The Development of an Algorithm for the Dynamic Adjustment of the Pulse Repetition Frequency for Minimising Back Corona in Electrostatic Precipitators

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Paper Presented at ICESP IX – Mpumalanga South Africa
17th – 21st May 2004

Abstract

Within the ESP industry, power supply synchronous pulsing is a well known method of dealing with Back Corona resulting from the precipitation of high resistivity particles. Often, especially in the case of moderate Back Corona, or on a stable process, a set-up once and forget method of adjusting the controllers is satisfactory. In these circumstances, the time taken and skill level required to establish the initial settings is not an important factor.

Under extreme conditions of Back Corona, or with an unstable process, this approach is not viable. Automated optimization algorithms were developed and run at regular intervals in order to establish and update the controller settings.

The paper describes the development of a dynamic algorithm which having established the optimum pulse repetition frequency, attempts to further optimize on-the-fly in order to compensate for short term changes in the operating conditions.

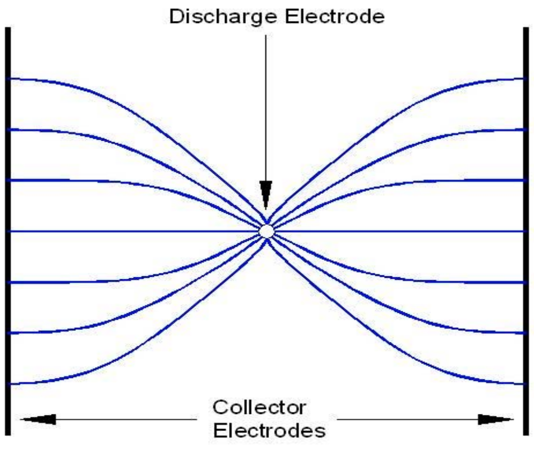
It is understood that this type of control algorithm is often required to be retro-fitted in older plants where these types of problems are already known to exist. The paper takes a practical approach to this in considering how to deal with less than perfect voltage divider signals when utilizing existing T/R sets for example.

Background

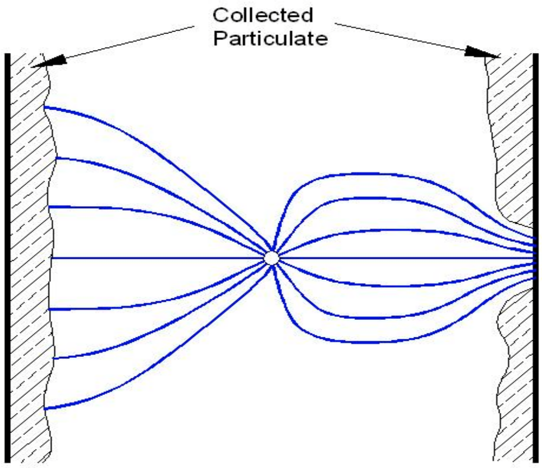
The phenomenon referred to within the Electrostatic Precipitator industry as either Back Ionisation or Back Corona has been known about for some time. It occurs when the collected particulate material has a very high resistivity. Plants where this is likely to happen include coal fired power stations burning low quality coal, sinter plants and cement plants. This paper describes the principals involved during the development of the algorithm at a coal fired power station in Queensland Australia. The difficult nature of the local coal supply was known before the station was built. Trial batches of coal were fired at existing power stations before construction of the plant commenced. By the time the last boiler was completed in 1986, an algorithm had been developed which allowed the plant to achieve its specified emissions. With the passing of time the original controls became obsolete, spare parts and reliability became a major issue for the end user. It was necessary to find a vendor who could supply equipment capable of matching or exceeding the performance of the original controller. Castlet Ltd won the contract to retro-fit the original controllers. Initial tests proved somewhat “mixed”, sometimes the new equipment would easily outperform the original equipment, others it fell somewhat short. It was quickly understood that the dynamically varying conditions in the process required a much more dynamic response from the controller.

Back Corona

Back Corona is a current induced phenomenon brought about by the voltage drop across the particulate built up on the collecting electrodes. When the collecting electrodes are clean, the electric field is distributed evenly across the collecting electrodes. This is shown in the plan view diagram below.



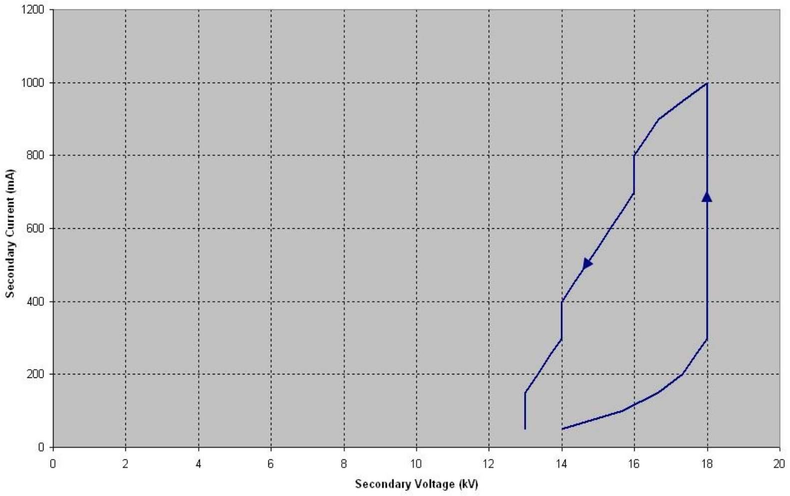
If the particulate collected as a result of this electric field has a significant resistivity, a substantial voltage can develop across this layer due to the corona current flowing between the discharge electrode and the collector electrode. If this voltage is high enough, dielectric breakdown can occur between the collector electrode and the surface of the collected particulate. This breakdown results in a hole being blown through the collected particulate, which further results in the electric field being increased in the vicinity of the this hole. This effect is shown in the diagram below:-



The effect of this is to generate a strong positive field in the vicinity of the hole in the collected particulate. This strong positive electric field generates positive ions which neutralize the negative charge on the collected particles as they migrate towards the discharge electrode. A flow of positive ions towards the discharge electrodes is no different from a flow of electrons from the discharge electrodes as far as the power pack is concerned, and is in effect a shunt path in parallel with the desired current path. Some particles will become positively charged during this process, and will collect on the discharge electrodes, (which is the origin of the word “back” in Back Corona). Once the hole has formed, the process is self-perpetuating. In summary, tell tale clues that Back Corona is at work include the following:-

- Craters or holes in the collected particulate.
- Sausages or tubes of particulate around the discharge electrodes
- High current low voltage operation of the T/R sets.
- A decreasing V-I plot does not follow the same path as an increasing V-I plot

The last point deserves some further explanation, Back Corona takes a finite time to establish, and as mentioned earlier is a current induced phenomenon. It is possible to take an automated V-I plot (or even a manual one) which leads (stays ahead of) the onset of Back Corona. The Castlet controller takes a V-I plot of secondary voltage for secondary current from 5% rated secondary current to 100% secondary current in 5% steps, it then plots the same curve in reverse. Under low to medium resistivity conditions, the decreasing portion of the plot overlaps the increasing section. Below is a plot from a high resistivity V-I plot:



Countermeasures

Possible countermeasures to this problem include.

1. Burn coal with better characteristics. In the case where it is only possible to generate electricity on the basis of a local coal supply this is not an option.
2. Condition the flue gas so that it produces lower resistivity particulate. This method has the disadvantage of the cost of the conditioning agent (usually sulphur or ammonia) and the attendant safety hazards associated with these materials. Despite these drawbacks, for the case in point, trials gave unacceptable results because the resulting "sticky" fly ash adhered solidly to the collecting and discharge electrodes within the precipitator.
3. An electrical solution. The approach used by the original controls is known by various pseudonyms, Intermittent Energization or Pulsing are understood by most engineers working in the industry. The approach followed by Castlet was to build upon their experience already gained throughout the world using this technology.

Intermittent Energization

The idea behind Intermittent Energization is to energize the precipitator with a pulse of energy and then maintain the voltage on the "knee point" of the characteristic to allow time for any charge in the collected fly ash to decay. The pulse time is referred to as T1 and the discharge time as T2. The fact that the control of the power to the T/R is via SCRs dictates that these periods are synchronized to the mains supply. The T1 time is programmed in multiples of half supply cycles. For the purposes of operation with high resistivity fly ash a T1 of 1 half cycle has been found to be almost always the most effective choice. In order to avoid saturating the HV transformer core, it is necessary to ensure that alternate pulses occur in alternate positive and negative half cycles. In order to ensure this T2 is programmed in multiples of complete supply cycles. The reason for operating the precipitator on the knee of the characteristic (also know as the onset of corona or Corona Threshold value) allow the maximum voltage to act as a base for the next pulse, without any current present to induce further Back Corona.

Variations on this technology have been around for a good many years and have proven to be very successful at plants where stable and consistent operating conditions can be achieved. The values for T1 and T2 were established with the aid of an oscilloscope, trial and error and experience. Stable and consistent conditions meant that once optimized, the established settings for T1 and T2 were always near enough to provide acceptable emissions. However, when there are large variations in both the coal quality and the operating conditions fixed values of T1 and T2 do not provide adequate performance.

Back Corona Detection

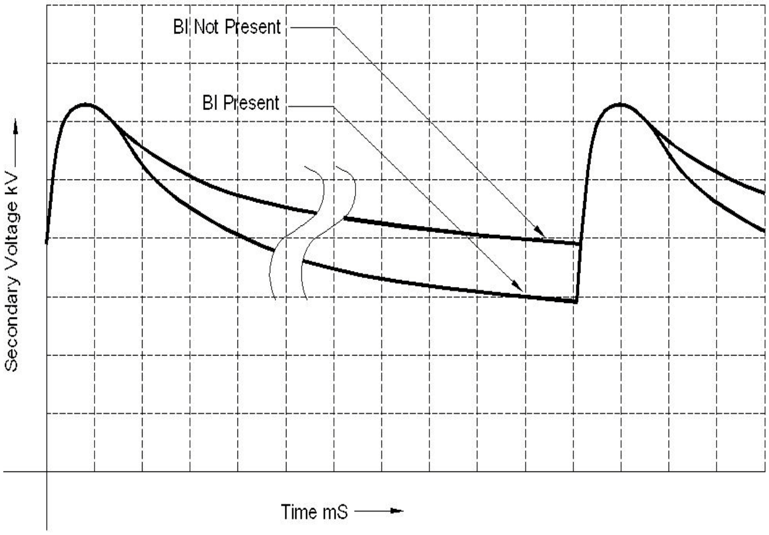
The VI characteristic shown previously gives some clue as to how to tackle back corona detection. Various methods have been proposed to detect Back Corona by examining the relationship between the peak and trough values of the kV waveform under continuous (normal energization). This approach suffers from a number of potential drawbacks.

1. Whilst the relationship between the peak and trough values do depend on the presence of Back Corona, they also depend on T/R impedance, supply frequency, precipitator load characteristics etc.
2. In even moderate cases, there will be Back Corona if the system is running in continuous energization.
3. Especially in the case of retro-fitting an existing unit, the voltage divider signal is not of sufficient quality to achieve accurate and reliable results

The method employed by Castlet is to inhibit SCR firing for a period of time immediately following the T1 pulse, and to analyze the decay characteristic of the voltage. As the SCRs are not firing during this time, this characteristic must be independent of the influences of T/R impedance, supply frequency etc. The measurement is performed at the point when the slope of the voltage decay is almost zero, this corresponds to the point where the corona current is also almost zero and hence represents the onset of Corona or the "knee" point on a V-I plot.

The following sketch shows two decay characteristics, with and without Back Corona present. In effect each curve represents the two portions of the VI plot shown previously. Firstly a measurement of the kV on a fixed period after a T1 pulse is recorded under non Back Corona conditions; this is achieved by using a very large value of T2, typically 255 cycles. This establishes a reference value which takes into account the plant and process variables, the most significant one being flue gas temperature. Let this measured reference value be V_{ref}. The controller can then progressively reduce T2 and monitor the effect each reduction has on the decay voltage. An offset parameter is used to determine the sensitivity of the detection, let the setting of this parameter be V_{offset}. Each time the controller assesses a new value of T2 it makes a new measurement of the decay voltage V_{decay}. Back Corona is considered to be present if the following relationship holds true:-

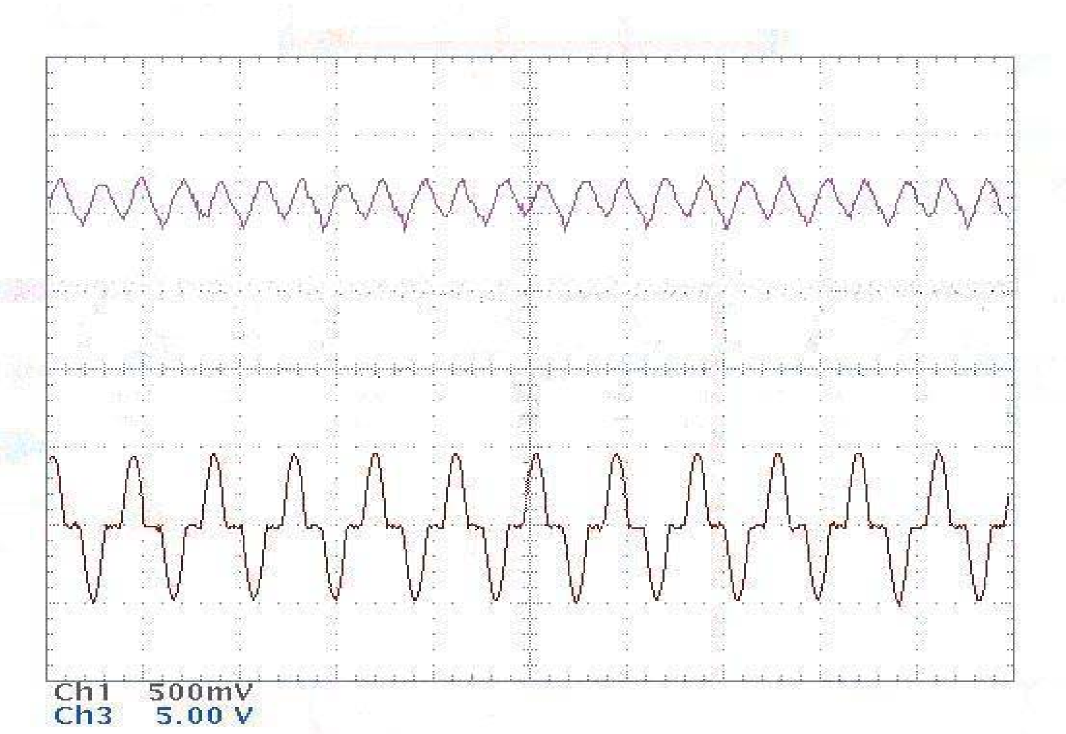
$V_{ref} – V_{offset} > V_{decay}$



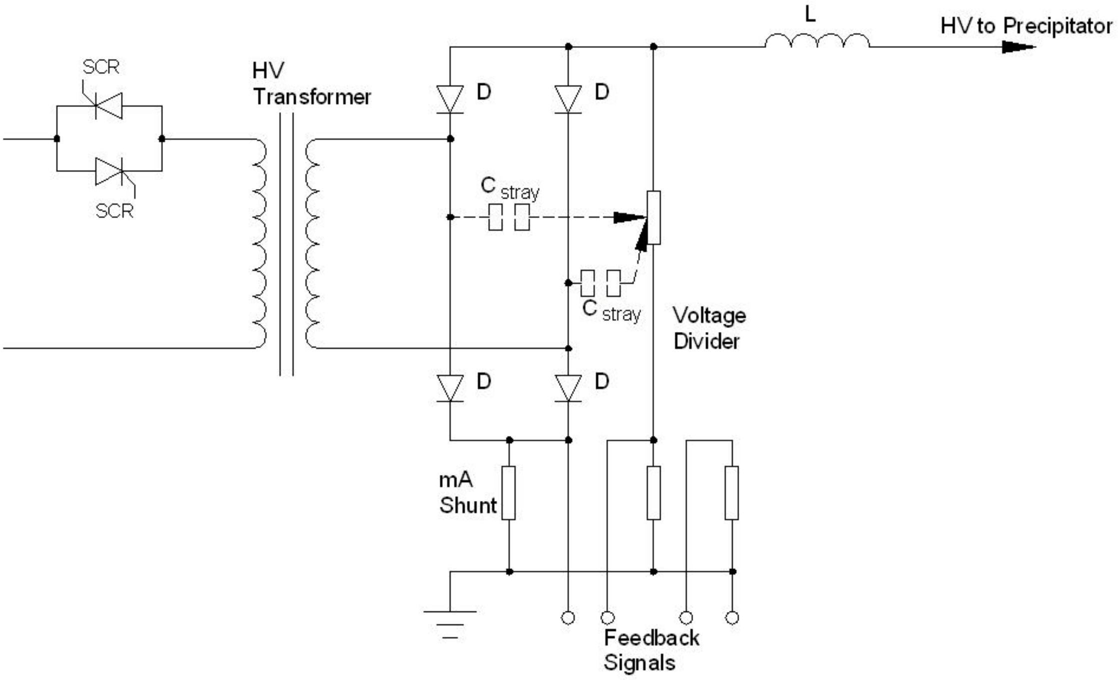
Once the largest value of T2 where the above relationship holds true is determined, the controller has established that this value of T2 is sufficiently low to induce Back Corona. The next step is to increase T2 to restore the non Back Corona condition. For a long time this was the basis of the Castlet Regupulse system successfully deployed throughout the world.

Factors Governing kV Feedback Signal Quality

The oscillogram below shows the secondary voltage and primary current waveforms for a T/R set where insufficient attention was paid to the voltage divider location.

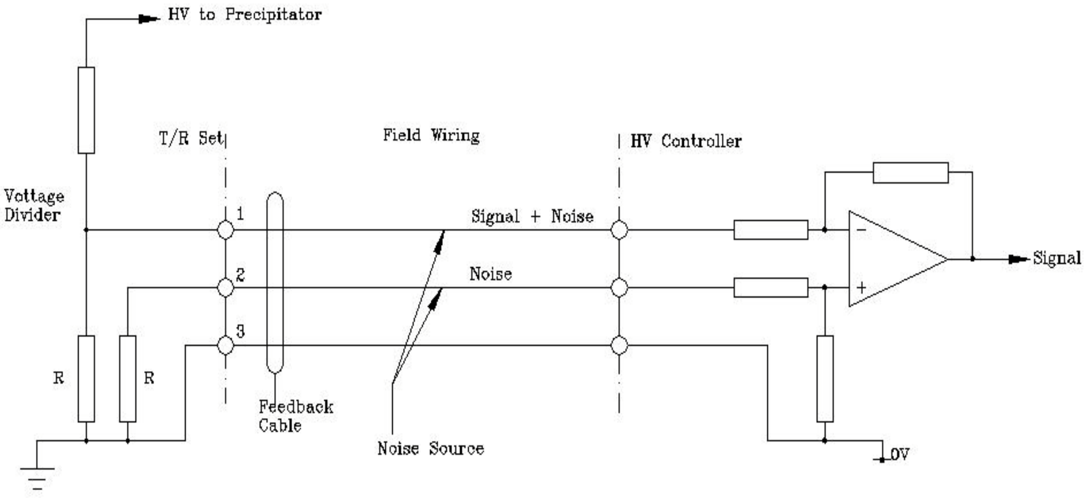


The primary current waveform (bottom trace) is undistorted and symmetrical, confirming there is no actual fault. The secondary voltage waveform has no constant value for its peaks and troughs. The mechanism by which this distortion of the secondary voltage waveform is introduced is shown in the following diagram:



The problem comes about because of the stray capacitance between the AC secondary winding of the HV transformer and the voltage divider itself. These are shown as C_{stray} on the drawing above. If these are neither insignificant nor equal, a net supply frequency signal is coupled into the voltage divider. The effect is most significant at the instant the SCRs are fired because the rapid rising edge produced has the highest frequency content and thus being capacitively coupled has the greatest effect. The instant the SCRs are fired is the trough of the secondary voltage waveform, this form of distortion is likely to have implications on a trough based Back Corona detection system. The SCRs are not fired during the Back Corona measurement method being described and therefore no corruption of the signal can occur as a result of stray capacitive coupling into the voltage divider.

The HV controller may be some considerable distance from the T/R set and hence the voltage divider generating the voltage feedback signal utilised for Back Corona detection. Inhibiting the firing of the SCR during Back Corona detection does not help prevent noise picked up in the field cabling between the voltage divider bottom and the controller. A long cable passing through an electrically noisy environment is likely to lead to erroneous results. The following diagram describes the steps taken by Castlet to avoid noise pick-up in the field wiring.



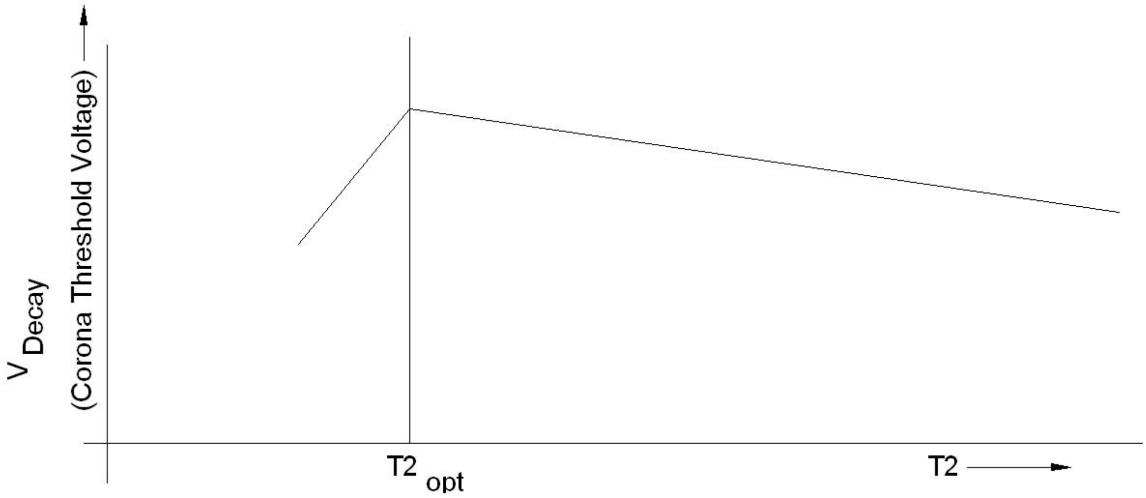
This method of connection of the voltage divider relies on a balanced line approach. The upper resistor in the voltage divider is very much larger than the sensing resistor R because the voltage on the precipitator must be divided down to a more manageable level for the controller, typically 5V. The source impedance of the voltage divider signal is for all practical purposes equal to R. A second line also terminated by a resistor R is used as a reference line. Both lines have the same source impedance (R) and run in the same physical cable, any noise affecting the line carrying the divider signal will have the same effect on the reference line. The feedback signal line thus carries a voltage equal to the signal + noise. The reference line carries a voltage equal to noise. The amplifier subtracts the voltage on the reference line from the feedback line.

(Signal + Noise) – (Noise) = Signal

Any noise picked up in the field cabling is thus subtracted before the signal is used for any control purposes.

Despite the above measures to ensure the quality of the voltage feedback signal, it is still important to avoid relying on a single spot measurement. Various factors including a recent spark (which will discharge the entire precipitator and quench any Back Corona) will affect the validity of the measurement. In order to avoid these effects a total of six readings are taken, the two highest and the lowest are discarded, the average of the remaining three is then calculated to generate the working value of the decay voltage V_{decay}.

The sketch below shows an idealised graph of T2 versus V_{decay} (the corona threshold voltage). Initially as T2 is reduced towards its optimum value $T2_{opt}$ the measured value of V_{decay} increases. Any further reductions in T2 results in a rapid fall in the measured value of V_{decay} due to Back Corona It can be seen that for values of T2 greater than $T2_{opt}$ a decrease in the measured value of V_{decay} indicates a change in operating conditions requiring a decrease in T2 to compensate. On the other hand, for T2 less than $T2_{opt}$ a decrease in the measured value of V_{decay} requires an increase in T2 to compensate. In order to be able to optimize T2 it is therefore not only necessary to identify any changes in the Corona Threshold voltage, it is also necessary to know which side of the $T2_{opt}$ the new value of V_{decay} belongs, in order to determine whether an increase or a decrease in T2 is required in order to compensate for the changed value of V_{decay} . This problem is made more difficult when it is understood that the “curve” moves horizontally for variations in the severity of Back Corona, and moves vertically for variations in operating conditions, flue gas temperature variations in particular, although these two variables are of course not independent.



In order to deal with this problem, rather than simply seek for the maximum value of V_{decay} in order to determine a value for $T2_{opt}$, the algorithm would be deliberately biased to operate on one side of $T2_{opt}$. As long as the amount of bias was sufficient, it would always be known which side of $T2_{opt}$ the system was operating. Increasing the setting of the offset parameter mentioned earlier had the effect of forcing the algorithm operating point to be further into the Back Corona region. It turned out that this was a fortunate decision. Although $T2_{opt}$ was optimum in that it corresponded to the value of T2 which generated the maximum value of V_{decay} it transpired that it did not correspond to the value of T2 which generated the lowest stack emissions. It is supposed that the reason for this is that whilst decreasing T2 below $T2_{opt}$ leads to the generation of some Back Corona, it also leads to the generation of more useful current. The condition for setting T2 is thus defined as the largest value of T2 which satisfies the relationship:

$$V_{ref} – V_{offset} > V_{decay}$$

Where V_{ref} is the Non Back Corona reference value established with a very Large T2.
V_{offset} is a controller parameter.
V_{decay} is the measured Corona onset voltage at the current value of T2.

This had two advantages, first it ensured lower emissions and second it ensured that the corrective action for a change in V_{decay} was always in the same sense. The next step was to implement an algorithm to continue re-evaluating $V_{ref} – V_{offset} > V_{decay}$. If the result was TRUE, T2 was increased by 5 cycles because Back Corona is considered to be present. If the result was FALSE, Back Corona is considered not to be present hence T2 is decreased by 1 cycle. It was established experimentally that the effect of too low a T2 had a worse effect on the emissions than an equally too high a value. The effect of the corrective action was scaled in order to reflect this disparity. An overall limit of -5 +15 cycles from the originally established $T2_{opt}$ is applied. It is considered that if so much correction is required it is likely that the original value for V_{ref} has become invalid due to process changes and that a new value of $T2_{opt}$ should be established before making any more changes to T2.

Step by Step Summary of the final Algorithm

1. A timer is started, the duration of which is a system parameter, and defines the time for which the reference value determined in Step 2 remains valid.
2. A non-BI reference point is established, this is achieved by selecting a T1 of 1 and a T2 of 1.5 times the Pulsing T2 setting or 255, whichever is smallest, and allowing a short time for any Back Corona to cease. This method allows for changes in operating conditions, such as temperature combustion conditions etc.
3. The precipitator characteristic is scanned in order to establish an estimate of the VI curve “knee” point (the voltage at which corona current commences). This is done by disabling SCR firing and measuring the secondary voltage. This is repeated a number of times and a voting algorithm employed to counteract the effect of precipitator sparking and abnormal readings.
4. The voltage measured in Step 3 above establishes a reference point (V_{ref}), which takes into account the process conditions prevailing at the time of measurement. SCR firing is inhibited so that the measurement is independent of any transformer/rectifier characteristic or the supply frequency.
5. When Back Corona does occur, the measurement performed above will be depressed. An offset is subtracted from the non Back Corona reference in order to establish a detection point for the onset of Back Corona. This test value ($V_{ref} – V_{offset}$) is stored for future testing.
6. If, for example, the set in question normally optimizes at a T2 of say 25, there is no value in allowing the algorithm to check T2 values in excess of 50. Before commencing optimization, the controller switches to the value programmed into the T2 parameter on the Pulsing page. This is to set an end stop for the optimization algorithm, thus reducing the time taken to optimize.
7. The precipitator is re-scanned as described in Step 3 and the result compared with the value for Back Corona detection established in Step 5.
8. The value of T2 is reduced and Step 7 repeated until either T2 reaches 1 or Back Corona has been detected. The value of T2 required to induce Back Corona is noted, and a small allowance subtracted in order to avoid Back Corona.
9. Back Corona is now present and must be quenched in order to gain optimum performance. This is achieved by inhibiting SCR firing in order to allow the collected dust layer to discharge.
10. The Onset of Corona point is re-established at 1 minute intervals between successive scans. This involves scanning the characteristic as described in Step 3 above; testing for Back Corona is performed by comparing the new knee point with the test value established in Step 4. If Back Corona is detected the operating value of T2 is increased by 5 cycles. If Back

Corona is not detected the operating value of T2 is decreased by 1 cycle. A limit lower of -5 and an upper limit +15 cycles is placed on the amount by which this dynamic mode can modify the optimum value of T2 established when Back Corona was first detected.

11. The timer started in Step 1 is tested, once it has timed out control is transferred back to Step 1 in order to re-establish the reference point for the current operating conditions.

Results

The development site had 4 boilers each boiler had 4 passes; emission monitoring equipment was installed on each individual pass. Performance was evaluated by generating historical data for both the pass to be retrofitted and a reference pass, a figure representing the average difference between the pass to be upgraded and the reference pass was calculated. The retrofit was completed and a new figure also representing the average difference between the upgraded pass and the reference pass was calculated. These evaluations were conducted under strictly controlled conditions, any excursions from the operating conditions necessitated re-starting the evaluation period. The effectiveness of the retrofit was calculated by comparing the before and after figures for the difference between the retrofitted pass and the reference pass thus cancelling any effects due to the reference pass. It was found that the average improvement for all 16 passes was 1.2%. It should be understood that this represents a 1.2% reduction in a baseline emission figure of 10 – 15%, (i.e. 12% - 8% in real terms) which is a very significant improvement.