1981 Winter Simulation Conference Proceedings
T.I. Ören, C.M. Delfosse, C.M. Shub (Eds.)

ON THE MODELING AND CONTROL OF INDUSTRIAL ELECTROSTATIC PRECIPITATORS

Carl C. Davis
Tennessee Valley Authority
Widows Creek Steam Plant
Stevenson, Alabama 35772

Naim A. Kheir
School of Science and Engineering
The University of Alabama in Huntsville
Huntsville, Alabama 35899

ABSTRACT

This paper recognizes electrostatic precipitators (ESP) as the primary machanism for the control of particulate emissions from such operations as in the cement, paper and power industries. Due to the ever increasing emission limitations placed on industry by the Environmental Protection Agency it becomes increasingly important that ESP's operate at peak efficiency. This means that the controllers which maintain the electrostatic effect must be designed for optimum performance. Design of ESP's has long been viewed as more an art than a science. This view is also true for the design of ESP controllers. Though the role of the control engineer as an artist will always exist, this paper seeks to bring the controller design more into the realm of science.

A lumped parameter model of the ESP is presented which adequately explains the response of the ESP over its effective range of operation. The operation of the ESP at the boundary of stability (known as "arcing" in the industry) is modeled by utilizing Townsend's first and second coefficients. As a result of this model it is found that the "arcing" phenomena is due to positive feedback in the process and that the ESP is not completely controllable. Though the ESP is not completely controllable it is found that the input voltage, which is controllable, has dominance over the stable range of operation of the ESP.

Current ESP control strategies are examined. It is found that the control philosophies of the various designs of ESP controllers are basically the same. The one or two most-recently developed digital controllers are found to be most effective in implementing this philosophy. This paper presents a modified control law through utilization of process information. It is viewed that relatively "arc-free" operation of the ESP can be achieved by using the proposed control philosophy. As a by-product of this control law, the quantity of surges on the system would be reduced resulting in a significant conservation of power requirements.

1. INTRODUCTION

The electrostatic precipitator (ESP) is the most widely used device for the control of air pollution in the United States at present.

The American industry is responsible for over a hundred megatons (1) of gas borne waste each year. This waste is in the form of smoke, dust and fumes produced from processes such as the cement, paper, and power industries. In some 70 years of usage, since F. G. Cottrell (2) first developed it in its modern form, the ESP has proven itself to be the most cost effective means for eliminating this public hazard.

Historically the electrostatic attraction of rubbed amber for small particles was known to the Greeks as early as 600 B.C. (3). Coulomb's discovery of the inverse square law in 1789 formed the basis for the science of electrostatics. Throughout the 1800's attempts were made to utilize this phenomena to eliminate the particulate from gases emitted from industrial processes. The most note-worthy example is that of London England where coal-fed industry was responsible for the deadly London fog. All attempts failed however due to the lack of a mechanism for producing the high D.C. voltage necessary for producing the electrical force.

In the early 1900's F. G. Cottrell, a young chemistry professor at U.C. Berkley, tried his hand at

81CH1709-5/81/0000-0625$00.75 © 1981 IEEE

eliminating the environmental problem caused by the large copper smelting industry in Southern California. Due primarily to the advent of the mechanical rectifier he was able to design and build the first workable industrial electrostatic precipitator. His device was quickly adapted to collecting fumes and particulate from gases produced by the smelting, cement, paper and power industries.

Electrostatic precipitation is accomplished by causing the gas to be subjected to a high voltage electric field. The particles in the gas become ionized and are attracted out of the gas stream. They attach themselves to collecting surfaces and are subsequently disposed of. Most industrial ESP's have a collecting duct as depicted in Fig. 1. The corona wires are suspended centrally between grounded collection electrodes. D.C. voltages are maintained in the 50 kilovolt range from wire to collection electrode, thus creating a strong electric field. The process gas flows through the duct formed by the panels. Provided the electric field is strong enough, the particles will be attracted out of the gas stream and deposited on the collection electrodes and corona wires.

The current-voltage characteristic of the ESP (4) is depicted in Fig. 2. Normally gases, unlike solids and liquids, have few free electrons. Therefore they are more like perfect insulators than conductors. But given sufficiently high voltages (on the order of 1000's of volts) current will flow.

At low voltages the current is small; linearity here is because most electrons and ions, which are freed, do not have adequate energy to traverse the gas to the electrodes but instead are recombined and neutralized. However, if the voltage is increased a point is reached where current no longer increases with voltage. This saturation region, which extends up to V_S (Fig. 2), is caused by the collecting out of all available electrons and ions in the gas.

Increasing the electric field voltage still further causes the current to again increase. This time the current is not linear but appears to increase exponentially with voltage. If the voltage is increased to a certain value (V_B) the current increases independent of the applied voltage. The continued increase of current with voltage is caused by the available electrons and ions becoming energetic enough to cause ionization upon collision with neutral gas molecules. Thus a chain reaction occurs which is controlled in magnitude by the applied voltage up until V_B at which point the process becomes self-sustaining.

The normal operation of the ESP is, ideally between V_S and V_B or the Townsend region (Fig. 2). Efficient electrostatic precipitation cannot occur without the aid of the chain reaction. Therefore, due to the necessity of operating in this zone the possibility arises of reaching V_B at which point the field collapses.

The occurence at V_B is the aspect of electrostatic precipitation which must be controlled is the subject of this study.

2. DERIVATION AND ANALYSIS OF THE ESP MODEL

In searching the literature, all ESP reported models were based on the assumption that applied voltage was static. In actuality this is not the case. However, since the applied voltage is slowly varying in most instances, the models are good approximations to the precipitator behavior near the saturation region. The dynamics occuring at $V=V_B$ were not found to be modeled.

The derivation of the current-voltage relationship for an ESP (assuming time-invarient applied voltage) proceeds directly from Poisson's equation which governs all electrostatic phenomena (5). This approach was taken by Townsend (6) and after various simplifying assumptions he arrived at the relationship:

$$\frac{I}{\beta} = V(V-V_S) \qquad (1)$$

Where β is a constant which depends on the configuration and the gas which is being treated. For discrete voltages this equation predicts reasonably accurate values for I in the range near saturation. Stability is inherent in such a static representation yet we know there is system instability beginning at $V=V_B$ (Fig. 2).

As can be seen from Fig. 2 there are a broad range of input voltages for which the output current is bounded. Thus some degree of system stability is assured. To look at the stability question from the point of view of controlling or modifying the process a more lumped model is needed (Fig. 3).

For most modern industrial applications, a high voltage transformer/rectifier is typically used to supply the high voltage for the ESP. In Fig. 3 1:w refers to the turns-ratio of the transformer. The depiction of the ESP as a time-varying resistance in parallel with a fixed capacitance is possible because of the obvious presence of capacitance and based on the work done by Edmund C. Potter (7) in which the dependence of the gas resistance on voltage was verified. Potter showed conclusively that gas resistance dropped on the order of 100 to 1000 times with increasing voltage.

Assuming the bridge rectifier is a voltage dependent switch we can arrive at a linear time-varient math model.

Summing the voltages we have the following equation:

$$f(V) = L\dot{I} + \frac{I}{w^2} Z_o$$

Where Z_o is the ESP impedence and is

$$Z_o = \frac{\frac{1}{C}}{s + \frac{1}{R(t)C}}$$

Where s is the laplace operator.

Substituting in the value for Z_o we have

$$f(V) = L\dot{I} + \frac{I}{w^2}\left[\frac{\frac{1}{C}}{s + \frac{1}{R(t)C}}\right]$$

Multiplying both sides by $s + \frac{1}{R(t)C}$ we have

$$sf(V) + \frac{f(V)}{R(t)C} = Ls\dot{I} + \frac{L\dot{I}}{R(t)C} + \frac{I}{w^2C}$$

Since multiplication by the laplace operator is equivalent to differentiation this yields

$$\dot{f}(V) + \frac{f(V)}{R(t)C} = L\ddot{I} + \frac{L\dot{I}}{R(t)C} + \frac{I}{w^2C}$$

Utilizing the state variable approach we can say

Let $X_1 = I$, $X_2 = \dot{I}$

Which leads to

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = -\frac{X_1}{w^2LC} - \frac{X_2}{R(t)C} + \left[\dot{f}(V) + \frac{f(V)}{R(t)C}\right]\frac{1}{L}$$

For $f(V) = 0$ we can assume $R(t)$ is constant. Therefore we arrive at the unforced case

$$\underline{\dot{X}} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{w^2LC} & -\frac{1}{R_0C} \end{bmatrix} \underline{X}$$

Where $\underline{\dot{X}}$ and $\underline{X}$ denote vectors.

From this we acquire the characteristic equation

$$\left|\lambda I - A\right| = \left|\begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} - \begin{bmatrix} 0 & 1 \\ -\frac{1}{w^2LC} & -\frac{1}{R_0C} \end{bmatrix}\right|$$

$$\text{C.C.EQ.} = \begin{vmatrix} \lambda & -1 \\ \frac{1}{w^2LC} & \lambda + \frac{1}{R_0C} \end{vmatrix}$$

Which gives us

$$\text{C.C.EQ.} = \lambda^2 + \frac{\lambda}{R_0C} + \frac{1}{w^2LC}$$

For the purpose of pole-zero analysis we will require the roots of this characteristic equation. They are

$$\lambda_{1,2} = \frac{\frac{-1}{R_0C} \pm \sqrt{\frac{1}{R_0^2C^2} - \frac{4}{w^2LC}}}{2}$$

Usually though R_0 is very large (on the order of 10^6) C is so small (10^{-9}F) as to make the term $\frac{1}{R_0C}$ on the order of 10 to 100.

It can also be assumed that

$$\frac{4}{w^2LC} \gg \frac{1}{R_0^2C^2}.$$

Therefore the equation for the roots becomes

$$\lambda_{1,2} = -\frac{1}{2R_0C} \pm j\left(\frac{1}{w^2LC}\right)^{\frac{1}{2}} \qquad (2)$$

Examination of Equation (2) shows that the roots are well into the left half of the s-plane for representative values of R & C, therefore the system is stable. Also, since R(t) decreases with increasing voltage, taking time-varying R into account only causes the roots of the characteristic equation to move further into the left half plane. This "lumped parameter" analysis serves to characterize the stability of the system in the operating region between V_S and V_B (Fig. 2) but does not explain the instability at $V = V_B$.

Referring to the voltage-current characteristics in Fig. 2, the part of the curve from the saturation voltage (V_S) to the breakdown voltage (V_B) and actual breakdown itself is explained by the use of the first and second Townsend coefficients (8).

The chain reaction, caused by energetic electrons striking neutral atoms and molecules and dislodging more electrons, is called the Townsend effect. To explain this chain reaction Townsend devised his first Townsend coefficient (α). He defined α as the number of ionizing collisions made by an electron as it travels one centimeter. When $\alpha > 0$ we have departed from the saturation region (Fig. 2) and progressed into the effective precipitation region.

A. M. Howatson (11) defines $\alpha = pf\,(Ee\sigma)$ where E is the electric field, e is the electronic charge, and σ is the mean free path of an electron (in the field direction) between all collisions with atoms. Then the product, $Ee\sigma$, is the mean energy gained by electrons between collisions. By making the observation that $\sigma \approx \frac{1}{n}$ (9) where n is the particulate concentration of the gas and also assuming pressure (P) constant we can say

$$\alpha = \Phi\left(\frac{E}{n}\right)$$

or Townsends first coefficient is some function of $\frac{E}{n}$. Townsend (12) derived the form of Φ to be approximately

$$\alpha = Ae^{\frac{Bn}{E}} \qquad (3)$$

in which A and B are gas constants.

Considering the increase dN, over a distance dx, in the number of electrons per second crossing a plane distance x from corona wires to collection electrodes (Fig. 1) we can write

$$dN = \alpha N dx$$

integrating, we get

$$\int_{N_0}^{N} \frac{dN}{N} = \int_0^x \alpha dx$$

or

$$N = N_0 e^{\alpha x} \qquad (4)$$

where N_0 is the number of electrons per second leaving the cathode.

Multiplying both sides by e we get

$$eN = eN_0 e^{\alpha x}$$

or

$$I = I_0 e^{\alpha x} \qquad (5)$$

Where I_0 is the saturation current. (13)

So, given an α we can determine the precipitator current I in the operating range between V_S and V_B. This does nothing to explain the occurence at V_B.

To explain the breakdown at V_B Townsend invoked his second coefficient (14). This he called γ and is defined as the average yield of electrons caused by each positive-ion striking the corona wire.

As when only the first Townsend coefficient is involved let

N = Total number of electrons in the current flow.

N_0 = Number of electrons at saturation.

But also let

N_+ = Number of electrons liberated by positive-ion bombardment of the corona wire.

Therefore from equation (4) we have

$$N = (N_0 + N_+)e^{\alpha x} \qquad (6)$$

Steady state conditions demand that

$$N - (N_0 + N_+) = \frac{N_+}{\gamma} \qquad (7)$$

Solving for N_+ in Equation (7) and substituting into Equation (6) we have

$$N = N_0 \frac{e^{\alpha x}}{1 - \gamma(e^{\alpha x} - 1)} \qquad (8)$$

or by multiplying both sides by e we have

$$I = I_0 \frac{e^{\alpha x}}{1 - \gamma(e^{\alpha x} - 1)} \qquad (9)$$

Therefore we have two equations which explain to some extent the happenings in the so called Townsend region (Fig. 2) between V_S and V_B and also including V_B. But the equations are dependent on solving for α and γ of which only α has been solved to any extent (Eq. 3). γ on the other hand has not been solved at this writing. But, as Howatson (15) conjectures, it is reasonable to assume

$$\gamma = f(E_n) \qquad (10)$$

Where E_n is the total energy in the precipitation provess. E_n would be a function obviously of applied voltage and temperature but also of something not so obvious called corona.

In the Townsend region the transition of atoms from one energy state to another causes the release of energy in the form of a violet glow called corona. Also at the onset of corona there is a distinct hissing noise. Corona extends only a few centimeters into the gas stream but it is felt (16) that the photoelectric effect adds to some extent, to the ionization of the gas. It is a fact (17) that when the ESP is maintained at power levels below that necessary for corona the ESP efficiency is greatly diminished.

Therefore we can say

$$\gamma = f(V,T,C). \qquad (11)$$

Where C is the corona contribution to the energy of the system. With this relationship and with the equation for α one can provide a more realistic model of the ESP process as shown in Fig. 4.

C is shown in Fig. 4 to be a function of input voltage and output ionizing current. Temperature (T) is a function of the process being treated and also ionizing current. The feedback from the current output must be considered positive since the energy level is increased with increasing ionization current. But ionization current usually makes a minute contribution to T and probably very little to C. Therefore at low voltages and on up to V_B the actual feedback contribution can probably be ignored. But at V_B this feedback may need to be considered.

A complete model of the ESP is prevented due to the three unspecified functions in Fig. 4. These relationships have, as yet not been ascertained. However, even without a complete model one can draw certain conclusions. First, the positive feedback in the system probably contributes to the instability at V_B. Secondly there are two inputs to the system (n and p) which we have no control over. The inability to control the inputs to a system clearly signals uncontrollability.

3. CONTROLLERS FOR ESP's

Even though the ESP process is not completely controllable some degree of control can be achieved by manipulating only the input voltage. This is because V is the dominating input up to the point of breakdown. At breakdown the input voltage to the system must be removed completely before stability can be regained.

This occurence at V_B (Fig. 2) is given various names in the industry. It has been called the avalanche phenomena, field collapse, and arcing. The latter is most often used because of the violent lightning-like flash which occurs.

When an arc occurs the electric field, responsible for the particulate collection, (Fig. 1) immediately disappears. At this point the ESP is nothing but an expensive gas duct at nowhere near the pollution control efficiency expected. Along with rendering the precipitator helpless these arcs cause large electrical surges on the power supply which shorten its life extensively.

Given the detrimentalness of the arc one would think industry would have found a way to avoid it. But this is not the case. The power supplies have been fortified with such things as linear inductors and high-frequency chokes. This has resulted in many manufacturers giving life expectancies of 20 years or more for power supplies. The ESP controllers, rather than prevent the field collapse, use the event as a measurement of optimum operation.

Because the ESP must be operated in the Townsend region to maintain efficient operation, it is felt that the higher in the region a field can be kept the better the efficiency. Therefore controllers are designed to maintain the ESP electric field as close as possible to the arc point.

There are many ways of reaching and maintaining this optimum point of operation. In some less critical applications this point is even manually maintained and given only intermittent attention. However, in most cases some sort of controller is used for constant feedback and control.

In most modern systems SCR stacks are utilized as the prime mover for varying the input voltage to the ESP. This is because of their quick reaction and low power consumption. Of the controllers on the market which command these SCR's the majority are analog with only one or two recent digital additions.

Whether digital or analog controllers are used, their control logic is the same. They seek to stay as close as possible to the V_B point and when, eventually, V_B is reached, and the field collapses, they want to turn off the voltage to the field long enough for stability to be reinstated. At this point voltage is put back on the field at a low point in the corona region and the process of creeping up on V_B starts all over again.

The operator of a typical ESP analog control sets only three variables. These are the output current limit, the length of time the input voltage is turned off after an arc has occured, and the rate of rise of the input voltage. Once these settings are made the output current can typically be seen ramping up to the arc, where high spikes representative of the arc are observed, dropping to zero for a set time period, and then ramping up at the same rate again. Regardless of process changes the controller continues to cycle at the same rate until the operator makes new settings or until the system current limit is reached.

The digital control, unlike the analog, has no comparitors or variable RC time constants. Instead comparing and timing are done with software programming. Figure 5 shows a typical digital controller for an ESP.

Though the digital controller tries to do the same thing as the analog, the ability to record and recall past events offers significant advantages. Probably the biggest advantage is that the actual value of V_B can be used by the control to modify subsequent operation. One example of this modification would be to bring the input voltage only up to the threshold of V_B and hold it there until a new V_B occurs or a search for a higher V_B is necessary.

Another advantage the digital controller has over the analog is the elimination of the necessity for operator interaction. Such things as readjustment of limits, off-times, and ramp-rates are not necessary. This is because the whole range of these values and the logical steps for using them are programmed into the control.

The digital controller is, by far, the most effective controller for the ESP application. It must be pointed out however that, at the present, price is one advantage the analogs have over digitals. This is a strong point and probably the determining factor in uses where efficiency is not an issue.

4. RECOMMENDATIONS TO IMPROVE THE ESP CONTROL

Figure 6 shows the primary inputs and outputs to the ESP. Of these the only input-output information typically used by the controller is input voltage and output current as shown in Fig. 7.

This presents the possibility of enhancing the ESP operation by providing more information to the controller. The unused output information could definitely improve the control of the system because of the direct cause-effect relationship. Knowing the desired effect, the input voltage can be modified to achieve it.

At the present time n_0 readily lends itself to utilization and is most important of all output information. After all, a proper n_0 is what the ESP system should be trying to achieve. Since the EPA sets specific levels of particulate emissions allowed at each location in the country, given these levels, the n_0 information could be used by the controller to even reduce the input voltage instead of constantly pushing it into the arc region.

Use of n_0 could greatly improve the analog controller performance on the ESP. By adding a comparator to the analog controller of an ESP, it can observe when the performance of the ESP is satisfactory or not. When the n_0 is at the proper level it is not necessary for the controller to increase the input voltage. Input voltage can be held at the point where the proper n_0 is maintained without the necessity of continually ramping it up to the arc point.

The equivalent could be done with a digital controller. Figure 5 could be modified to include another analog to digital converter. But in this case the majority of the changes would be reflected in software instead of hardware.

The control modification suggested here would eliminate the blind dancing of the system around the

V_B point. Most important, the quantity of surges on the system could be reduced and there would be a factor of power-conservation.

Therefore, at present the most effective improvements in control of the ESP process are not in the controller but in proper utilization of the available information. If the information is used properly arcing can be minimized to the point of insignificance.

5. REFERENCES

1. White, Harry J. (1963), *Industrial Electrostatic Precipitation*, 1st Ed. Addison-Wesley Publishing Company, Inc., p.1.
2. White, Harry J. (1963a), p. 6.
3. Hanson, John. (1978), *Operating and Maintenance Manual for the ESP's Installed on the Power Boilers Units 1 through 6 at the Widows Creek Steam Plant*, Birmingham, Alabama, Pollution Control-Walther, Inc., p.1.1.
4. Idu, Huang and You-Nian, Hua. (1975), *Electrostatic Dust Precipitation*, *Wuli (Physics)* Peking, Vol. 4, NR6, pp. 340-345.
5. Jeans, J. H. (1927), *Electricity and Magnetism*, 5th Ed., New York, Cambridge University Press, p.41.
6. Townsend, J. S. (1915), *Electricity in Gases*, New York, Oxford University Press, p.375.
7. Potter, Edmund C. (Jan. 1978), *Electrostatic Precipitation Technology A Different Viewpoint*, Journal of the Air Pollution Control Association, Vol. 28, No.1.
8. Howatson, A. M. (1976), *An Introduction to Gas Discharges*, New York, Pergamon Press, 2nd Ed.
9. Meek and Craggs (Editors). (1978), *Electrical Breakdown of Gases*, New York, John Wiley & Sons, 1st Ed.
10. White, Harry J. (1963b).
11. Howatson, A. M. (1976a), p.57.
12. Townsend, J. S., (1915a), p.291.
13. Howatson, A. M., (1976b), p.55.
14. White, Harry J., (1963c), p.82.
15. Howatson, A. M., (1976c), p.63.
16. White, Harry J., (1963d), p.83.
17. White, Harry J., (1963e), p.74.

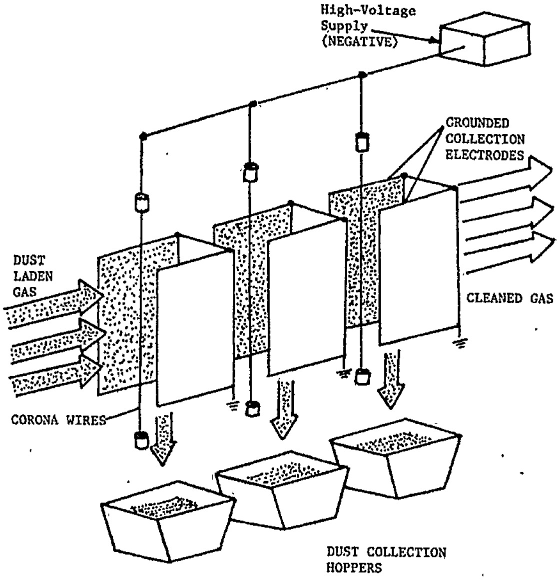

Fig. 1 Schematic diagram of an electrostatic precipitator collecting dust.

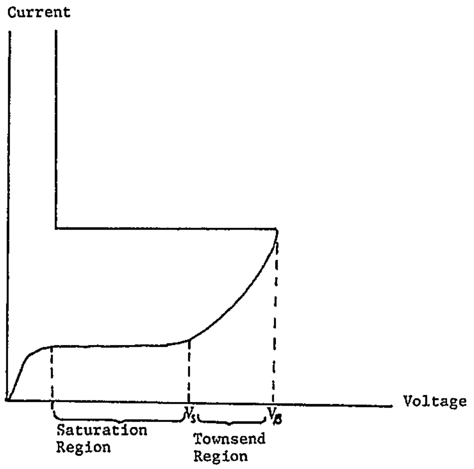

Fig. 2 Voltage - Current Characteristic for an Electrostatic Precipitator

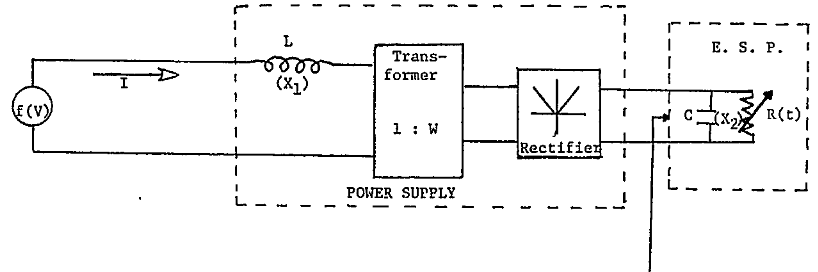

Fig. 3 LUMPED PARAMETER MODEL OF AN ESP

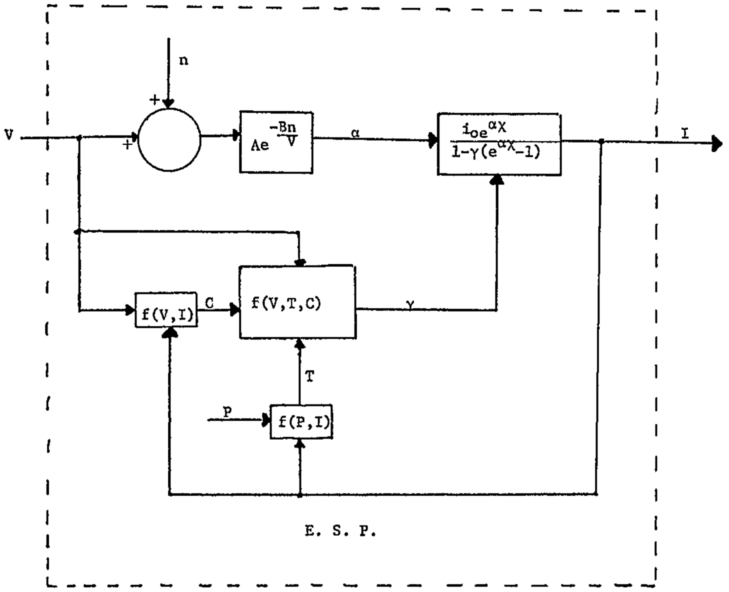

Fig. 4 TOWNSEND MODEL OF THE ESP
P=PROCESS INPUT

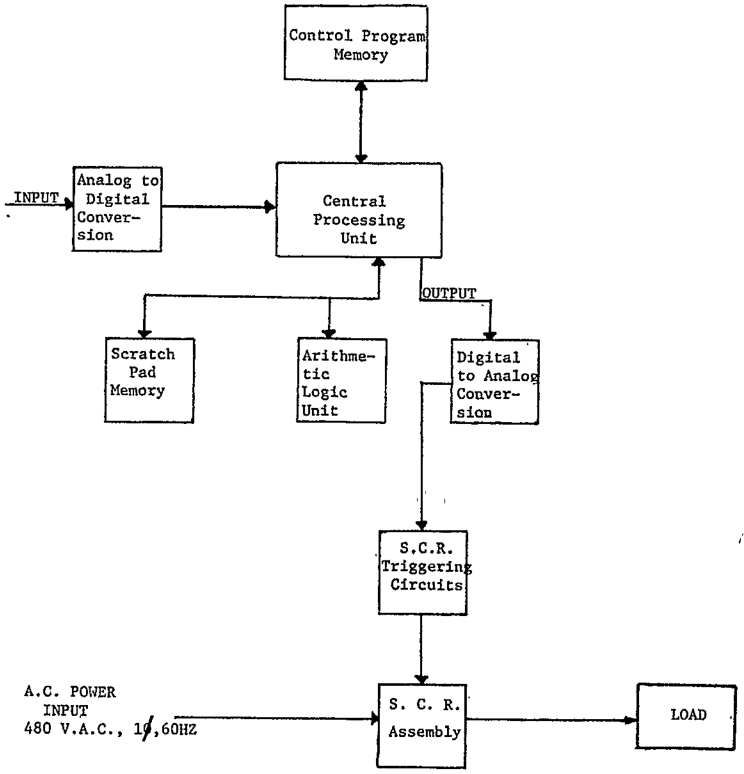

Fig. 5 DIGITAL CONTROLLER FOR AN ELECTROSTATIC PRECIPITATOR

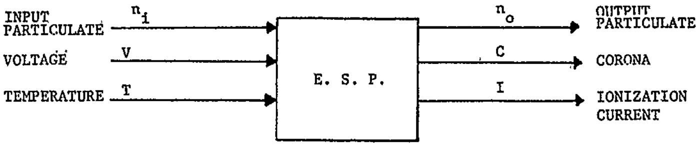

Fig. 6 PRIMARY INPUTS AND OUTPUTS FOR AN ESP

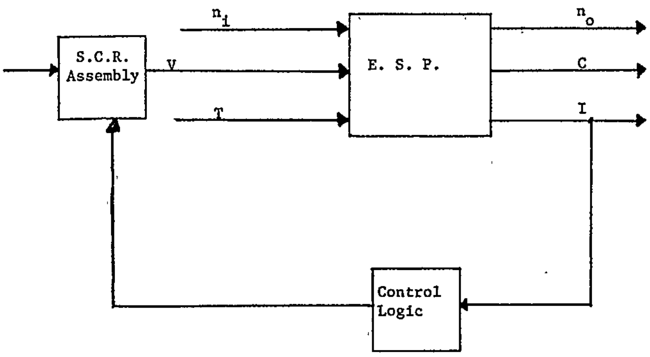

Fig. 7 INPUTS AND OUTPUTS USED BY A TYPICAL ESP CONTROLLER