, including variations thereof, at whatever motor speed is intended to be selected at transformer tap 13 whereby the value of V^N is initially determined, the voltage V^{12} to be added to voltage V^N should be just sufficient to substantially match the IR drops in the armature circuit in order to maintain the speed of the motor constant. However, the resistance-drop of the rectifiers employed, usually of the selenium type, does not vary as a straight-line function of the current flowing through them. At low current values flowing through them, the resistance is relatively high; as current increases, the resistance decreases along a characteristic curve and approaches a practically constant and mate-

rially lower value of resistance with continued increases in current values. Therefore the amount of voltage V^{12} to be added to voltage V^N , if made proportional to armature current, results in departures from constancy of armature speed which, for some applications, are tolerable but which, for many other applications such as those requiring high or extreme precision or such as involve elements of timing as a function of selected R. P. M., make such an arrangement unsuitable.

Accordingly, I make provision for readily and economically varying the magnitude of the added voltage V^{12} , throughout armature current changes, substantially in keeping with the accompanying varying and non-linear change in resistance, and preferably I employ means that enable me to vary or shift the achieved characteristic of added voltage versus resistance to improve or vary the compensation as may be needed according to particular requirements that may be met. I am thus enabled to provide a range of flexibility appropriate to meet various practical requirements, particularly where relative preciseness of speed regulation is required.

Disregarding the condenser C, for the moment, and thus leaving switch 27 closed, the inductance L is in series with the A. C. reactor windings 23, this series circuit being across the substantially constant-voltage A. C. supply circuit L-1, L-2. Reactor windings 23 and inductor L constitute a voltage-dividing circuit; the reactance of inductor L is given a magnitude X^L such that the voltage V^L across it and across its parallel-connected primary winding 20 of transformer T-2 is substantially proportional to the direct-current (the current energizing motor armature A) through the saturation-control winding 28 of the saturable reactor 21; this is achieved by proportioning the inductor L so that its inductance is relatively small compared to the inductance of the reactor windings 23.

Thus, considering first the characteristics of the saturable reactor 21, for any constant voltage applied to its A. C. windings 23, the reactance (X^{23}) of the latter is substantially inversely proportional to the current in the D. C. winding 28; accordingly, the reactance of reactor windings 23, which are in series with inductor L, is inversely proportional to the D. C. armature current through D. C. winding 28 of the reactor. And if the reactance X^L of inductor L is made relatively small compared to the reactance X^{23} of the reactor windings 23, the voltage drop V^L across inductor L will vary substantially as the D. C. armature current I^{dc} varies. The following relationships make this clearer, where V is the voltage across A. C. circuit 24-25 and I is the current therein, V^L being the voltage across the parallel circuit comprising the inductor L and transformer primary 20:

$$(1) \quad I = \frac{V}{X^L + X^{23}} \text{ (ignoring transformer current)}$$

$$(2) \quad V^L = V \frac{X^L}{X^L + X^{23}}$$

But X^L is small compared to X^{23} , therefore:

$$(3) \quad V^L \text{ approaches } V \frac{X^L}{X^{23}} \text{ or } \frac{V X^L}{X^{23}}$$

Since

$$X^{23} = \frac{K}{I^{dc}}$$

then:

$$(4) \quad V^L = \frac{V X^L I^{dc}}{K}$$

or:

(5) V^L varies substantially directly as I^{dc} . This relationship is somewhat modified, but not detrimentally, by the current to the transformer T-2 but this can be kept, by appropriate design of the related parts, low in its

significance or effect relative to the magnitude of the D. C. current (I_{dc}).

Since the voltage V (across the supply circuit 24—25), assumed to be substantially constant, is divided between the reactor windings 23 and the inductor L (with transformer primary 20 in parallel with it), the reactance drop across reactor windings 23 and the reactance drop across inductor L, while one increases (or decreases) as the other decreases (or increases) with change of D. C. current (armature current), do not follow straight line characteristics. The relative characteristics, which are controllably variable as later described, may be substantially as shown, by way of illustration, in Figure 2 where curve C-1 shows how the compensating voltage applied to the transformer primary 20, by the coacting effect of inductor L with saturable reactor 21, can be made to vary in desired non-linear manner with change in D. C. armature current. This non-linear variation is closely suited to the IR-drop versus current characteristic of the rectifiers employed.

This may be better understood by brief consideration of Figure 5. Earlier above I described the non-linear IR-drop versus current characteristics of the rectifiers, and I pointed out that the resistance is relatively high at low current values and decreases, with increase in current, along a characteristic curve that approaches a practically constant and materially lower value of resistance with continued current increases in the higher ranges of the latter. Were such a characteristic translated graphically into voltage changes that need be applied to the rectifier in the armature circuit in order to hold the selected armature speed constant over the normal load range, a set of curves, illustratively for four selected speeds (low constant speed, high constant speed, and two intermediate constant speeds), as indicated in Figure 5 would result. It will be seen that compensating voltage has to be applied or increased at a higher rate at increasing low armature currents than at the ensuing higher ranges of increasing armature currents as motor load, at the intended armature speed, increases.

Recurring now to Figure 2, which shows illustratively the coacting effects between the saturable reactor 21 and the inductor L, the latter being of relatively small reactance, it will be seen that at light loads, when the resistance of the rectifiers R, etc. in the armature circuit are relatively high, the rate of increase of additive or compensating voltage, shown by curve C-1 and supplied by the transformer T-2, as determined by the inductor L which is in parallel with the transformer primary 20, is relatively high, and as load and armature current increase, and the resistance of the rectifiers changes at lesser rate, approaching substantially constant value in the higher current ranges as above noted, the rate of increase in additive or compensating voltage becomes less and less and the compensating voltage approaches or becomes substantially constant. The coacting characteristic of the saturable reactor 21, that is, its A. C. windings 23, is indicated at SR-1; it is the inverse, substantially, of curve C-1 just described. At any value of armature current I_{dc} (or current in D. C. saturation-control winding 28), the sum of the reactance drops (in effect, impedance drops) across the reactor windings 23 and across the parallel circuit L-20 equals the relatively constant supply voltage V (across the supply circuit 24—25) shown by the characteristic E.

Accordingly, the voltage impressed upon the transformer primary 20, which is in parallel with inductor L of the voltage-dividing series circuit (reactor windings 23 and inductor L), can be far more closely controlled and made to vary substantially directly with the D. C. armature current and thereby the corresponding compensating voltage supplied by its secondary 12 (which is in series with the selected turns N of the secondary of transformer T-1) more readily suited to the variables in the armature-energizing circuit to achieve the desired

speed regulation for any speed selected at the transformer tap 13.

Moreover, while the arrangement above described may be readily embodied so that its described coactions and relationships provide the desired characteristic of non-linear change in compensating voltage to suit any given circuit and load conditions or characteristics, it has the material advantages of ease and facility of modification so that its coactions may be readily varied or changed to meet other characteristics or to change at will, as may be required as in some installations of variable speed shunt-motor drives, the whole or a part of an achieved speed-regulation characteristic. For example, I may include, in the voltage-dividing circuit above-described, the condenser or capacitor C already mentioned previously; this I may do by permanently including it in the circuit or as by making provision, such as switch 27, to include it or exclude it.

When included in the circuit, or by opening switch 27, it effects modification of the rate and character of voltage or impedance-drop division between the inductor L (in parallel with transformer primary 20) and the A. C. windings 23 of saturable reactor 21 where it is desired to modify or to meet still more closely a peculiar or inherent variation of resistance of the rectifiers with change in current flowing through them. Its inclusion modifies the above-described coactions so as to achieve a net reactance (as between that of A. C. reactor windings 23 and itself) that decreases faster than in substantially direct proportion to the D. C. armature current and has the effect of increasing or raising to a higher level the voltage compensation that is to accompany increase in load.

This effect is indicated in Figure 3 where the characteristics or graphs C-1 and SR-1 of Figure 2 are repeated but shown in broken lines; due to the inclusion of the capacitor C in Figure 1, the curve SR-1 of Figure 2 drops more rapidly as indicated at SR-2 and curve C-1 of Figure 2 rises more rapidly as indicated at C-2 in Figure 3. In this manner, compensation with increase in load can be raised to a higher level.

To further illustrate the facility of achieving desired variability, or flexible suitability to particular existing factors in order to vary or mold them as may be desired, I may provide the saturable reactor 21 (Figure 1) with a biasing winding 40 on the same core leg as the D. C. winding 28 and connect it to a suitable source of unidirectional current, such as the source S that supplies the field winding F with selectable field excitation current. These connections are made preferably by suitable means, such as a variable resistance 41, by which the degree of bias of winding 40 may be set or selected and preferably also by way of a suitable reversing switch such as switch 42 by means of which the direction of bias effect of winding 40 may be determined. This may be used with or without the capacitor C, preferably without the latter.

The effect of bias winding 40 is indicated in Figure 4, in which again the curves of Figure 2 are reproduced, curves C-1 and SR-1 being shown in broken lines. By energizing bias winding in the same direction as D. C. winding 28 which is responsive to D. C. armature current, the reactance of the windings 23 of the saturable reactor 21 may be made to vary more slowly at lower armature currents as is indicated by the curve SR-3 of Figure 4, particularly by comparison to the curve SR-1, that comparison showing the lesser degree of slope, at lower armature currents, than the slope of curve SR-1, both curves practically merging into the horizontal at higher armature currents where the resistance of the rectifiers is more or less constant in value. Correspondingly curve C-3 shows how the compensating voltage applied to the transformer primary 20, by the coacting effect of inductor L with saturable reactor 21, increases more slowly, at lower armature currents, than is the case represented by curve C-1, both curves practically merging into the

horizontal at higher armature currents where the rectifier resistance is more or less constant as above noted.

By reversing the effect of biasing winding 40, by way of reversing switch 42, reverse effects, at lower armature currents, from those just described can be achieved as is indicated by the corresponding curves SR-4 and C-4 which show, in relation to the respective curves SR-1 and C-1, how the slope can be increased at lesser armature currents and, correspondingly, how the amount of voltage compensation at light loads can be increased.

In the curves or graphs of Figures 2, 3 and 4, I have indicated at E, as a substantially straight horizontal line, the relatively constant voltage across the supply circuit 24-25 which supplies the reactance windings 23 of saturable reactor 21 and the serially connected parallel circuit comprising the inductor L and the transformer primary 20; the "C" curves and their respective companion "SR" curves show how this constant voltage E can be, according to the principles of my invention, variably divided according to the desired characteristic of added compensating voltage, shown by the "C" curves, that is to be added by way of the transformer T-2 to whatever voltage, and hence motor speed, that is selected at the variable tap 13 of transformer T-1. The effective voltage applied to the input of rectifier R is thus a variable voltage while the effective voltage across the armature A is substantially constant (though, in compensating for internal armature IR drop, it would correspondingly vary, as will now be understood) throughout changes in load and therefore the speed of motor M can be maintained constant through the inherent speed regulation of the motor where the current-resistance characteristic of the armature supply circuit is substantially matched as it is possible to do, throughout a wide range of such current-resistance characteristics, by means of my invention.

Thus, a characteristic such as C-1 of Figure 2 illustrates one possible form resulting from any one selected relation or ratio of the reactance X_L^2 of the inductor L to the reactance X_{23} of the reactance windings 23 of the saturable reactor 21, the former being kept small compared to the latter, as above explained. For any such selected relationship, illustrated by the curve C-1 of Figure 2, that in turn may be changed or modified, according to the desired rate of change of compensating voltage with change in load current, by bringing into action the modifying effect of a capacitance C as above described and as indicated in Figure 3, or by positive or negative bias, in turn selectively variable as by the rheostat 41 of Figure 1, to achieve modifications as illustrated in Figure 4, and as will now be understood, particularly in view of the circuit arrangement shown in Figure 1, these several modifying effects may be made jointly effective for still further modification of the compensating voltage characteristic. Thus, by opening switch 27, the capacitor C is made effective and with it may also be made effective, at selectable value, either a positive or a negative bias through bias winding 40 of the saturable reactor 21.

In such manner also I may provide a compensating voltage curve or characteristic, relative to any given or inherent current-resistance characteristic in the armature supply circuit, with over-compensation or under-compensation, at lighter motor loads and armature currents where it may be desirable, depending upon the character or purpose of the load D driven by the motor M, that the motor speed depart progressively, within suitable overall margin, from its substantially constant speed at higher loads. In other words the voltage effective at the armature A, instead of being substantially constant throughout load changes as where substantially precise speed constancy is desired, may be made to vary at pre-determinable rate, particularly at lighter loads, and a correspondingly pre-determined speed change of the motor throughout load changes achieved for any selected setting of the control or tap 13 of transformer T-1.

It will thus be seen that there has been provided in

this invention a system and apparatus for efficiently and effectively achieving desired motor speed regulation of a D. C. motor deriving its armature current by rectification from an A. C. source of electrical energy, functioning and controllable at relatively high precision throughout a wide range of selected motor speeds and well adapted, for voltage-drop compensation, to meet varying requirements or characteristics met with in practice, particularly with respect to the current-resistance characteristic of rectifiers employable in such a system. It will be seen that the system and apparatus are of thoroughly dependable character and that the several objects above set forth or indicated, together with many thoroughly practical advantages, are successfully achieved.

As many possible embodiments may be made of the above invention and as many changes might be made in the embodiment above set forth, it is to be understood that all matter hereinbefore set forth or shown in the accompanying drawing is to be interpreted as illustrative and not in a limiting sense.

I claim:

1. In a system for improving the speed regulation of an adjustable-speed direct-current motor, in combination, an alternating-current supply, a direct-current motor having an armature and a field winding and provided with means for supplying the latter with exciting current, a main transformer energized from said alternating-current supply and having secondary turns with controllable means for adjusting to any one of a range of voltages the voltage of its alternating current secondary output, a compensating transformer having a primary winding and a secondary winding with the latter connected in series, aiding, with the secondary turns of said main transformer, a rectifier having its A. C. input supplied with energy by said serially-connected secondary winding and secondary turns, said rectifier having a non-linear current-resistance characteristic in which its resistance is higher and varies at higher rate throughout current changes at lower motor loads than at higher motor loads, a saturable-core reactor having an inductive winding and a flux-control winding thereon which is connected to respond to changes in motor armature current supplied from the D. C. output of said rectifier and thereby, for any selected voltage at the secondary output of said first transformer corresponding to a selected armature speed, vary the reactance of said inductive winding substantially inversely with changes in armature current, a voltage-dividing circuit adapted to be energized by alternating-current energy of substantially constant voltage and comprising said inductive winding and an inductor connected in series therewith, said primary winding being connected across said inductor and said inductor having a reactance that is small compared to the reactance of said inductive winding to effect non-linear voltage division therebetween as D. C. energization of said flux-control winding increases and with the reactance drop across said inductor and hence the voltage across said primary winding increasing at a higher rate throughout current changes at lower motor loads than at higher motor loads.

2. A system as claimed in claim 1 in which said voltage-dividing circuit includes a capacitor coacting with said inductive winding to provide with the latter a net reactance that decreases faster with increase in D. C. energization of said flux-control winding and thereby raises the level at which the reactance drop across said inductor increases as aforesaid and thereby raises the level at which the voltage across said primary winding increases.

3. A system as claimed in claim 1 in which said saturable-core reactor is provided with a bias winding and has means for energizing the latter with uni-directional current and thereby change the reactance of said inductive winding to change the standard of reactance of the latter and thereby alter the division of said substantially constant voltage between the reactance drop across said inductive winding and the reactance drop across said

9

inductor and thereby change the standard of variable voltage across said primary winding.

4. A system as claimed in claim 3 in which there is provided means for selecting the direction of flow through said flux-control winding of its uni-directional energizing current for effecting positive biasing action or negative biasing action thereof according to the direction in which it is desired to change the standard of variable voltage applied to said primary winding.

5. In a system for facilitating speed regulation of a direct-current motor, in combination, a direct-current motor having an armature-supply circuit comprising a rectifier that has a substantially non-linear current-resistance characteristic in that its resistance varies at higher rate throughout current changes at lower magnitudes than at higher current magnitudes, said rectifier having an A. C. input circuit comprising the serially-connected secondaries of a main transformer and a compensating transformer, and means for varying the voltage applied to the primary winding of said compensating transformer and thereby affect the voltage of said A. C. input to the rectifier and control the D. C. voltage applied to the motor armature throughout changes in armature current as the motor load changes comprising a voltage-dividing circuit that includes the inductive winding of a saturable-core reactor of which the D. C. flux-control winding is connected to respond

10

to armature-current changes and an impedance device in series with said inductive winding and in parallel with said primary winding, said inductive winding of the reactor and said impedance device having relative impedance characteristics to provide, throughout D. C. current changes in said flux-control winding corresponding to lower motor loads, higher rate of change of impedance drop across said impedance device than throughout current changes corresponding to higher motor loads.

6. A system as claimed in claim 5 in which said impedance device is an inductor of low reactance relative to the reactance of said inductive winding.

7. A system as claimed in claim 5 in which said voltage-dividing circuit includes a capacitance for changing the standard of change in impedance drop across said impedance device.

8. A system as claimed in claim 5 in which said saturable-core reactor is provided with a bias winding energizable by direct current to change the relative impedance-drop characteristics of said inductive winding and said impedance device.

References Cited in the file of this patent

UNITED STATES PATENTS

2,708,260 Comstock ----- May 10, 1955