Oct. 6, 1959 M. P. FOLEY 2,907,403

APPARATUS FOR CONTROLLING THE OPERATION OF ELECTRICAL PRECIPITATORS

Filed March 31, 1955 3 Sheets-Sheet 1

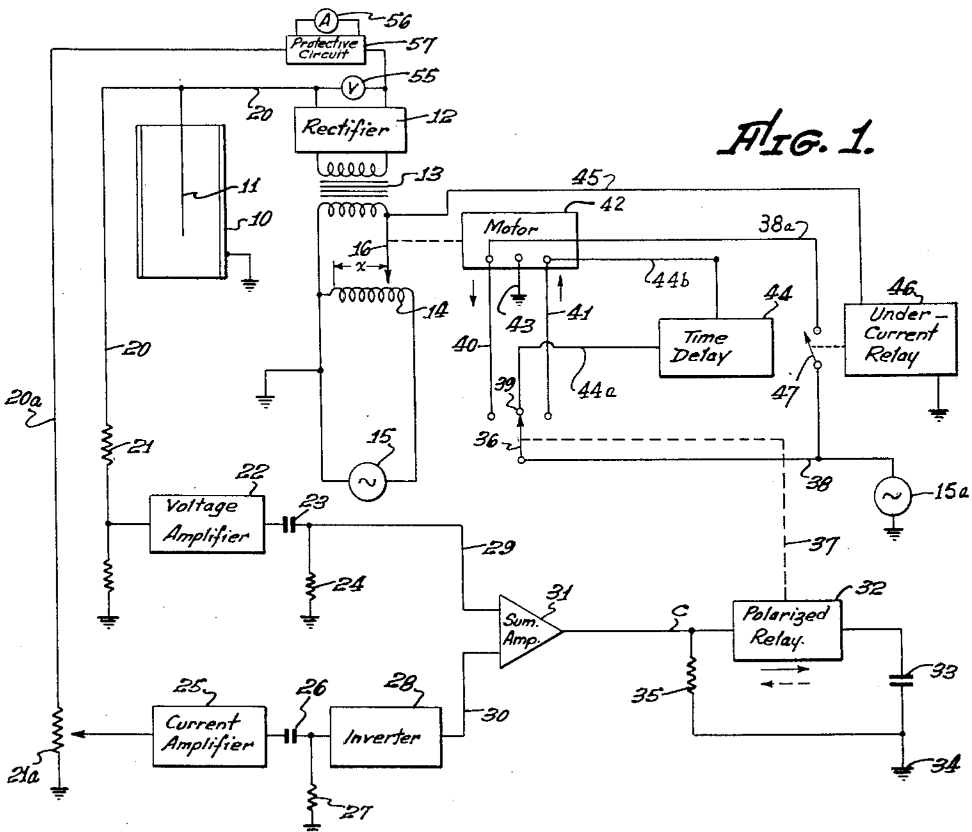
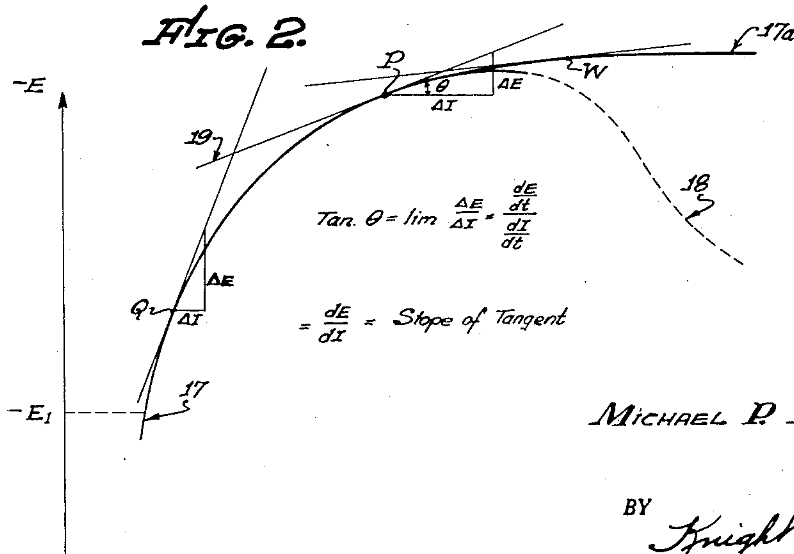


FIG. 1.

FIG. 2.



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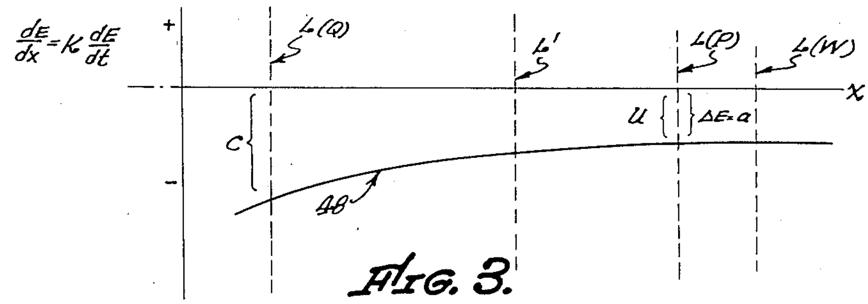

FIG. 3.

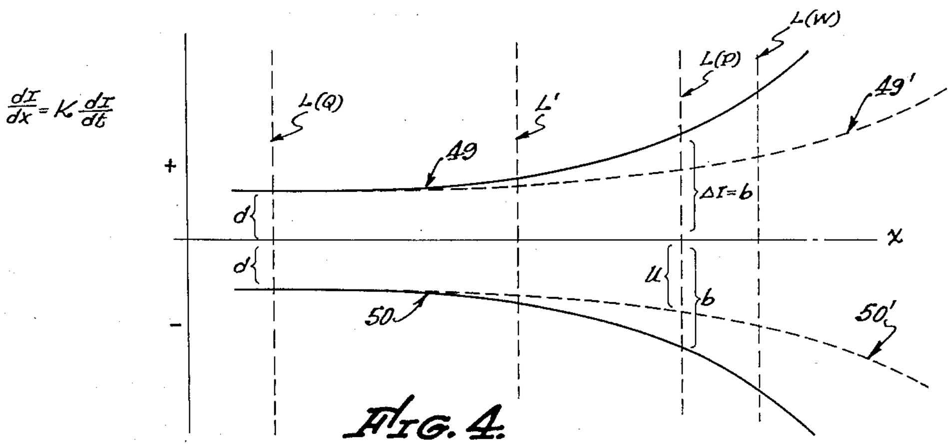

FIG. 4.

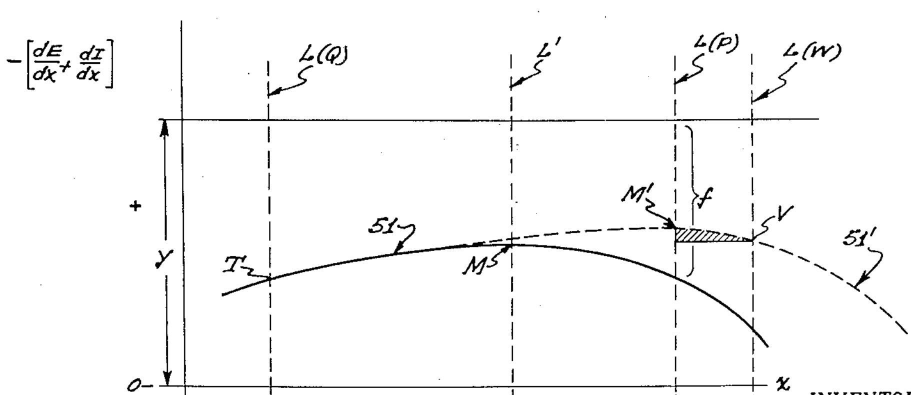

FIG. 5.

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Oct. 6, 1959 M. P. FOLEY 2,907,403

APPARATUS FOR CONTROLLING THE OPERATION OF ELECTRICAL PRECIPITATORS

Filed March 31, 1955 3 Sheets-Sheet 3

FIG. 6.

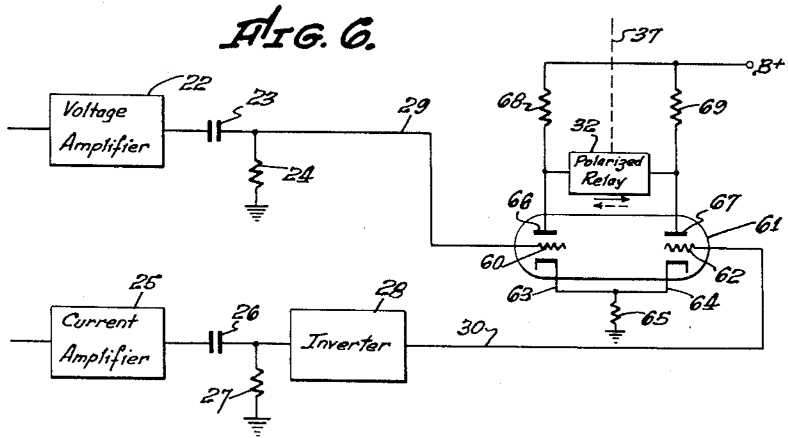


FIG. 7.

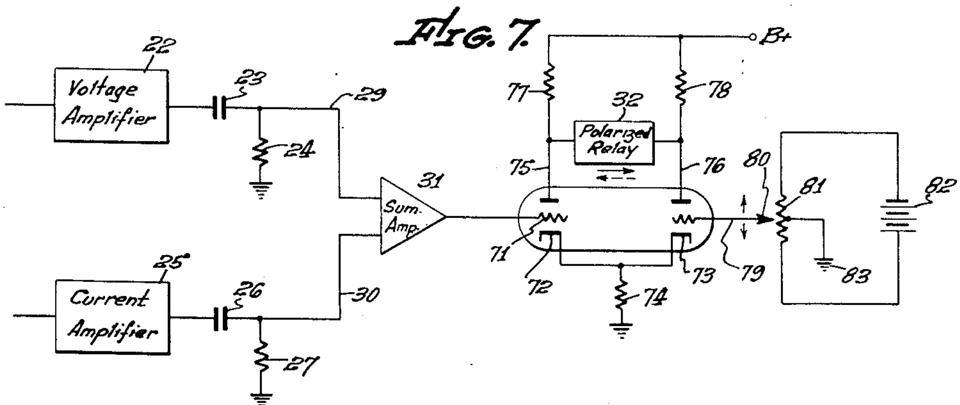
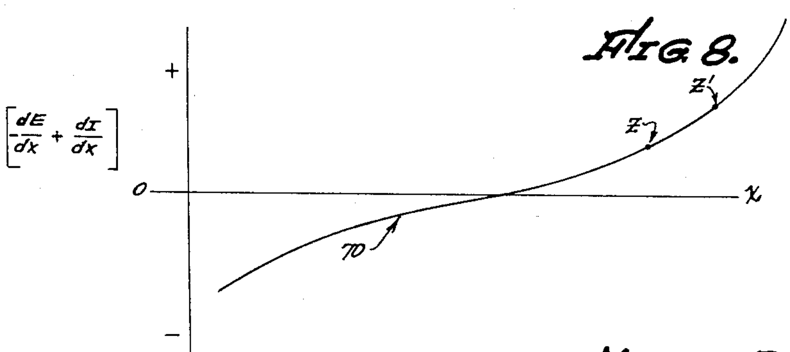


FIG. 8.



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APPARATUS FOR CONTROLLING THE OPERATION OF ELECTRICAL PRECIPITATORS

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Application March 31, 1955, Serial No. 498,222

8 Claims. (Cl. 183—7)

This invention relates to an apparatus for maintaining the average discharge current between the electrodes of an electrical precipitator at optimum values for maximum particle collection efficiency.

Basically, an electrical precipitator comprises one or more pairs of opposing electrodes between which a high voltage electric field is maintained. One electrode of each pair is normally grounded and the other electrode is energized from a high voltage source of electric power. The latter electrode is termed the discharge electrode since it is so designed as to facilitate corona discharge at this electrode. As the applied voltage is raised from zero, a voltage is reached at which corona discharge is initiated; and as a consequence there is a small but measurable current flow between the electrodes. This is commonly referred to as the corona discharge current.

As the applied voltage is further increased, the amount of corona current flowing also increases. Eventually a voltage is reached at which intermittent sparking between the electrodes occurs and adds to the current flow between electrodes. The presence of a spark greatly increases the instantaneous value of the total discharge current flowing between the electrodes but has a comparatively small effect in increasing the average discharge current between the electrodes. Corona discharge represents a relatively steady state and is the primary factor in charging the particles suspended in the gas stream.

If the applied voltage is raised high enough, sparking takes place between electrodes at an increasing rate until eventually conditions become unstable, resulting in breakdown and arc-over. When arc-over between the electrodes occurs, the voltage falls rapidly and the total discharge current rises but collection efficiency becomes very low. Since corona current is, in general, a measure of the ability of the precipitator to charge suspended particles to be collected, it is desired to operate the precipitator at the highest practical value of the corona current. This condition does not necessarily bear any fixed relation to the rate of sparking, as that rate is determined in a given installation by several factors, including the applied voltage, electrode spacing, character of the gas stream, and the amount of and characteristics of collected material accumulated on the electrodes. Likewise, the quantity of electricity per spark is not constant, so that a given frequency of sparking does not add to the corona current by a determinable amount, nor is it considered to be a reliable index of the imminence of arc-over.

The voltage at which arc-over occurs is not constant and may fluctuate in any given installation. Therefore a somewhat lower operating voltage which is the highest favorable to maintenance of a relatively stable operating condition is usually preferred and this is termed the optimum voltage. Since this optimum voltage is not a fixed value that can be set by fixed controls, the present invention is concerned with means for automatically maintaining the precipitator at this pre-selected optimum voltage and average discharge current by direct reference to the average discharge current flowing between the electrodes.

There are known control systems which rely upon the rate of sparking as a reference for control; but in the present invention the rate of sparking as such is of no consequence, even though the sparking may have an incidental effect upon the value of the average discharge current.

In applicant's co-pending application Serial No. 442,415, filed July 9, 1954, and entitled, Method and Apparatus for Controlling Electrical Precipitators, there is disclosed a system for maintaining the discharge current between the precipitator electrodes at a value slightly under that value at which arc-over occurs. Since this optimum current value is not usually constant, the above referred to method and apparatus operates on the principle of effecting regulation with reference to the maximum point on the voltage-current characteristic curve for the particular precipitator involved. Thus, while the actual optimum current values change, the general shape and characteristics of the voltage-current curve remain substantially constant so that the precipitator can, in many instances, be made to operate at the maximum point of the curve. Advantages of such a system over prior attempts to automatically control a precipitator for maximum particle collection efficiency, are fully set forth in the referred to co-pending application.

It will be evident however, that regulating a precipitator with reference to the maximum point on the voltage-current characteristic curve depends for its success on the fact that a maximum point exists. In other words, it is necessary that the curve double back on itself within the range of stable operating conditions in order to provide a unique point, deviations from which may be employed to generate the necessary error signal to bring the discharge current back to its optimum value. This fact limits the use of the invention described in the above referred to co-pending application to precipitators having a characteristic voltage-current operating curve that doubles back on itself or exhibits a unique, maximum point.

A general object of the present invention is to provide an improved apparatus for regulating the discharge current in a precipitator, whereby the precipitator may be adjusted to operate automatically at any arbitrary point on its voltge-current characteristic curve regardless of whether or not such arbitrary point corresponds to a maximum or inflection point of the curve.

It is also an object of the invention to provide an improved control apparatus for automatically maintaining the discharge current between the electrodes of a precipitator at a selected value by direct reference to characteristics of the voltage-current operating curve and not by reference to some indirectly related function.

More particularly, an object of the invention is to provide an improved control apparatus for adjusting the discharge current between the electrodes of a precipitator and automatically maintaining it at optimum values for maximum particle collection efficiency, based on the particular shape of its characteristic voltage-current operating curve.

Briefly, these and other objects and advantages of this invention are attained by initially selecting the desired point on the characteristic voltage-current operating curve at which the precipitator operates with optimum discharge current for maximum particle collection efficiency and yet is safely under that discharge current value at which arc-over occurs. The tangent to the operating curve at this point can be determined. This tangent is equal to the rate of change of voltage with respect to the current at the particular point, and has a unique value. In order to operate the precipitator at this point in accordance with the invention, a first signal that is a function of the rate of change of the voltage is generated and combined with a second signal that is a function of the rate of change of the discharge current. The combination of these two functions results in a third signal that follows a curve having a unique maximum or inflection point. This characteristic of the combined or third signal results, as will be clearer from the description, because the rate of change of the voltage is always greater than the rate of change of the current in the early portion of the voltage-current characteristic curve, and it is always less than the rate of change of the current in the latter portion of the voltage-current characteristic curve.

The fact that the combination of the two rate of change functions in a preferred manner provides a curve that passes through a minimum point enables the precipitator to be regulated to operate at any desired point. This regulation is accomplished by simply adjusting the rates of change functions such that the maximum point in the curve of the combined signal corresponds to the desired operating point on the voltage-current characteristic curve. This signal may then be fed into a regulating apparatus similar to the system disclosed in the above referred to co-pending application to maintain the operation of the precipitator on said operating point.

In a modified form of my invention, the combined curve has an inflection point which can be used in a similar manner to keep the operation at a desired point on the operating curve.

A better understanding of the invention and various embodiments thereof will be had by referring to the accompanying drawings, in which:

Figure 1 is a block diagram of a precipitator and control apparatus for regulating the precipitator in accordance with the method and apparatus of the present invention;

Figure 2 is a plot of a typical voltage-current characteristic operating curve for the precipitator of Figure 1;

Figure 3 is a graph illustrating the rate of change of voltage with respect to the value X which represents the position of the tap of the auto-transformer;

Figure 4 is a graph illustrating the corresponding rate of change of current with respect to the same value X and the result obtained by inverting this function;

Figure 5 is a plot of the sum of two of the functions illustrated in Figures 3 and 4 obtained by inverting the current signal, being the control signal used in the circuit of Figure 1;

Figure 6 is a portion only of a modified type of control circuit;

Figure 7 is a portion only of another modification of the control circuit; and

Figure 8 is a plot of the control signal obtained by combining signals in Figures 3 and 4 without inverting the current signal, for use in the circuit of Figure 7.

Referring to the upper left hand portion of Figure 1, there is schematically illustrated an electrical precipitator comprising electrodes **10** and **11**. The collecting electrode **10** is shown in the form of a cylindrical member as being typical of an electrode providing an extended surface on which particles collect from a gas stream passed between the electrodes. The center electrode **11** is a thin conducting member coaxially disposed within the cylinder and of a surface configuration, for example a fine wire to facilitate production of corona discharge at the electrode. Usually the outer plate or collecting electrode **10** is grounded as shown and is positive with respect to the discharge electrode.

The discharge electrode **11** is energized at a negative polarity by a high voltage source diagrammatically illustrated as a rectifier **12** connected to the high voltage secondary coil of a transformer **13**. The primary of the transformer **13** is in turn energized by an auto-transformer **14** connected to an A.-C. power source **15**. The negative voltage applied by rectifier **12** to discharge electrode **11** of the precipitator may be varied by means of the tap **16** on the auto-transformer **14**. The elements described thus far are entirely conventional and are examples of suitable equipment.

In operation, voltage from the power source **15** is stepped up to several thousand volts by the auto-transformer **14** and high voltage transformer **13**. This high voltage is then rectified by the rectifier **12** and applied by conductor **20** to the discharge electrode **11** of the precipitator to establish between electrodes **10** and **11** a unidirectional high voltage electric field, hereafter designated E. This electric field, E, gives rise to a discharge current from the electrode **10** towards the electrode **11**. The actual electron flow is ordinarily, but not always, from the center electrode **11** to the outer electrode **10**. This discharge current, hereafter designated I, serves to charge particles in a stream of gas passed between the electrodes, and causes the particles to drift toward the relatively positive outer electrode **10**. Control of this discharge current may be effected by regulating the high voltage E across the electrodes by means of the auto-transformer **14**.

As explained in the above referred to co-pending application, a certain amount of sparking may exist between the electrodes. This sparking is normal at the upper range of operating voltages. It is usually found to exist when the value of the discharge current I approaches the desired optimum value for maximum particle collection efficiency. Below this optimum value, the discharge current is caused largely, if not entirely, by corona discharge at electrode **11**. Above the optimum value, sparking and eventually arc-over cause the major portion of the current flow. The optimum value of the discharge current often fluctuates inasmuch as it depends upon many independent variables such as atmospheric conditions, the type of gas passing between the electrodes, the nature of the particles being collected, etc. For a given installation, it can vary from hour to hour.

The average value of the discharge current I flowing between the electrodes is a function of the average voltage value E, as distinguished from the voltage peak value, of the potential between the electrodes. This function is shown in a qualitative manner only as a voltage-current characteristic operating curve **17** in the graph of Fig. 2. The ordinates in this graph represent the average value of the inter-electrode voltage E, and the abscissae represent the corresponding discharge current I. Plotting this graph may be accomplished by means of a suitable voltmeter **55**, preferably of the electrostatic type so that substantially no current is drawn, connected across the electrodes **10** and **11**. The average reading of the discharge current between the electrodes is then obtained from a suitable current meter **56** in conjunction with a protective circuit **57** of the type described and claimed in applicant's co-pending application Ser. No. 422,440, filed April 12, 1954, and entitled, Analyzer Circuit for Electrical Precipitators now abandoned. The protective circuit is in series with conductor **20***a* connected to the ground return side of rectifier **12**. Prior to the development of a circuit as disclosed in the above noted application, it was not possible to obtain sufficiently reliable readings of the average discharge current to plot accurately such a curve as that shown in Fig. 2.

From an examination of the voltage-current characteristic curve **17** of Fig. 2, it will be observed that the voltage initially rises negatively quite rapidly with only small increases in the current, and then the curve at **17***a* tends to level out, the current increasing quite rapidly for only small changes in the voltage. In many types of precipitators, the curve usually doubles back on itself in its later stages, such as indicated by the dashed line **18**. Curves of the **17**—**18** type are characterized by a unique maximum point, use of which may be taken advantage of for automatically controlling the discharge current, as fully set forth and claimed in the first mentioned co-pending application Ser. No. 442,415.

The graph **17**—**17***a* of Fig. 2, typical of a number of

P on the curve 17—17*a* of Fig. 2 and the potential of the signal from summing amplifier 31 applied to the condenser through the polarized relay approaches the point M' in Fig. 6. When the point M' is reached no current flows through the polarized relay and the switch arm 36 returns to neutral position shutting off the motor.

As a possible variation in the circuit of Fig. 2, the summing amplifier 31 may be made of the push-pull type; and in this event it is possible to eliminate condenser 33, but the operation of the circuit is still basically the same.

It will be noted from Figs. 2 and 5 that should the voltage E decrease below the points P and M', respectively, current from the condenser 33 back-tracks through the polarized relay to operate motor 42 and move tap 16, and thereby decrease the voltage further. In order to prevent the regulating mechanism from back-tracking down the curve 17—17*a* from the point P, the precipitator is always regulated to operate in the shaded area between the points V and M' of Fig. 5. This is accomplished by means of the time delay circuit 44. This circuit is arranged to pass power to terminal lead 41 of the motor a given length of time after energization by switch arm 36 engaging contact 39. A typical length of time for such purpose is 15 or 20 minutes, though a longer or shorter period may be used as best suited to operating conditions. Thus, when the switch arm returns to neutral position, a given length of time later, power will be applied to the motor 42 through the time delay to move the tap 16 in a direction to increase the voltage. This increase in voltage towards the point W in Fig. 2 and V in Fig. 5 results in a signal in the polarized relay which throws the switch arm to terminal lead 40, as described previously, thereby removing power from contact 39 and the time delay circuit 44. The precipitator therefore will always operate within the shaded area between M' and V, and since this area corresponds substantially to the desired point of operation of P, regulation is attained.

Time-delay circuit 44 is an optional feature of this entire circuit, but its inclusion is preferred. It is possible to design and build the various elements of the circuit to almost any desired degree of sensitivity so that the control circuit will respond to even very slow changes in the discharge current. However, it is undesirable for practical reasons to build a circuit which is unduly sensitive and it may be preferred to design the circuit so that it is not responsive to very slow changes in the discharge current. It has been found in some instances that there are changes in the current which take place at such a low rate as not to cause the control circuit to bring back the current values automatically to the desired point.

For this reason the time-delay circuit is designed to disturb operating conditions periodically and arbitrarily, thus causing the control circuit to readjust to the optimum point P. When operating conditions fluctuate, the switch arm 36 may shift in position with such frequency that the time-delay circuit does not come into operation; but where operating conditions are relatively static, the time-delay circuit functions at any pre-established interval of time.

Another optional feature is under-current relay 46 which belongs in the general category of circuits known as "fail-safe." This relay is designed to come in to operation in the event of stoppage of electric power from source 15 or a short circuit between electrodes 10 and 11. In either one of these conditions there is a marked drop in voltage between the precipitator electrodes; and this condition is reflected in the primary of transformer 13. A corresponding decrease in current supplied through lead 45 to relay 46 takes place. Relay 46 may be designed to operate only upon complete failure of power, although it preferably is designed to operate when current supplied it drops below some pre-determined value. At this pre-determined low value, relay 46 closes switch 47, thus supplying power from source 15*a* through conductor 38*a* to terminal lead 40 of motor 42. This energizes the motor in a direction to move tap 16 to reduce the voltage supplied to the precipitator. It is preferable that tap 16 cannot be moved to a zero voltage position, but only to some value E_1 which, as shown in Fig. 2, is high enough on curve 17—17*a* to produce signals in networks 22 and 25. Thus when power is restored, transformer 13 is operating under reduced load and the control circuit is able to automatically raise the voltage again to the desired operating value. Relay 46 is preferably provided with time-delay mechanism of any conventional type which delays closing switch 47 when relay 46 is deenergized. This makes the relay non-responsive to purely transient conditions, as, for example, a heavy spark.

Power source 15*a* is preferably a separate source than source 15 in order to provide power for the operation of relay 46 and motor 42 in the event of power failure from the primary source. In a conventional installation this normally involves stringing power over separate circuits. For example source 15 may be a 440 volt circuit while source 15*a* is a 110 volt circuit. If the circuit is not designed to react in this manner to power failure, of course all power can be derived from a single source. The regulating mechanism will then operate in a normal manner.

Fig. 6 illustrates a modified circuit which may be used in place of the summing amplifier 31 and the differentiating circuit 33, 35 associated with the polarized relay 32. In Fig. 6, the rate of change of voltage signal, as represented by curve 48 in Fig. 3, is passed by lead 29 directly to a first grid 60 of a twin triode tube 61. The rate of change of current signal after inversion, as represented by curve 50' in Fig. 4, is passed from lead 30 directly to a second grid 62.

Tube 61 has its cathodes 63 and 64 tied together to a common cathode resistance 65. The plates 66 and 67 connect to opposite sides of the polarized relay 32 and thence through conventional plate resistance 68 and 69 to B+. The polarized relay 32 is identical to the relay 32 of Fig. 1 and is arranged, as indicated by dashed line 37, to operate the switch arm 36 in the same manner.

In operation, the potential of the signal 50' of Fig. 4 is set to equal the potential of the signal 48 of Fig. 3, at the desired operating point indicated by the line L(P). This setting is accomplished by changing the gain of one of the amplifiers as before. These potentials are indicated in Figs. 3 and 4 by the letter U, and so long as they equal each other, their absolute magnitude is unimportant. Note that if the desired operating slope were 45 degrees then dE/dt would be equal to dI/dt and the potentials of curves 48 and 50 would be equal without any necessity of changing the gain of one of the amplifiers.

With equal potentials on the curves 48 and 50' at the desired operating point L(P), the signals from leads 29 and 30 to the grids 60 and 62 of the tube 61 in Fig. 6 will be the same and both sides of the twin triode tube will draw equal currents. Thus the potentials of plates 66 and 67 will be equal and no current will flow through the polarized relay 32.

Should the precipitator move off the operating line L(P), say to the point W in Fig. 2, then the potential on grid 60 from lead 29 will no longer equal the potential on grid 62 from lead 30. This inequality is evident from an inspection of the points at which line L(W) intersects the curves 48 and 50' of Figs. 3 and 4, wherein it will be noted that curve 50' is at a more negative potential than curve 48. Grid 62 is therefore more negative than grid 60 and less current will pass through the plate 67 as compared to plate 66. As a result of this less current, the potential of plate 67 will be higher than the potential of plate 66 and current will pass through the polarized relay in the direction of the dotted arrow to control the regulating apparatus of Fig. 1 as previously described. In essence then, the tube 61 of Fig. 6 will pass an error signal through the relay 32 when the grid potentials are not equal, which error signal is used by the regulating apparatus of Fig. 1 to bring the precipitator back to an operation point on the curve at which the two signals to the grids are equal. As stated previously, when the grid signals are equal, the plate potentials are equal and no current flows in either direction through the relay 32.

Fig. 7 illustrates yet another embodiment in which the inverter 28 is omitted from the circuit. In the embodiment of Fig. 7, the current signal is passed directly into the summing amplifier 31 without being inverted. Thus, the output of the summing amplifier represents the sum of the curves 48 and 49 of Figs. 3 and 4 rather than the sum of the curves 48 and 50.

Fig. 8 illustrates the result of summing curves 48 and 49 and it will be seen that this third sum signal designated 70 passes through the zero axis when the positive potential of curve 49 equals the negative potential of curve 48. These points of the curves 48 and 49 coincide with the operating line L′ of Figs. 3 and 4.

In Fig. 7, this resulting sum signal 70 is passed to one grid 71 of a twin triode tube. The cathodes 72 and 73 are tied together through a common cathode resistance 74 and the plates 75 and 76 are connected to opposite sides of the polarized relay 32. These plates also include plate resistances 77 and 78 connected to B+.

The other grid 79 of this triode tube connects to a tap 80 from a resistance 81. Opposite ends of the resistance 81 connect to the positive and negative poles of a battery 82. The center point of resistance 81 is connected to ground. With this arrangement, potentials from a given negative value up through zero to a given positive value may be applied to the grid 79 by simply moving the tap 80 down or up.

In operation, assume it is desired to operate the precipitator on the line L(P) of Figs. 3 and 4. At this line, the sum of the curves 48 and 49, determined by adding the potentials whose magnitudes are given by "*a*" and "*b*," results in a potential represented by the point Z on curve 70 of Fig. 8. This potential Z is applied to grid 71. A similar potential is then applied to the grid 79 by moving the tap 80 a suitable distance above the mid-point of resistance 81. Thus the potentials on the two grids are equalized and both sides of the tube will draw equal currents resulting in no current flow through the relay 32. If the precipitator deviates from the point represented by the line L(P), say to line L(W), then point Z will move up to Z′ and the potential on grid 71 will be more positive than the potential on grid 79. Therefore more current will pass through plate 75 than through plate 76 resulting in less potential on plate 75 as compared to plate 76. This potential difference between the plates will again cause current to flow in the direction of the dotted arrow through the polarized relay 32 to control the precipitator as previously described.

In the embodiment of Figs. 7 and 8, the point of precipitator operation is varied by changing the tap 80 rather than the gain of the current or voltage amplifiers, although this latter method could be used if desired.

It will be appreciated from the above description that the present invention provides apparatus for automatically maintaining the operation of a precipitator at any desired point on its voltage-current characteristic curve. Further, it will be understood, that the control signal fed to the polarized relay 32 is a function of the slope of the voltage-current characteristic curve at the desired operating point and does not depend for its controlling features on the absolute magnitude of either the voltage or discharge current. Thus, so long as the characteristic curve maintains its shape, this slope will always be the same at the desired operating point and operation of the precipitator for maximum particle collection efficiency is assured.

It should be noted that the present method and apparatus will operate equally as well on voltage-current characteristic curves that double back on themselves. In such instances the optimum operation point would be the maximum point having a tangent line of zero slope. Thus the gain of the voltage and current amplifiers 22 and 25 would be adjusted so that the sum of their rates of change at the point where the tangent is zero results in a minimum point in the sum curve and a maximum point in the inverted sum signal fed to the polarized relay.

While this invention has been described with reference to one type of regulating mechanism for carrying out the method, it is to be understood that other electrical control systems using the same principles may be employed. The invention, therefore, is not to be thought of as limited to the particular apparatus shown and described.

I claim:

1. In an electrical precipitator in which the average discharge current between opposing high voltage and grounded electrodes of the precipitator is a characteristic function of the average voltage across said electrodes, an apparatus for automatically maintaining operation of the precipitator in the neighborhood of any given point on said characteristic function, comprising: means for generating a first signal that is a function of the rate of change of said average voltage; means for generating a second signal that is a function of the rate of change of said average current; means for generating a third signal that is a function of said first and second signals, said last mentioned means including a twin-triode tube connected to receive each of the first and second signals on a separate grid, the net output from the tube constituting the third signal; and means responsive to said third signal for varying the average voltage across said electrodes.

2. In an electrical precipitator in which the average discharge current between opposing high voltage and grounded electrodes of the precipitator is a characteristic function of the average voltage across said electrodes, an apparatus for automatically maintaining operation of the precipitator in the neighborhood of any given point on said characteristic function, comprising: means for generating a first signal that is a function of the rate of change of said average voltage; means for generating a second signal that is a function of the rate of change of said average current; means for generating a third signal that is a function of said first and second signals, said last means including a summing amplifier connected to receive the first and second signals and add them, a twin-triode tube with one grid connected to receive the output signal of the summing amplifier, and means applying a fixed balancing potential to the other grid of the tube, the net output of the tube constituting the third signal; and means responsive to said third signal for varying the average voltage across said electrodes.

3. In an electrical precipitator in which the average discharge current between the electrodes of the precipitator is a characteristic function of the average voltage across said electrodes, an apparatus for automatically maintaining operation of the precipitator in the neighborhood of a given point on the curve representing said characteristic function, comprising: first means for generating a first signal that is a function of the rate of change of the voltage across said electrodes; second means for generating a second signal that is a function of the rate of change of the discharge current between said electrodes, whereby the ratio of said first signal to said second signal at any given instant of time is equal to the slope of the tangent at said point on said characteristic function curve at which said precipitator is operating at said instant of time; third means for generating a third signal that is a function of said first and second signals, whereby said

third signal is a function of the tangent at said point at which the precipitator is operating on said characteristic curve; fourth means for adjusting at least one of said first and second signals such that when the ratio of said first and second signals corresponds to said given tangent, a point on the curve of said third signal is unique; and fifth means for varying the voltage across said precipitator electrodes in accordance with the deviations of said third signal from said unique point corresponding to said given tangent, whereby the voltage of said precipitator is brought back to a value corresponding to said given tangent point.

4. An apparatus according to claim 3, in which said first means includes a resistance element connected between the high voltage electrode and ground, a voltage amplifier connected to tap off a voltage above said resistance proportional to the voltage across said precipitator electrodes, and a differentiating circuit connected to the output of said voltage amplifier, whereby the output of said differentiating circuit comprises said first signal; said second means comprises a current amplifier connected in series with another resistance and with the high voltage electrode to receive and amplify a current that is proportional to the discharge current between said precipitator electrodes, and a differentiating circuit connected to the output of said current amplifier, whereby the output of said differentiating circuit comprises said second signal; said third means comprises a summing amplifier and inverter circuit for inverting one of the first and second signals and then algebraically adding said first and second signals, the output of said amplifier and inverter circuit comprising said third signal; said fourth means comprising a gain control on one of said voltage and current amplifiers, whereby the gain of one of said first and second signals may be varied such that their sum results in a maximum point in said third signal when the ratio of said first and second signals is equal to said given tangent; and said fifth means comprises a control circuit for generating a signal responsive to the slope of said third signal, and a regulating means connected to said control circuit, whereby deviations of the slope of said third signal from zero may be used to energize said regulating means to vary the voltage across the electrodes of said precipitator.

5. An apparatus according to claim 4, in which said control means comprises a polarized relay coil and a storage condenser serially connected across the output of said inverter circuit; a resistance element shunting said serially connected relay coil and condenser; and switch means operable in response to current flow in said relay coil for energizing said regulating means.

6. An apparatus according to claim 4, in which said regulating means comprises a reversible motor and an autotransformer, said motor being adapted to increase the output voltage of said autotransformer when operating in one direction, and decrease the output of said autotransformer when operating in a reverse direction; said switch means energizing said motor in one direction when the current flow through said polarized relay is in one direction, and reversing said motor when the current flow through said relay is in a reverse direction.

7. An apparatus according to claim 6, including time delay means for applying energy to said motor for increasing the voltage output of said autotransformer a predetermined time after the current flow through said polarized relay coil ceases, and means for rendering said time delay inoperative when current is flowing through said polarized relay.

8. An apparatus according to claim 6, including an undercurrent relay energized by current received from the low voltage portion of said precipitator and operating switch means adapted when closed to energize said motor in a direction to decrease the voltage output of said autotransformer when the voltage between the precipitator electrodes drops below a predetermined value.

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