

[54] **AUTOMATIC VOLTAGE CONTROL FOR AN ELECTRONIC PRECIPITATOR**

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[63] Continuation of Ser. No. 275,820, July 27, 1972, abandoned.

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[58] Field of Search **55/105, 139; 307/252 T; 321/18, 25; 323/9, 17, 20, 22 SC, 24, 34; 336/184**

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Primary Examiner—A. D. Pellinen

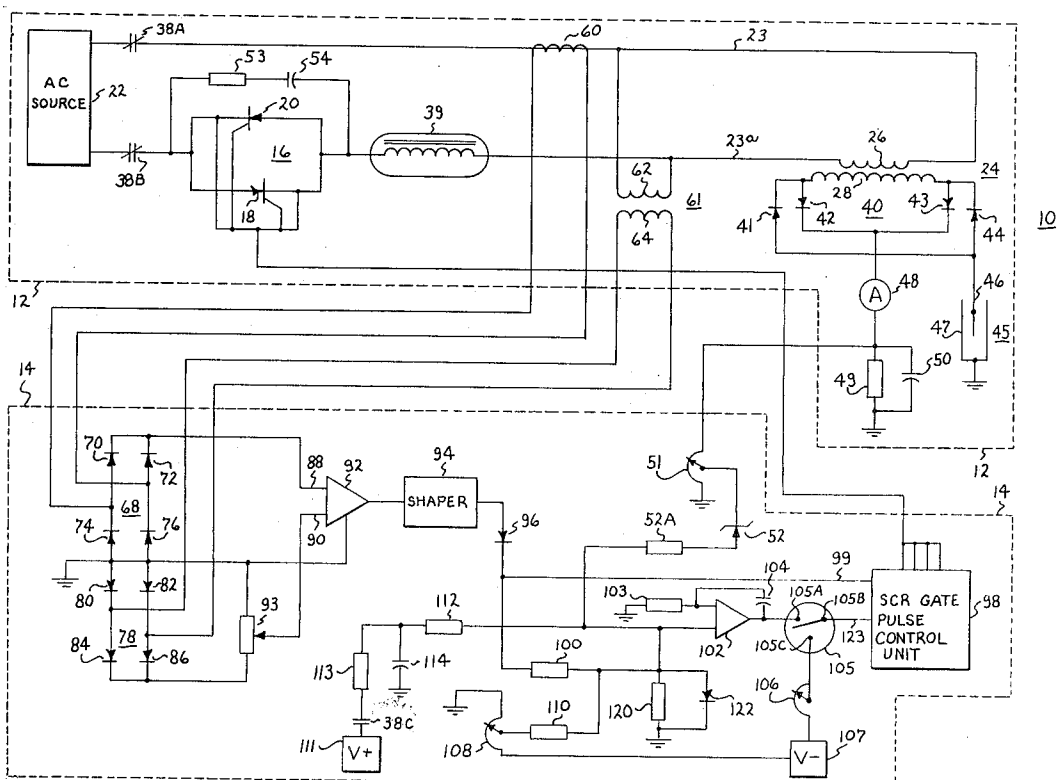
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[57]

ABSTRACT

In a system for automatically controlling the voltage applied to an electronic precipitator there is included a lockout circuit for inhibiting gate pulses to controllable switch means during sparking states of the precipitator, and a delay circuit for blocking gating pulses to the controllable switch for a period of time after the precipitator has sparked. The system further includes a current limiting reactor for use in limiting current flow through the controllable switch which reactor comprises a plurality of series-connected solenoids each having single-layer windings including spaced-apart turns and a combination air-iron core magnetic path where the air section of the magnetic path is greater than that of the iron core section.

15 Claims, 6 Drawing Figures



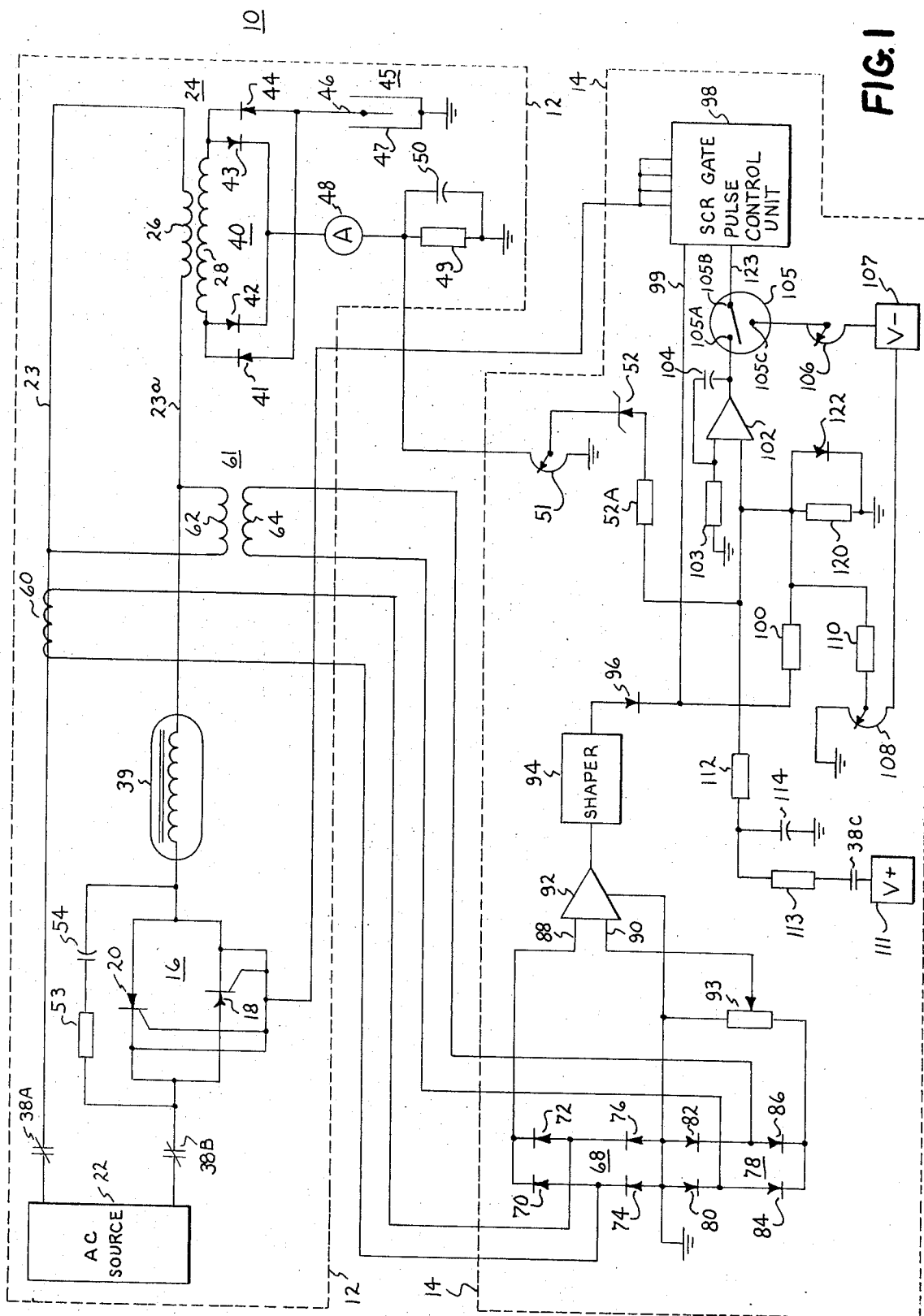


FIG. 1

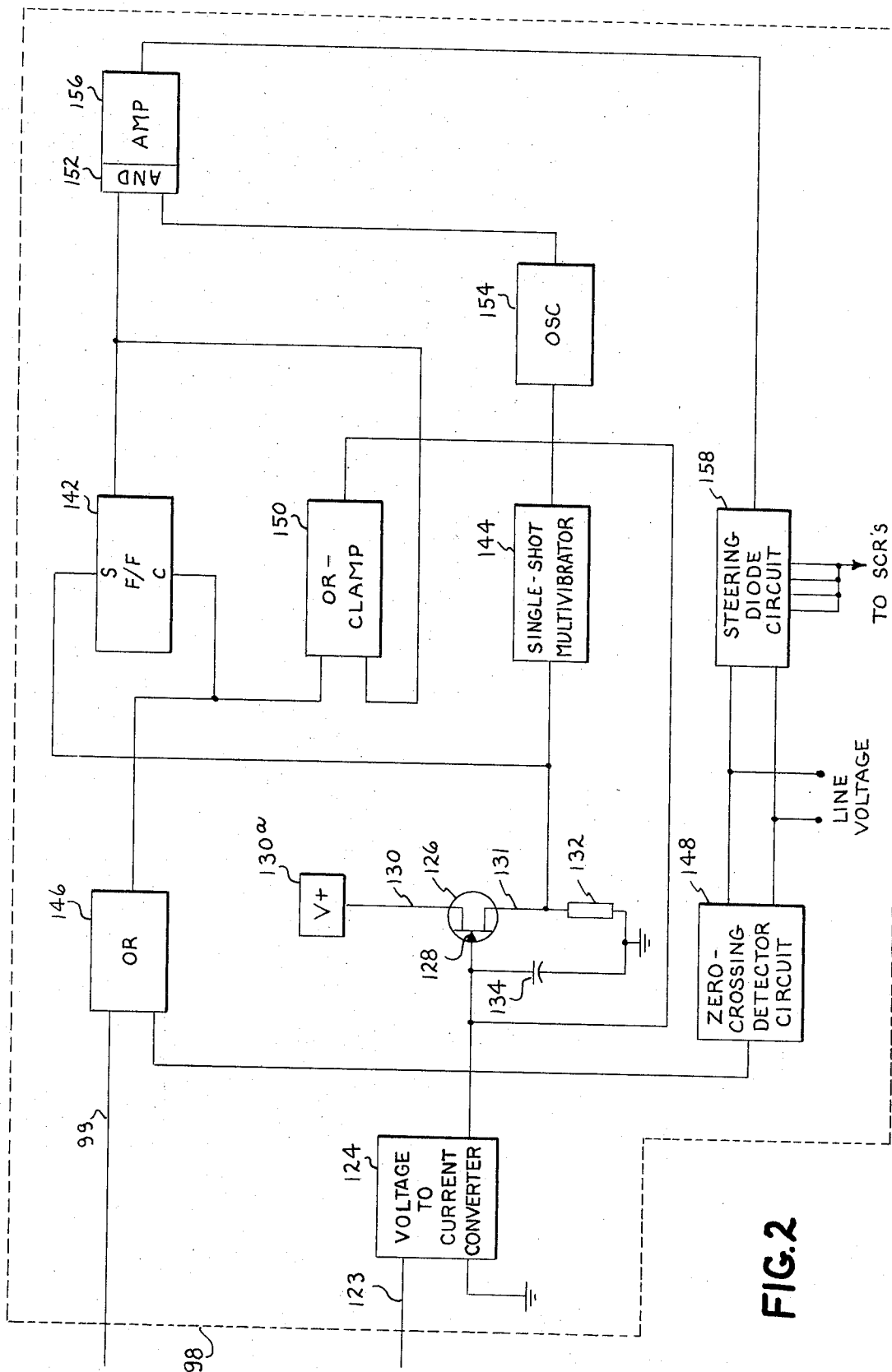


FIG. 2

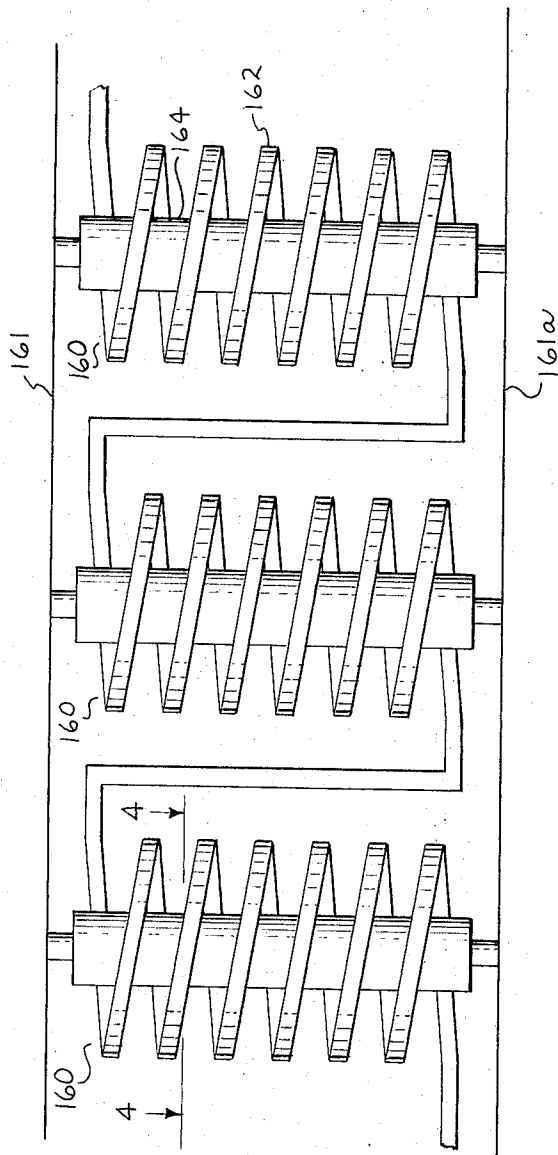


FIG. 3

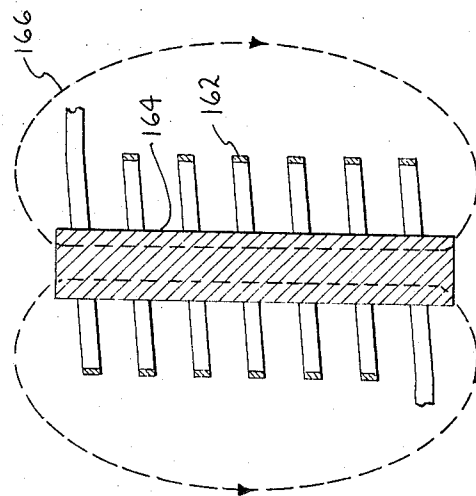


FIG. 5

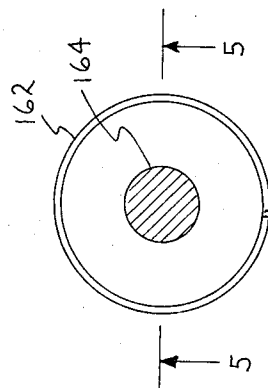
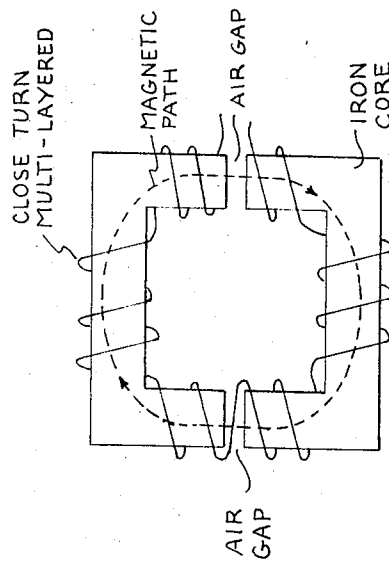


FIG. 4



(PRIOR ART)

FIG. 6

AUTOMATIC VOLTAGE CONTROL FOR AN ELECTRONIC PRECIPITATOR

This is a (X) continuation, of application Ser. No. 275,820, filed July 27, 1972, now abandoned.

BACKGROUND OF THE INVENTION

The invention relates to electronic precipitators and more particularly to a system for automatically controlling the voltage applied thereto.

Electronic precipitators are well-known in the prior art, most notably in the industrial field where such devices perform an important function in removing much of the deleterious particulate matter present in the gases discharged from some industrial centers. In recent times the need for electronic precipitators has increased considerably, largely because of the demand of an environmental conscious society which has applied increasing pressure to virtually all industries to clean up the discharged gases from their plants. This demand has placed a heavy burden on many of the industries, which in the past, have found the operating costs of available electronic precipitators prohibitively high. The precipitators of the prior art, although somewhat adequate, generally demonstrated an inefficient and somewhat unreliable operating cycle requiring more or less constant supervision.

The operating principle employed by virtually all electronic precipitators is to charge the particulate matter suspended in the exhausted gases by applying a voltage between a system of discharging and collecting electrodes so as to cause an electrical current to flow therebetween. When the electrical current begins to flow the exhausted gases become ionized and the precipitator may be considered to have advanced from a nonconducting state to a conducting state. Precipitator operation in general is considered most favorable when the current flow between the discharging and collecting electrode systems increases at a much faster rate than the voltage being applied thereacross. Such a condition is said to be a spark discharge and the precipitator is said to be sparking. In the preferred embodiment when the precipitator is in a conducting state it will be considered to be sparking.

Thus, as the voltage across the electrode systems is increased so as to cause sparking, the charged particles migrating through the exhausted gases are attracted to the collecting electrode system. The required voltage necessary to cause the sparking is a variable dependent upon ambient atmospheric conditions, such as humidity, pressure, temperature, fly ash, and the like. Thus, as the gaseous effluence passes between the charging and collecting electrodes, the voltage level is gradually raised until sparking occurs, at which time the voltage level is then quickly reduced to a lower voltage level to terminate the sparking. The cleansed gas is continuously being exhausted, and as the region between the discharging and collecting electrodes is again filled with uncleansed gas, the precipitator voltage once again achieves a level high enough to cause sparking.

The practice, therefore, has been to provide an automatic voltage control means for gradually increasing the voltage between the discharging and collecting electrodes until sparking occurs, and then quickly lowering that voltage to terminate sparking and prepare for the next gradual voltage build-up.

In the early development of automatic voltage controls for electronic precipitators, saturable reactors were used as a gating means for regulating the gradual increase in voltage applied to the precipitator's electrodes. In recent times, the refinement of solid-state rectifiers as controllable gating means has provided a more convenient gating means for accomplishing the same objectives. These rectifiers are generally called thyristors, the most common form of thyristor being the silicon controlled rectifier (SCR) which term, SCR, will be used in the remainder of this specification for sake of convenience. As is well known in the art, SCRs are responsive to a control signal to be gated into conduction at a certain phase angle of a cycle of line voltage. At the next zero current crossing or end of the half cycle during which the SCR was gated into conduction, it will cease to conduct until gated once again. Thus, in order to provide a gradually increasing voltage to the charging electrodes of the precipitator on each successive half cycle of operation, means are provided for slightly increasing the total conduction period of the SCR over the previous half cycle. Means are also generally provided such that when the precipitator sparks, the control voltage providing conduction to the SCRs is rapidly decreased, thereby reducing the voltage applied to the precipitator and allowing it to come out of its sparking state. When sparking does cease, the voltage is once again built up to a level to cause precipitator sparking, and the cycle is again repeated.

The automatic voltage control systems of the prior art, however, have not been without problems. With respect to the precipitator itself, reignition of the spark and continued arcing can and does occur due to the fact that although the voltage applied to the precipitator has been decreased, dust swirls caused by air currents can change the ambient atmospheric conditions to allow reignition at an even lower voltage than was required for initial ignition. Such operation presents an extremely hazardous situation since dust particles under these circumstances are capable of supporting an explosion. The improved control circuit according to the invention introduces a time delay circuit to avoid the reignition problem.

Another source of problems relates specifically to the SCRs themselves. Although the voltage applied to the precipitator's discharging electrodes in response to the sparking of the precipitator will have been lowered by a control providing gating signals to the SCRs at a later time or a larger phase angle in a cycle of line voltage, the gating signals triggering the SCRs will still continue to be generated. The continuing gating signals to the SCRs, therefore, may actually feed the spark of the precipitator if the spark was not completely extinguished. Prolonged sparking or reignition of the precipitator as mentioned above would result in excessively high current transients which could possibly cause saturation of the high voltage transformer feeding the precipitator. The invention disclosed herein provides for a lockout circuit which overcomes the foregoing problem by inhibiting the gating signals to the SCRs whenever the precipitator is sparking.

Still another problem related specifically to the use of SCRs as voltage regulating devices exists with the protection of the SCRs themselves. When the voltage level applied to the precipitator is sufficient to cause sparking, and in fact sparking does occur, current rapidly increases in both the precipitator circuit and the

circuit providing the voltage control which includes the SCRs. Thus, if care were not taken, the sharply increasing current would quickly destroy the SCRs forming the current controlling means. For this reason, the prior art has included a current limiting reactor in series with the SCRs for insuring the protection thereof. These reactors generally included a single iron core having multi-layered windings with turns packed closely together. At best the iron core included a small air gap or gaps in the magnetic path for the purpose of increasing saturation current. Predictably, these reactors of the prior art have been less than satisfactory. One problem encountered has been the reluctance to employ the reactors in thermally high environments because of their inherent inability to dissipate heat at a reasonably fast rate. A second problem relates to the incremental inductance. Since the iron core reactors have an inherently low incremental inductance, arcing currents associated with these reactors have been proportionally higher. The present invention overcomes these limitations of the prior art by providing a new and improved system for automatically controlling the voltage applied to an electronic precipitator, which system includes a new and improved current limiting reactor for protecting controllable switch means used for selectively applying voltage to the electronic precipitator.

SUMMARY OF THE INVENTION

The present invention provides an improved means for automatically controlling the voltage applied to an electronic precipitator. In general, a gradually increasing voltage is applied to the precipitator by controlling the conduction angle of a pair of controllable switching means (SCRs) in series with a power supply and the precipitator. When the voltage level applied to the precipitator becomes sufficiently high, a spark discharge or sparking will occur. At that time, a sudden rush of electrical current will be caused to flow through the particle-laden gas passing between the discharging and collecting electrodes of the precipitator. Means are provided for detecting this sparking of the precipitator, and in response thereto, lowering the voltage applied to the electrodes thereof. By this operation the precipitator voltage is thereby caused to closely track the sparking voltage of the precipitator, thereby obtaining maximum efficiency.

The invention further provides for a lockout circuit responsive to the sparking of the precipitator such that when the precipitator sparks, gating signals to the SCRs are immediately suspended, thereby insuring against the possibility of the gating signals prolonging the high voltage applied to the discharging electrodes and causing prolonged sparking and possible transformer saturation if the precipitator does not self-extinguish in one half cycle. Moreover, at that time when the precipitator does cease sparking, the subject invention also provides for a time delay means which insures nonconduction of the SCRs for at least a preselected period of time after sparking ceases. The purpose of the time delay is to prevent reignition of the arc, thus, it is not excessively long and thereby inefficient, but merely long enough to insure against restriking the arc.

The subject invention also provides a new and improved current limiting reactor in series with the SCRs and the primary winding of the high voltage transformer feeding the precipitator. The winding structure of the new and improved reactor allows for operation

in thermally higher environments by providing greater heat dissipation, while the core structure provides a relatively higher incremental inductance than the prior art reactors without requiring an excessively large number and size of windings.

It is, therefore, an object of the present invention to provide a new and improved control for an electronic precipitator.

Another object is to provide a new and improved control for an electronic precipitator employing solid-state controllable switching means.

A further object is to provide a new and improved control for an electronic precipitator whereby a lockout circuit is included for inhibiting gating signals from being applied to the gates of controllable switching means during precipitator sparking.

Still another object to provide a new and improved control for an electronic precipitator which control includes a time delay circuit for preventing gating signals from being delivered to the gates of controllable switching means for at least a preselected period of time after the precipitator has ceased sparking.

A still further object is to provide a new and improved current limiting reactor for use in an automatic voltage control circuit of an electronic precipitator.

Yet another object is to provide a current limiting reactor for use in an automatic voltage control system of an electronic precipitator, which current limiting reactor is thermally superior to conventional iron core reactors and which reactor has a higher incremental inductance.

These and other objects of the subject invention will become apparent from the following detailed description including the accompanying drawings forming a part of the specification.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 of the drawing depicts a schematic for an automatic voltage control circuit for an electronic precipitator embodying the present invention.

FIG. 2 reveals in more detail a portion of the circuit shown in FIG. 1.

FIG. 3 discloses a pictorial representation of a section of a current limiting reactor of the subject invention.

FIG. 4 discloses a cross-sectional view of a portion of the current limiting reactor of FIG. 3.

FIG. 5 discloses a cross-sectional view of that portion of the current limiting reactor of FIG. 4.

FIG. 6 reveals a current limiting reactor of the prior art.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIG. 1 of the drawing, there is shown in schematic form an electronic precipitator voltage control system 10, including a firing circuit 12 and a control circuit 14. The firing circuit includes a controllable current conducting circuit 16 comprising a pair of oppositely poled, controllable unidirectional current conducting devices, or switch means such as SCRs 18 and 20. The controllable current conducting circuit 16 is utilized as a switching device to control the amount of energy supplied from an AC source 22 via lines 23 and 23a to a high voltage transformer 24, including a primary winding 26 and a secondary winding 28. The energy from the AC source is supplied to the

transformer primary 26 through normally closed contactors 38a and 38b of a circuit breaker (not shown), the SCRs 18 and 20 and a current limiting reactor 39. From the secondary winding 28, the supplied energy is coupled through a bridge rectifier 40, including diodes 41, 42, 43 and 44, to a precipitator 45 including a discharging electrode system 46 and a grounded collecting electrode system 47 such as are well-known in the art. An ammeter 48 and an RC network, including a resistor 49 and a capacitor 50, are also tied in series with the precipitator 45 and the rectifier 40. The ammeter is provided for monitoring precipitator current while the RC network functions as a means for developing a control signal proportional to the precipitator current and delivering that control signal to a current limit potentiometer 51. A movable arm of potentiometer 51 is connected to a zener diode 52, and a resistor 52a included in the control circuit 14 of the system for the purpose of providing an upper limit on precipitator current flow.

A second RC network, including a resistor 53 and a capacitor 54, having properly selected parameters as is well-known in the art, is electrically connected in parallel with the SCRs 13 and 20 of the controllable current conducting circuit 16. This second RC network functions as a bypass circuit for any current spikes associated with the current line supply, which spikes could cause unpredictable operation of the SCRs. Also, connected in series with the controllable current conducting circuit 16 and the primary winding 26 of the high voltage transformer 24 is the current limiting reactor 39, functioning to limit current peaks which might damage the SCRs during precipitator sparking.

The control circuit 14 is inductively linked from lines 23 and 23a to the firing circuit 12 through a current transformer 60 and a potential transformer 61. Current transformer 60 is inductively coupled to line 23, while a primary winding 62 of potential transformer 61, having a secondary winding 64, is connected electrically in parallel with the primary winding 26 of the high voltage transformer 24, between lines 23 and 23a of the firing circuit 12. Outputs from the current transformer 60 and the secondary winding 64 of potential transformer 61 are tied respectively to the inputs of a first bridge rectifier 68, including diodes 70, 72, 74 and 76, and a second bridge rectifier 78, including diodes 80, 82, 84 and 86, each located in control circuit 14. Rectifier 68 develops a DC voltage proportional to the current flowing through primary winding 26 of the high voltage transformer 24, and rectifier 78 develops a DC voltage proportional to the voltage developed across the primary winding 26. The output from each of the bridge rectifiers 68 and 78 is introduced into separate input terminals 88 and 90 respectively of a differential amplifier 92, which amplifier generates either a positive voltage output or a negative voltage output in response to the sparking or nonsparking states, respectively, of the precipitator 45. A balance potentiometer 93 is included between the output of bridge rectifier 78 and input terminal 90 of amplifier 92 for balance and alignment purposes. The output from the differential amplifier 92 is introduced to a shaper circuit 94, which raises the negative voltage output to a level of zero volts and adjusts the positive voltage output to a more useful higher positive level. The output from shaper circuit 94 is then applied to the anode of a diode 96, such that when the precipitator sparks, the positive voltage or

output signal appearing at the output of shaper circuit 94 forward biases diode 96 causing it to conduct and pass an output signal. The level of zero volts appearing at the output of shaper circuit 94 during periods of precipitator nonsparking will cause diode 96 to be reversed biased, and hence, become nonconductive.

During periods of precipitator sparking, the positive output signal taken from the cathode of diode 96 is coupled to an SCR gate pulse control unit 98 via line 99 and serves as a lockout signal for preventing the feeding of gating signals to SCRs 18 and 20. The positive output signal from diode 96 is also fed through a resistor 100 and introduced as a positive flowing, first control current to an integrating amplifier 102. Amplifier 102, which includes a pair of feedback components, resistor 103 and capacitor 104, has its output terminated in an automatic position 105a of an automatic-manual selector switch 105, a select arm 105b of which is coupled through to the input of SCR gate pulse control unit 98. A potentiometer 106, connected between a manual position 105c of the automatic-manual selector switch 105 and a negative DC supply source 107, serves to control the reference signal fed to SCR gate pulse control unit 98 when operating in a manual mode. This position is not normally used for actual circuit operation but is intended primarily for use during checkout and repair.

A negative flowing, second control current to amplifier 102 is generated by the voltage developed across sparking rate potentiometer 108 and fed through resistor 110 to the input of amplifier 102. The relative size of resistor 100 to resistor 110 is such as to allow the positive flowing first control current from conducting diode 96, to be approximately ten times the value of the negative flowing second control current from sparking rate potentiometer 108. Thus, when the positive current does flow, for all practical purposes the negative current, though still flowing, is insignificant with respect to circuit operation.

A source of positive DC voltage 111 is connected through a normally open third contactor 38c of the circuit breaker (not shown), through an RC filter network including resistors 112, 113 and a capacitor 114, and into the input of amplifier 102 where it serves to latch amplifier 102 in an OFF condition when contactor 38c is closed. The OFF condition is that condition which exists when power is removed from the primary winding 26 of the transformer 24. Finally, a parallel connected resistor diode combination, including resistor 120 and diode 122, is tied between the input to the amplifier 102 and ground, and serves to limit the positive swing of the input current from diode 96 when that diode is conducting.

Referring now to FIG. 2 of the drawing, it is seen that the reference control signal from amplifier 102 being fed into SCR gate pulse control unit 98 is coupled via line 123 and ground, through a voltage-to-current converter circuit 124, and applied to an emitter terminal 128 of a unijunction transistor 126, having a first base terminal 130 tied to a source of positive voltage 130a. A second base terminal 131 of the unijunction transistor is tied to ground potential through a base resistor 132, while a timing capacitor 134, which serves as a timing means for coordinating the firing of SCRs 18 and 20, is connected between the emitter terminal 128 of the unijunction transistor 126 and ground.

The output from unijunction transistor 126 is taken from the second base terminal 131 of the unijunction transistor 126 and coupled to the set terminal of a flip-flop 142, and the input terminal of a 100 microsecond single-shot multivibrator 144. Feeding the clear terminal of flip-flop 142 is an output from a two-input OR gate 146, one of the inputs of which is the lockout signal from the cathode of diode 96, the other input being derived from a zero-crossing detection circuit 148. The zero-crossing detector circuit, which receives the line voltage as an input signal, produces an output pulse at the end of each half cycle thereof. The output from OR gate 146 is also coupled as a first input to an OR CLAMP circuit 150 which includes as a second input, an output signal taken from flip-flop 142. The output of OR CLAMP circuit 150 is, in turn, coupled back to the emitter lead 128 of the unijunction transistor 126.

Flip-flop 142 provides a first input to an AND gate 152, while a second input to that AND gate is provided from a 15KHz pulse trigger oscillator 154. When oscillator 154 is gated by the single-shot multivibrator 144, oscillator 154 is caused to remain in a steady ON condition for 100 microseconds before the 15KHz pulse triggers are produced. That is, the single-shot multivibrator 144 insures that the first pulse out of oscillator 154 is at least 100 microseconds long. This feature acts to guarantee conduction of the SCRs when triggered. Thus, when AND gate 152 receives inputs from both flip-flop 142 and pulse trigger oscillator 154, a burst of 15KHz firing pulses including a lead pulse 100 microseconds long, is passed through a power amplifier 156 and fed to the gate lead of the proper SCR through the action of a steering diode circuit 158 responsive to the line voltage. The type of steering diode circuit used is well-known in the art, one example of which may be found at page 197 of the "G.E. SCR Manual, 4th Edition."

Referring to FIGS. 3, 4 and 5 of the drawings, a preferred embodiment of the current limiting reactor of the present invention is shown. FIG. 6 discloses an example of a reactor of the prior art. The current limiting reactor 39 of the preferred embodiment, includes a set of eight, series-connected solenoids 160 (three are shown), having single-layer windings with spaced-apart turns. Each of the solenoids are supported in an upright position with the aid of nonconductive top and bottom members 161 and 161a respectively. As best seen in FIGS. 4 and 5 of the drawings, each of the individual solenoids 160 include an iron core 164, conveniently formed from silicon steel laminations, while the windings themselves are fashioned from an aluminum conductor and generally include an insulating material (not shown) between each of the spaced-apart turns. Each of the solenoids also include a magnetic path 166, which path, as is shown most clearly in FIG. 5 of the drawings, includes both an iron core section and an air section. From that same figure it is clearly seen that the length of the air section is greater than the length of the iron core section.

The prior art reactor as shown in FIG. 6 does not include spaced-turn, single-layer windings as does the subject invention, but instead includes close-turn, multilayered windings as well as a magnetic path having an iron core section greater in length than the air gaps separating the split iron core.

Operation of the precipitator system will now be described. Referring first to FIG. 1 and the firing circuit

12 of the drawing, activating the circuit breaker (not shown) will close normally open contacts 38a and 38b (simultaneously opening contactor 38c) and permit line voltage to be applied to the controllable conducting circuit 16 including SCRs 18 and 20. Since the SCRs are oppositely poled, conduction thereof will occur on opposite half cycles of the line voltage when gating signals are received by the appropriate SCR from SCR gate pulse control unit 98. The gating signals, which occur on each successive half cycle of the line voltage at an increasingly earlier time, permit an increasingly greater period for conduction of the SCRs, and hence, allow an increasingly larger voltage to be applied to the primary winding 26 of the high voltage transformer 24. The voltage developed across the secondary winding 28 of transformer 24 feeds the bridge rectifier 40, the diodes whereof are poled to develop a large negative potential between the discharging electrode system 46 and the collecting electrode system 47 tied to ground potential. Eventually, the conduction angle of the SCRs during one half cycle of the line voltage will be sufficient to cause ionization of the particle laden gas between the electrode systems of the precipitator. At that time, the previously nonconducting precipitator will advance to a conducting state and the current flow between the electrode systems will increase rapidly and appreciable. The voltage between the electrode systems will, at the same time, fall sharply toward zero. The voltage level at which sparking occurs is a variable depending upon the ambient atmospheric conditions prevailing between the two electrode systems. Under those conditions where a relatively low level of contaminating matter is present in the discharging gas, a relatively high precipitator voltage would be required to cause the precipitator to spark. On the other hand, high concentrations of particulate matter present between the discharging and collecting electrode systems will cause sparking at a relatively low voltage applied thereto.

When the precipitator 45 advances from a nonconducting state to a conducting state, the secondary winding 28, and the primary winding 26, of high voltage transformer 24 are required to carry large currents, since the current through primary winding 26 increases rapidly from a relatively low value to a relatively high value. Similarly, when the precipitator changes from a conducting or sparking state to a nonconducting or nonsparking state, the voltage across primary winding 26 and the current therethrough return once again to their respective high and low states as when before sparking occurred. The current and voltage changes associated with the primary winding of the high voltage transformer, as occasioned by the precipitator changing states, are sensed by current transformer 60 and the primary winding of potential transformer 61, and coupled to the control circuit 14 as inputs to the pair of bridge rectifiers 68 and 78. Rectifier 68, which responds to changes associated with current transformer 60 provides a first input to differential amplifier 92 through input terminal 88 thereof, while rectifier 78, which is responsive to potential transformer 61, provides a second input to differential amplifier 92 through input terminal 90 thereof. During periods when the precipitator is not sparking, current transformer 60 will be generating a relatively low voltage thereacross and, hence, the voltage input to terminal 88 will be practically zero. At the same time, trans-

former 61 will be generating a relatively high voltage which will cause a relatively high positive potential to be developed at input terminal 90 of the differential amplifier 92. Similarly, during periods when the precipitator is sparking, rectifier 68 causes a high positive potential to be developed at terminal 88 while rectifier 78 causes a larger negative to be developed at terminal 90. Shaper circuit 94 responds to the voltage changes of differential amplifier 92 by developing an adjusted positive voltage out when terminal 88 is positive with respect to terminal 90 of the differential amplifier, and developing a zero voltage out when terminal 90 is positive with respect to terminal 88 of the differential amplifier. Thus, shaper circuit 94 produces a positive or zero voltage signal indicative of whether the precipitator is in a sparking or a nonsparking state respectively. It should be noted that the positive voltage signal out of shaper circuit 94 will persist for the duration of the precipitator spark, while the zero voltage signal will be present whenever the precipitator is not sparking.

During those periods of operation when the precipitator is in a nonsparking state, shaper circuit 94 will be developing a zero voltage output signal so as to cause diode 96 not to conduct. Hence, with the circuit breaker actuated and contactor 38c open, amplifier 102 will be influenced only by the current generated by negative DC supply source 107. In response to the negative current from source 107, integrating amplifier 102 generates a negative going ramp voltage having a slope dependent upon the level of current being introduced. A higher level of current will cause the ramp voltage generated to have a steeper slope. Further, since the level of that current is determined by the level of voltage picked off by the wiper arm of the spark rate potentiometer 108, potentiometer 108 determines the slope of the negative going ramp voltage output developed by the integrating amplifier 102.

As will be later explained in greater detail, the negative going ramp voltage, which is introduced as a reference signal into SCR gate pulse control unit 98 through automatic-manual selector switch 105 when in the automatic position, is used in determining the rate or periodicity at which the precipitator sparks. A reference signal having a steeper slope will cause the precipitator to spark more frequently than a reference signal having a more gradual slope. This result follows because the precipitator will spark whenever the negative going ramp voltage reaches a definite level determined by the ambient atmospheric conditions of the precipitator 45. And since a ramp voltage having a steeper slope will achieve that level at an earlier time than a ramp voltage having a more gradual slope, by adjusting the spark rate potentiometer 108, the slope, and hence, the rate of precipitator sparking may be regulated.

When the precipitator sparks, a positive output signal will be developed at the output of shaper circuit 94, thereby causing diode 96 to become conductive. The positive output signal from shaper circuit 94 is fed through resistor 100 to serve as a second input to integrating amplifier 102. The signal developed by negative source 107, however, which although still continuing to be applied to the input of amplifier 102, practically speaking will have no effect on the output voltage. This is because the relative sizes of resistors 100 and 110 are chosen such that the current developed by the positive signal from shaper circuit 94 is approximately ten times the current developed by the negative signal from nega-

tive voltage source 107. When the precipitator is sparking, therefore, the much stronger positive signal from shaper 94 will not only override the weaker negative signal from source 107 to cause amplifier 102 to generate a positive going ramp voltage, but will also cause the ramp voltage that is generated to have a much steeper slope than the negative going ramp voltage developed during nonsparking conditions. The positive going ramp voltage generated by amplifier 102 during sparking of the precipitator serves to quickly drive the reference voltage further away from the definite negative level required to cause precipitator sparking. Thus, if the precipitator sparks for a relatively long period of time, the reference voltage will be driven much more positive than if the precipitator had sparked for only a short period of time. This allows the precipitator a greater time for recovery after relatively long sparks, while providing for a relatively short recovery period following what would be considered a short sparking time. Hence, the voltage applied to the discharge electrode system 46 of the precipitator 45 is caused to more closely track the sparking thereof, thereby obtaining maximum efficiency.

The reference voltage introduced into the SCR gate pulse control unit 98 is fed to voltage-to-current converter circuit 124, as shown in FIG. 2, where the reference voltage signal is converted into a reference current signal of a reversed polarity.

The reference current signal is applied to capacitor 134, and during a nonsparking state of the precipitator, the reference signal would be positive going and would charge the capacitor 134 relatively quickly each half cycle of the line voltage to the predetermined level necessary to fire the unijunction transistor 126. When that level is reached, the capacitor discharges through the unijunction transistor 126 causing a pulse to be generated, which pulse triggers the circuit to cause SCRs 18 and 20 to be gated on. The particular phase angle of the line voltage at which the SCRs are gated on, however, is determined by the voltage level of the reference voltage applied to capacitor 134. This follows since the rate at which the capacitor charges to the predetermined level required to fire the unijunction transistor 126 is determined by the level of the voltage applied to the capacitor. And since on each successive half cycle of line voltage the reference current signal from voltage-to-current converter circuit 124 will be slightly greater because of a continuously increasing ramp voltage, capacitor 134 will charge to the predetermined level more quickly than on the previous half cycle. Consequently, unijunction transistor 126 will be caused to fire at an earlier phase angle of a half cycle of the line voltage, causing the SCRs to fire earlier and hence, a higher voltage will be applied to the precipitator.

Synchronization of SCR firing with the line voltage is assured through the operation of zero-crossing detector circuit 148 which generates a pulse to enable OR gate 146 in an ON condition at the end of each half cycle of the line voltage. OR gate 146, when gated ON, causes OR CLAMP circuit 150 to clamp capacitor 134 to ground, thereby insuring that the capacitor 134 starts charging from zero volts at the beginning of each half cycle.

When capacitor 134 does develop a charge great enough to fire the unijunction transistor 126, conduction thereof causes a voltage spike to be developed across base resistor 132, initializing the 100 microsec-

and one-shot multivibrator 144 and setting the enable flip-flop 142. Examining first the circuitry related to the one-shot multivibrator 144, it is seen that the output pulse from that circuit is used to inhibit, for 100 microseconds, the 15KHz signal being fed from oscillator 154 to the input of AND gate 152. It should be noted, however, that the 100 microsecond inhibit pulse does not inhibit an output from oscillator 154, but to the contrary, it insures an output of at least 100 microseconds long. That is, the inhibit pulse merely inhibits oscillation of the 15KHz output which, under all other conditions, generates a continuous output train of pulses approximately 66 microseconds long at the 15KHz frequency. And since the 15KHz frequency pulse train being continuously generated is used to trigger the SCRs 18 and 20, AND gate 152 is employed to limit the application of the pulses to the SCRs by requiring an output pulse from flip-flop 142 before it is enabled. Flip-flop 142, which had been set by the firing of unijunction transistor 126, generates the required output pulse at that time.

As the ramp voltage from integrating amplifier 102 gradually increases in a negative direction, the reference current signal from voltage-to-current converter circuit 124 is gradually increased in a positive direction. Capacitor 134 changes increasingly sooner to the preselected voltage level required to fire unijunction transistor 126, thereby increasing the conduction angle of SCRs 18 and 20. Eventually, depending upon the ambient atmospheric conditions existing between the discharging and collecting electrode systems 46 and 47, respectively, of the precipitator 45, a conduction angle of the SCRs will be reached that will cause a sufficient voltage to be applied to the precipitator to cause it to spark. At that time when the precipitator does spark, the voltage signals generated by the current and potential transformers 60 and 61, are coupled to shaper circuit 94 which develops a positive output signal causing diode 96 to become conductive. The positive output signal from diode 96 is introduced via line 99 as a second input into OR gate 146 and serves as a lockout signal. In response to this lockout signal, OR gate 146 enables OR CLAMP circuit 150 to clamp one side of timing capacitor 134 to ground. The positive output signal, and hence, the lockout signal will persist for as long as the precipitator continues to spark, thereby preventing the capacitor from recharging and delivering a firing pulse to the SCRs. The lockout signal, therefore, avoids the problem of the SCRs trigger pulses feeding the spark of the precipitator, which could result in excessively high currents and even saturation of the high voltage transformer if the precipitator did not self-extinguish in one half cycle.

And while the positive output signal from shaper circuit 94 is used as a lockout signal, the positive output signal is also applied to the input of integrating amplifier 102 causing that amplifier to integrate in a positive direction at an accelerated rate relative to that rate at which it was integrating in the negative direction. Thus, the reference current signal for charging capacitor 134 from voltage to current converter circuit 124 is made increasingly less positive for as long as the precipitator is sparking. When sparking of the precipitator ceases, the positive output signal from shaper circuit 94 ceases and hence, the lockout signal preventing capacitor 134 from charging is removed, and once again the capacitor charges to the new, though less positive, level as devel-

oped by voltage to current converter circuit 124. It should be noted, however, that at the moment sparking of the precipitator ceases, control of the firing of the SCRs is not necessarily in synchronization with the line voltage. That is clear since the precipitator can stop sparking at any time during a half cycle of line voltage, and the capacitor will start charging from zero volts whenever sparking does cease. Thus, a delay is introduced into a firing circuit. The delay will be at least equal to the new phase retard angle as determined by the new ramp voltage, but since the charging of the capacitor is not synchronized with the line voltage, the delay may be up to almost twice that length of time. That is, since the precipitator could cease sparking at any time during a half cycle of operation, it is entirely possible that the capacitor would be clamped to ground because of the operation of the zero-crossing circuit before it has had time to charge to the preselected level required to fire the unijunction transistor 126. Conceivably, a zero-crossing could occur immediately prior to the capacitor charging to the preselected voltage level necessary to fire the unijunction transistor 126. In that instance, the capacitor would be discharged at the zero-crossing of the line voltage and an even longer delay would be introduced. It should also be noted that at the first zero-crossing the capacitor 134 and unijunction transistor 126, which had stepped out of synchronization with the line voltage when the precipitator sparked, would step back into synchronization and proceed as described above at that time.

The result of this time delay, therefore, insures that the high voltage transformer 24 is not saturated by DC components in the SCR controlled voltage waveform. The time delay allows for insurance of extinction of the arc while still avoiding excessive lockout which would promote inefficiency.

With respect to the current limiting reactor as shown in FIGS. 3, 4 and 5, it has been found that individual, single-layered windings having spaced-apart turns provide greater heat dissipation, and hence, allow for operation in thermally higher environments, while the provision of a magnetic path having an air section of greater length than an iron section provides for a much higher incremental inductance than is found in reactors having an air section or gap that is relatively short compared to the iron section length of the magnetic path. The increased incremental inductance has the effect of reducing precipitator arcing currents by an amount proportional to that of increased incremental inductance. Hence, the greater incremental inductance and the higher heat dissipating ability are combined in the reactor of the present invention to provide a final resultant of an improved, lower cost current limiting reactor.

Thus, by the above described invention a system for automatically controlling the voltage is provided, which system includes a lockout circuit for inhibiting the transmission of trigger pulses to gates of control SCRs during periods of precipitator sparking, and a time delay circuit which delays the transmission of trigger pulses to the gates of the control SCRs for at least a predetermined period of time after the precipitator has ceased sparking.

The subject invention further discloses a current limiting reactor comprising a plurality of individual, series connected solenoids, each having single-layer windings with spaced-apart turns for use in limiting current flow

through the control SCRs during periods of precipitator sparking.

While there is shown and described a specific embodiment of this invention, it will be understood that the invention is not limited to the particular construction shown and described, and it is intended by the appended claims to cover all modifications within the spirit and scope of this invention.

I claim:

1. A system for automatically controlling the voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for coupling an AC voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator to selectively provide a gating signal to said controllable switch means during said nonconducting state of said electronic precipitator;
- d. said controllable switch means being responsive to said gating signal to control the application of said AC voltage to said electronic precipitator; and
- e. said control circuit further including means responsive to the conducting state of said electronic precipitator for varying the relationship between said AC voltage and said gating signal as a function of the time duration and intensity of said conducting state.

2. The system for automatically controlling a voltage applied to an electronic precipitator as recited in claim 1, wherein said gating means includes means for generating a control signal responsive to said conducting and nonconducting states of said electronic precipitator, said control signal increasing in a first direction when said precipitator is in a nonconducting state, and said control signal increasing in an opposite direction from said first direction when said precipitator is in a conducting state; said gating means being responsive to said control signal increasing in said first direction to provide said gating signal at a progressively decreasing phase retard angle with respect to said AC voltage.

3. A system as recited in claim 1 and including a current limiting reactor coupled in circuit with said controllable switch means including an inductive element having a single-layer winding with a plurality of electrical turns spaced apart from each other; said inductive element having a magnetic path which includes an air section and an iron section, the length of said air section being greater than the length of said iron section.

4. A system for automatically controlling the voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for coupling an AC voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator to provide a gating signal having a progressively changing phase relationship to said AC voltage to said controllable switch means during said nonconducting state of said electronic precipitator;

d. said controllable switch means being responsive to said gating signal to control the application of said voltage to said electronic precipitator; and

e. said control circuit further including means responsive to the conducting state of said electronic precipitator to reinstitute said gating signal upon termination of said conducting state, said reinstituted gating signal having a phase relationship to the AC voltage which differs from said relationship of the previous gating signal as a function of the duration of said conducting state.

5. A system as recited in claim 4 and including a current limiting reactor coupled in circuit with said controllable switch means and including an inductive element having a single-layer winding with a plurality of electrical turns spaced apart from each other.

6. A system for automatically controlling the voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for coupling an AC voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator to provide a gating signal having a progressively changing phase relationship to said AC voltage to said controllable switch means during said nonconducting state of said electronic precipitator to provide a gating signal having a progressively changing phase relationship to said AC voltage to said controllable switch means during said nonconducting state of said electronic precipitator;
- d. said controllable switch means responsive to said gating means to control the application of said voltage to said electronic precipitator;
- e. said control circuit further including means responsive to the conducting state of said electronic precipitator for varying the relationship between said AC voltage and said gating signal as a function of the time duration and intensity of said conducting state; and
- f. lockout means responsive to said conducting state of said electronic precipitator to inhibit said gating signal to said controllable switch means during said conducting state.

7. the system for automatically controlling a voltage applied to an electronic precipitator as recited in claim 3 wherein said lockout means includes switch means.

8. A system as recited in claim 6 and including a current limiting reactor coupled in circuit with said controllable switch means and having a magnetic path which includes an air section and an iron section, the length of said air section being greater than the length of said iron section.

9. A system for automatically controlling the voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for coupling an AC voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator to provide a gating signal having a progressively changing phase relationship to said AC

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voltage to said controllable switch means during said nonconducting state of said electronic precipitator;

- d. said controllable switch means responsive to said gating means to control the application of said voltage to said electronic precipitator; and
- e. said control circuit further including means responsive to the conducting state of said electronic precipitator to reinstitute said gating signal upon termination of said conducting state, said reinstituted gating signal having a phase relationship to the AC voltage which differs from said relationship of the previous gating signal as a function of the duration of the conducting state.

10. A system for automatically controlling a voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for applying an alternating voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator for providing a gating signal at a progressively changing phase retard angle to said controllable switch means during said nonconducting state of said electronic precipitator;
- d. said controllable switch means responsive to said gating means to control the application of said voltage to said electronic precipitator; and
- e. said gating means including time delay means responsive to said conducting state of said electronic precipitator to delay said gating signal to said controllable switch means for a variable period of time which varies as a function of the time duration of said conducting state following an alternation of said electronic precipitator from a conducting state to a nonconducting state.

11. The system for automatically controlling a voltage applied to an electronic precipitator as recited in claim 6 wherein said control circuit includes logic means.

12. The system for automatically controlling a voltage applied to an electronic precipitator as recited in claim 10 wherein said time delay means include capacitive means.

13. A system for automatically controlling a voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for applying an alternating voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator for providing a gating signal at a progressively decreasing phase retard angle to said controllable switch means during said nonconducting state of said electronic precipitator;
- e. said controllable switch means being responsive to said gating means to control the application of said voltage to said electronic precipitator;
- e. lockout means responsive to said conducting state

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of said electronic precipitator to inhibit said gating signal to said controllable switch means during said conducting state; and

- f. said gating means including time delay means responsive to said conducting state of said electronic precipitator to delay said gating signal to said controllable switch means for a period of time which varies as a function of the duration of said conducting state following an alternation of said electronic precipitator from a conducting state to a nonconducting state.

14. A system for automatically controlling the voltage applied to an electronic precipitator having alternating conducting and nonconducting states, said system comprising:

- a. controllable switch means;
- b. means for applying an alternating voltage to said controllable switch means;
- c. a control circuit including gating means responsive to the nonconducting state of said electronic precipitator to selectively provide a gating signal to said controllable switch means during said nonconducting state of said electronic precipitator;
- d. said controllable switch means responsive to said gating means to control the application of said voltage to said electronic precipitator;
- e. lockout means responsive to said conducting state of said electronic precipitator to inhibit said gating signal to said controllable switch means during said conducting state;
- f. said gating means including time delay means responsive to said conducting state of said electronic precipitator to delay said gating signal to said controllable switch means for a variable period of time following an alternation of said electronic precipitator from a conducting state to a nonconducting state, said variable period of time varying as a function of the duration of said conducting state;
- g. a current limiting reactor coupled in circuit with said controllable switch means and including a plurality of inductive elements, each of said inductive elements connected in electrical series with each other; each of said inductive elements including a single-layer winding having a plurality of electrical turns spaced apart from each other; and each of said inductive elements having a magnetic path, said magnetic path including an air section and an iron section, the length of said air section being greater than the length of said iron section.

15. A control circuit for an electronic precipitator, said control circuit comprising:

- first means for providing a progressively increasing voltage to said precipitator;
- second means for detecting a conducting state of said precipitator and responsive thereto to provide an output signal corresponding to the time duration of said conducting state;
- third means responsive to said output signal for inhibiting said voltage to said precipitator during said conducting state and for reducing said voltage as a function of the time duration of said conducting state upon the reapplication thereof.

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