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Method for Modeling and Classifying Voltage and Current Characteristics of an Electrostatic Precipitator

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Abstract— **This paper discusses methods for characterization of voltage and current data from a cold-end electrostatic precipitator on a unit burning a wide range of fossil fuels. Methods include algorithms to curve fit noisy data from plant historian and provide visualization to be fed into an advisory system to help engineers in the optimum maintenance and operation of the equipment. Three algorithms, "Least Square Method", "Piece Wise Least Square Method" and "Bézier Curves", are presented and discussed herein to identify the best experimental modeling technique.**

Keywords- Electrostatic Preciptators, Bézier curves, least squares method, modeling, optimization Introduction

I. INTRODUCTION

Background

Under current stringent environmental regulations such as the regulatory actions under the Mercury and Air Toxics Standards (MATS), it is very important to optimize air quality control equipment to maximize its performance and comply with new or existing particulate matter limits, especially when co-benefits of precipitators become important to help in the collection of particulate matter under high carbon in the ash conditions for and supporting the higher ash loading from sorbent injection for Mercury and acid gases control under MATS.

Electrostatic Precipitator

The Electrostatic Precipitator (ESP) is a filtration device that collects and removes fly ash from boiler flue gas. The ESP consists mainly of thin vertical wires (electrodes), large vertical metal plates and a rapping system. The electrodes, charged with several thousand volts, ionize the flue gas which flows horizontally through the gaps between the electrodes and the plates. Negatively charged particulates in the flue gas will then migrate to and accumulate on the metal plates. The rapping system hammers the plates periodically to clean and collect ash in hoppers below for each corresponding electrical section.

The optimum operation of the ESP also reduces ash loading on the backend systems such as flue gas desulfurization system and fans thus decreasing the operational burden and wear/tear on the equipment. Upgrading or retrofitting existing particulate control devices is a significant capital investment and at some points can lead to plant retirement depending on its age and condition. Particulate control devices include hot, cold or wet electrostatic precipitators (ESPs) and fabric filters.

In this paper, a cold electrostatic precipitator is used for analysis due to their popularity and wide use in the industry. The ESP utilizes electricity to charge and collect particulates, therefore the voltage and current (V-I) characteristics are critical parameters for the performance and efficiency of the equipment. The V-I characteristics has been used in different applications to analyze devices performances [6-8]. Most ESPs are instrumented with sampling and measurement systems to capture, store and display this data[1-5]. However, they are limited to collect and store data that does not detect section startup V-I characteristics of an ESP electrical section. Therefore, an algorithm is needed to model and present actual operating conditions to help engineers and plant operation develop countermeasures that maximize collection, efficiency and minimize particulate matter emissions.

Voltage-Current (V-I) characteristics of an ESP section is an important factor that directly affects collection efficiency and thus particulate emission. Therefore, they are key tools for diagnosing problems with ESP operation [1] V-I curves, when plotted and compared to baseline optimum performance on a precipitator section startup, can reveal performance degradations, electrical, mechanical and process issues within the ESP. Variations in the shape of secondary V-I curves can indicate a variety of problems including[1]:

- Extreme misalignment of plates or discharged electrodes
- Electrical shorts
- Abnormal sparking
- Back corona caused by high ash resistivity
- Thickness of ash layer collected on the plates

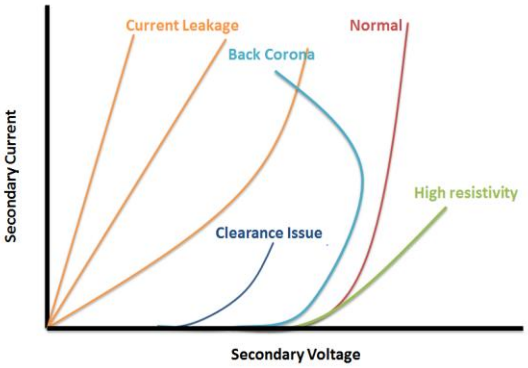

Fig 1: General V-I Plot Showing Abnormal Conditions of an ESP.

However, existing technology needs to be applied to properly fit V-I characteristics and compensate for sensor noise and sampling inconsistency in order to capture issues within the ESP. The data can then be fed into an advisory system for plant operation and engineering decision making.

It is important to mention that each electrical section will produce voltage current characteristics depending on its mechanical condition and parameters of the process at that particular instant which causes the corona onset potential, maximum spark-over voltage and secondary current limit to change dynamically, thus changing the shape of the curve. The latter will help plant engineers or operators detect and determine abnormal conditions of a particular ESP section by comparing to baseline normal and abnormal conditions for a particular ESP as shown in figure 1.

This paper discusses the application of the least squares method, Bézier and piecewise linear algorithms to curve-fit actual operating data of a 191 Specific Collection Area (SCA) ESP on an 850 Gross Mega Watts (GMW) unit.

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II. TESTING ESP CONFIGURATION

The configuration of an ESP, such as electrode arrangement, plate size, and channel width, plays an important role in the V-I characteristics [2]. The ESP used for the actual voltage (V) and current (I) operating data collection consists of four chambers (Upper North, Upper South, Lower North, and Lower South) with 5 fields in each chamber. An individual section is fed by a high frequency power supply with two separate subsections. The figure below shows the layout of the upper south chamber of the ESP.

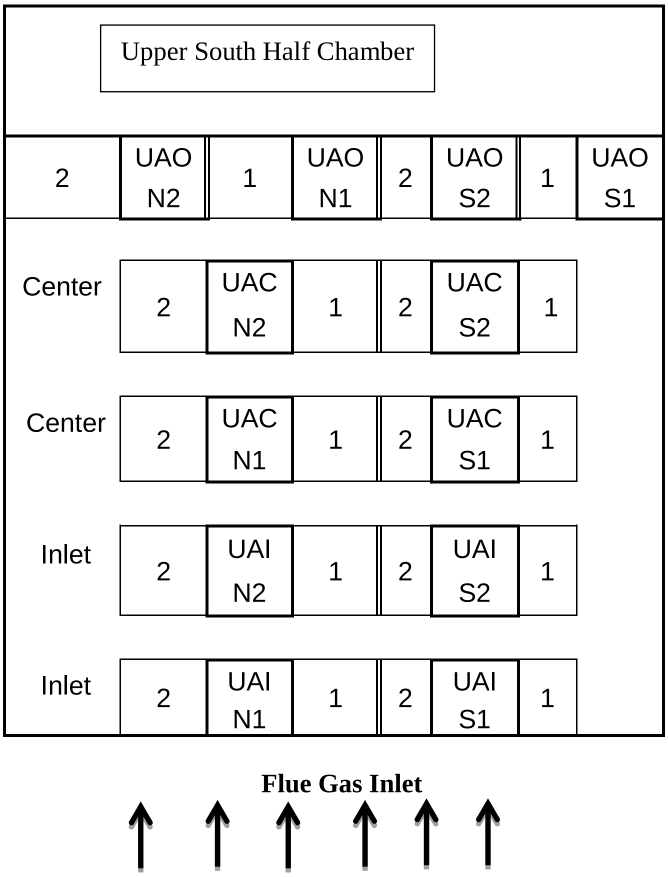

Fig. 2: South Half Chamber Layout of the ESP. "U" stands for upper. "A" denotes chamber designation. "I", "C", and "O" indicates inlet, center, and outlet respectively. "N" and "S" stand for North and South respectively. "1" and "2" represent subsections. Arrows represent flue gas direction of flow into the ESP.

The ESP design consists of weighted wire electrodes with 9 inch spacing plate to plate. Each plate is 9 feet deep and 30 feet high for the inlet and center fields. On the other hand, the outlet field is 6 feet deep.

III. LEAST SQUARES METHOD

The least squares method is one of the best estimation techniques used in engineering and statistical studies. The least squares method is commonly used to approximate the solution of over determined systems by minimizing the sum of the squares of residuals from the results.

Suppose there are "n" V-I data points $(x_1, y_1)...(x_n, y_n)$, an approximation function of these points can be written as follows:

$$f(x) = a_1 f_1(x) + ... + a_k f_k(x) \qquad (1)$$

Where $a_1 \dots\ a_k$ are the coefficients to be determined. Let

$$A = \begin{bmatrix} f_1(x_1) & \dots & \dots & f_k(x_1) \\ f_1(x_2) & \dots & \dots & f_k(x_2) \\ \dots & \dots & \dots & \dots \\ f_1(x_n) & \dots & \dots & f_k(x_n) \end{bmatrix} \qquad b = \begin{bmatrix} a_1 \\ \dots \\ a_k \end{bmatrix}$$

$$\text{And} \quad y = \begin{bmatrix} y_1 \\ \dots \\ y_n \end{bmatrix} \tag{2}$$

Then the errors between the actual data and the approximation function are:

$$e = \begin{bmatrix} e_1 \\ \dots \\ e_n \end{bmatrix} = y - Ab \tag{3}$$

The least squares method is applied by minimizing the following cost function using the following gradient method:

$$J = \frac{1}{2} e^T e \qquad \text{And} \qquad \frac{\partial J}{\partial b} = 0 \tag{4}$$

Thus, the coefficients of the approximation function are:

$$b = (A^T A)^{-1} A^T y \qquad (5)[3]$$

The least squares method will be utilized in this paper to fit a second-degree regression, applied to a Bezier curve to fit control points and utilized to fit two separate regressions in a piecewise polynomial model.

IV. BÉZIER CURVE

. The Bézier curve is a parametric curve that was developed in 1959 by mathematician Paul de Casteljau. In 1962, Bézier curves were first used by French engineer Pierre Bézier to design automobile bodies.

A 2D Bézier curve is defined by a set of control points, $P_0(x_0, y_0) \dots P_n(x_n, y_n)$, where n designates the order of the curve. Given the control points, the corresponding Bézier can be formulated as follows,

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} t^i P_i \qquad t \in [0,1] \tag{6}$$

Note that the first and last control points (P_0, P_n) are the end points of the curve. The parametric curve can be adjusted by tweaking the control points in between. However, they do not locally define the curve, meaning that any change to a control point would affect the entire curve. The Bézier curve was not originally designed for curve fitting, but proper use of the technique, along with the least squares method, can model the V-I characteristics of a back corona situation.

V. V-I CURVE-FITTING RESULTS

Curve Fitting for Back Corona V-I

The back corona will form if the resistivity of the ash collected on the plate is high. Back corona phenomenon changes the V-I characteristics and decreases the efficiency of the ESP [6]. The V-I characteristics of back corona, as shown in Figure 1, cannot be described by a single function $V = V(I)$ because multiple currents exist for one voltage. As will be shown later, piecewise function algorithm can be utilized, but it may fail to ensure the smoothness of the curve in the inflection region. The implementation of Bézier curves along with least squares method will successfully overcome the challenge mentioned above.

To explore the modeling capabilities of Bézier curves to a back corona curve, one set of back corona actual operating data is parameterized and modeled. The degree elevation theorem of Bézier curve states that a Bézier curve of degree n can be transferred into a Bézier curve of degree $n+1$ with the same shape. Thus, a quadratic Bézier curve would theoretically be sufficient to fit and model the back corona V-I data. However, accurately determining the second control point (P_1) will require a large number of iterations and burden the computing system. A more efficient way is to increase the degree of the curve, taking advantage of all data points such that every data point helps determine its corresponding control point (A n degree Bézier curve can be developed based on $n+1$ data points).

The control point describing the inflection point plays an essential role in shaping the final Bézier curve and consequently determines the accuracy of the model. To find the optimized control point in the inflection region, trial-and-error is performed utilizing least squares and gradient method. The possible control points in the right side of the inflection region will have the same current coordinates (y values) as the existing inflection point. A voltage value (x value) for the control point is chosen to equal the (x value) of the inflection point. The least squares method is then applied to evaluate the sum of the square of the errors between the curve and the actual data points. The errors are evaluated in x direction. The least squares method calculates the difference of the voltage value (x value) between the points on the curve and the actual data points that have same current value (y value). The voltage value (x value) of the control point is then accumulated and least squares method is applied (see figure 3).

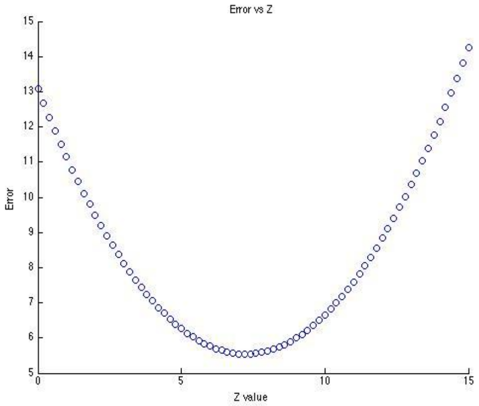

Fig. 3: Iteration Result.The Z value in the plot, 7.2, is the voltage value (x value) of the control point relative to that of the inflection point, 36.2 kV. This control point minimizes the sum of the square of the errors to be 5.55 kV.

After the determination of all the control points, an algorithm is developed in Matlab to calculate other Bézier parameters and generate the curve. The figures below demonstrate the Bézier curve fitting the actual back corona operating data with and without control points.

Shown below are two graphs (figures 4 and 5) showing the application of the Bézier algorithm to real startup operating data:

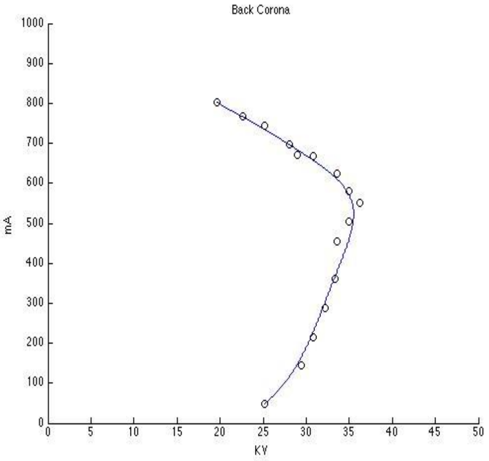

Fig. 4: Bézier Curve-fit without Control Points. This represents the regression using the oscillating method described below.

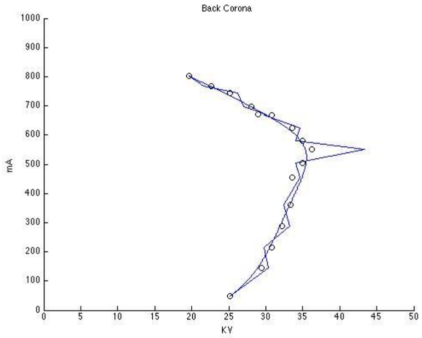

Fig. 5: Bézier Curve-fit with Control Points. This represents the regression resulting from not using the oscillating method described below.

As shown in Figure 4, the Bézier curve models the V-I characteristics for a back corona condition. Since Bézier Curve is a parametric curve, it is not feasible to have a single equation to describe the V-I characteristics of back corona.

It is found by trial and error that the curve described by a set of control points that "oscillates" around the actual data points will provide best results. This is shown in the difference between Figure 4 and Figure 5.

Since the first data point coincides with the first control point, the oscillation represented by Figure 4 starts at the second data point. Given the coordinate of the second data point (x_2, y_2), the second corresponding control point can be determined by keeping the "current" coordinate (y_2) the same while adding "1" to the voltage coordinate (x_2), thus the coordinate of the second control point is $(x_2 + 1, y_2)$. Similarly, the coordinate of the third control point is determined as $(x_3 - 1, y_3)$ "hence the oscillation" and so on until we reach the last control point (x_n, y_n).

The oscillation algorithm is performed on all data points except the inflection region, which is represented by the highest x voltage coordinate. Adding or subtracting values other than 1 may also work, but using the value 1 would yield a curve that is accurate enough to describe the V-I characteristics of back corona

Curve Fitting of V-I Data – No Back Corona

To explore where methods not utilizing the Bézier curve fall short, we must show their application to a similar data set and compare the results to that of the combined least squares – Bézier method described above.

Utilizing the least squares method, it is possible to curve-fit the V-I data to determine the approximating equations. The V-I curve characteristics can then be modeled by a second order polynomial. Polynomials with higher order may yield a better fit in some cases, but not necessarily determine actual V-I characteristics and behaviors of a precipitator electrical section.

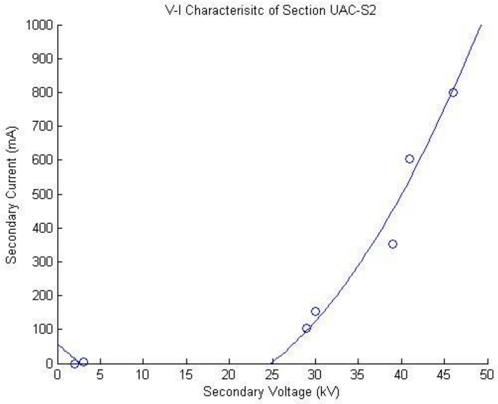

Figure 6: Curve-fitting for S2 Center Section V-I characteristics. Note the corona onset potential detection.

The approximation equation obtained by the least squares method for "UAC-S2" is:

$$I = 0.7V^2 - 18.7V + 1.2 \tag{7}$$

Where V is in KV and I is in mA. The root-mean-square error for this approximation is 20.6 mA.

From the plot above, it is clear that the corona onset potential is 25 KV and spark over voltage is not yet reached, as modeled by the resulting second-degree polunomial. It is desired on an inlet type section to reach the spark over voltage before any other limit (primary current, secondary current, primary voltage or secondary voltage) on a cold ESP [4].

Because this method fails to capture the effects of a back corona, it falls short in describing the actual behavior of the ESP.

Piecewise Least Squares Algorithm for Back Corona Curve Fitting

An alternative method for back corona curve fitting is the piecewise least squares method. The actual back corona operating data are split into two segments, which come together at a discontinuous point of intersection at the inflection point. The corresponding curve for each segment is generated using least squares method. Figure 7 below shows the curve fitting result:

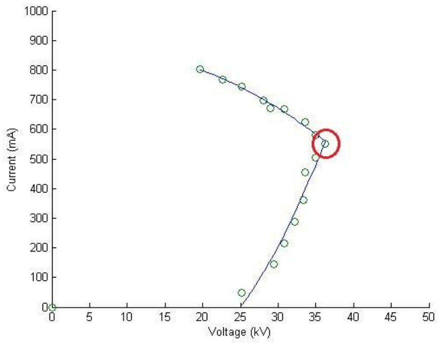

Fig. 7: Piecewise Least Squares Curving Fitting Result for Back Corona. Notice red circle around discontinuous point.

The piecewise least squares algorithm is simpler than Bézier curve-fitting methodology, consuming less computing resources. However, it is difficult to ensure the curve smoothness in the discontinuous region as shown in figure 7 above. Therefore, this algorithm is not able to appropriately model the actual back corona V-I characteristics and guarantee smoothness in the inflection region.

VI. CONCLUSION

The V-I characteristics of an ESP section is an important factor that affects particulate collection efficiency.

By applying the least squares method, a second order polynomial was obtained to curve-fit the normal actual voltage and current operating data. However, this method fails to capture the effects of a back corona curve.

To attempt to model this back corona curve, a piecewise least squares method joins two polynomial at a discontinuous point of intersection at the inflection point. However, this method fails to produce a smooth curve in this point of intersection and cannot accurately describe data in this region.

An algorithm is also developed using Bézier curve parameterization and least squares method to curve-fit the back corona voltage and current operating data. An oscillating parameterization of the Bézier curve data points produces a smooth regression that models the back corona smoothly with no points of discontinuity. The oscillating algorithm produces far smoother regression curves than the non-oscillating, control point algorithm.

The curves generated by the combined Bézier curve – least squares method can then be used to determine the onset corona discharge and electrical limits of a precipitator section such as spark over voltage, primary/secondary current or voltage limits. The curve parameters and shape can then be evaluated and compared to a series of conditions where any mechanical, electrical or flue gas process issues can be detected and corrected when possible.

Utilizing these curves, an advisory system will be developed in the future to feed engineers and operators with a performance evaluation of individual precipitator sections. Once an advisory system is applied and utilized, it can be converted to an adaptive modern intelligent control methodology to look at power plant draft and flue gas systems holistically to optimize environmental control equipment such as electrostatic precipitators, flue gas desulphurization systems and selective catalytic reactors.

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