Current Trends in Power Electronic Devices in Ecological Equipment

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***Abstract*—Emerging technologies for removing pollutants from waste gasses, released by industry and power plants, provide the means for removing COx, Nox, sulfur and fine dust particles. These technologies impose very stringent requirements on the power supply. The choice of the high-voltage supply can play an important role in the optimization of electrostatic precipitators. Widely discussed, the environmental pollution problems are the outcome of the world wide increase in energy consumption and industrial growth. The overall amount of waste gasses has increased, including the emission of fine, 1–50 μm particles, particularly harmful and being a well known health risk. Therefore, both large industrial sites and the power plants require dust cleaning equipment and on-line pollution control. Automated control is required for the equipment to operate on its own, without the need for a continuous operator intervention. Control goals include the need to meet the environmental regulations, keeping at the same time the power losses and the overall energy consumption under control, in order to reach the energy efficiency goals. In this article, an overview of electric filter performance problems is discussed, and the summary of available technologies and solutions is outlined. Experimental data is obtained from TE Morava, Svilajnac, where concurrent tests have been performed with conventional, 50 Hz power supply, and with high frequency power supply.**

***Index Terms*—Electrostatic precipitation, waste gasses, pollution control, electro filters, power plants.**

I. Introduction

CONTEPMPORARY dust cleaning equipment comprises electrostatic precipitators (ESP), forcing the waste gas to flow between large electrode plates, exposed to pulsating DC voltages of several tens of kV. Exposure to high strength electric field charges dust particles and they migrate towards the collecting plate, which is the positive one, and in most cases grounded. The other, negative electrode is attached to the negative supply rail of the controllable DC voltage source. The electrode surface is barbed and equipped with appropriate protruding spikes, responsible for an enhanced ionization. The migration of the charged dust particles takes place due to the electric forces exerted by the field. The drift velocity of the particles and their collection efficiency largely depend on the gas speed and the eventual turbulent flow. To enhance the filtering, the ESP comprise several (up to 8) series connected sections, wherein the output gas from the previous section becomes the input to the next. In such cases, the subsequent section may collect the dust particles that were properly ionized within the previous section, but were not collected due to an insufficient particle drift and/or too large speed of the gas stream.

In an attempt to enhance the ionization, drift speed and filtering, the voltage between electrodes can be increased. Though, along with the voltage increase, corona effects do pass into arcing. The electric arc within the filter effectively short circuits the power source and results in large currents and mass ionization. Following the arcing, the filter should be kept off the power source for several tens of milliseconds in order to allow for the ionized gasses to evacuate. Otherwise, at the reconnection without the de-ionization interval, the filter won't be able to withstand the reconnected voltage and will fall into arcing and short circuit again.

University of Belgrade and INT EE Institute developed and deployed the ESP controller [4] which integrated and coordinates control and monitoring of ESP process, rapping process, rappers, heaters and hoppers, enhancing the ESP performance and energy efficiency.

Basic features include integration of voltage control and rapping, and adaptive intermittent power supply for improved collection efficiency. Time-based and spectral analysis of voltages and currents helps the estimation of the dust layer thickness and resistivity, relevant for the voltage and rapping control. Adaptive rapping with simultaneous voltage profiling helps clean the electrodes and reduces particles re-entrance. Control is customized for input, middle and output zones of the ESP. Pre-arcing state detection based on the spectral analysis helps adjusting the operating regime so as to maximize the corona current without an excessive number of actual sparks. Back corona detection mechanism provides the input to the intermittent power supply, adjusting the dwell-intervals and relax-intervals in such way so as to optimize the collection efficiency. Controller provides internal data logging, providing the energy meter in [kWh] and the overall emissions meter in [mg/Nm^3 × h]. Controls can be set to provide desired number of arcings per minute, to maximize the cleaning efficiency disregarding the energy consumption, or to keep the emissions on the legal threshold, saving on the power consumption.

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II. Coordinated Voltage and Rapping

Keeping track of the key variables of the ESP units installed in TENT A1 and A4 since their installation, it has been found that the key requirement for the filtering efficiency is the proper operation of the input zone. The input zone of the ESP collects major part of the flying ashes weight. Collected particles are mostly of a larger diameter. Roughly speaking, the input zone collects the particles with D > 10-20 μm, accounting for more than 80% of the overall weight. Flue gas exiting the input zones caries small particles (D<10 μm) to middle zones.

Low sulfur coals in Serbia are highly resistive. Thick layers of the collected dust are highly resistive. Therefore, the spatial electric current (*electric wind*) causes significant voltage drop within the dust layer. As a consequence, resulting electric field keeps the dust sticky and presses the dust layers against the collection plates. In such conditions, rapping does not provide for the complete cleansing of the plate, and it has to be repeated more frequently. On the other hand, frequent rapping contributes to mechanical wear of the filter and increases the particle re-entrance into the gas stream.

A. Solution: Adaptive Rapping with Simultaneous Voltage Control

ESP controller [4] tracks the voltage and current waveforms during the ON pulses of the intermittent power supply, as well as during the OFF intervals. Their time change and spectral characteristics comprise sufficient information for determining the thickness of the dust layer. Hence, the rapping can be performed when really needed, avoiding in such way the unnecessary rapping instances, inherent to conventional, pre-programmed rapping sequences.

Prior to rapping, the last OFF interval of the intermittent power supply is extended, in order to relax space charges and have the dust layers ready to be detached from the plates.

As the rapping of the input zone collection plates begins, certain small voltage is re-applied, in order to reduce the particle re-entrance into the gas stream during the rapping interval.

Whenever mechanical construction of the filter allows, the rapping hammers hitting individual plates should be phase shifted, in order to avoid simultaneous rapping of all the plates at the same instant.

B. Resistivity and the Rapping Frequency

There is no fixed threshold for the dust layer thickness that will trigger the rapping. Namely, the ESP unit increases the rapping frequency in cases when the dust resistivity increases. This is done in order to increase the overall efficiency of the filter.

In cases with an increased resistivity, the plates withstand more or less the same voltage as they do with the normal resistivity of the dust. Yet, the spatial current (*electric wind*) is reduced, and the current density drops significantly below desirable 1 mA/m^2. Any attempt to increase the current by increasing the voltage results in sparking. When the input zone operates in such condition, collection is notably reduced, and vast quantity of dust passes in the subsequent sections, compromising the overall efficiency.

In order to alleviate the queer consequences, the rapping frequency is increased, giving in turn a reduced average thickness of the dust layers.

C. Hopper Control

The outcome of the ESP intermittent power supply is an increased quantity of dust collected in the input zones. At the same time, adaptive rapping with simultaneous voltage control provides for rather even surfaces and uniform thickness of the dust layers. All these consequences are positive, yet, there is one aspect that needs particular attention. Adaptive rapping and intermittent control do increase the quantity of ashes falling into the hopper during one single rapping session. Therefore, it is suggested the hopper be equipped with adequate number of sensors, securing a proper and timely operation of the dust removal system.

If the above measures are not fulfilled, there is an increased risk of the hopper getting full, which dramatically increases re-entrance of the collected particles into the gas stream. In some cases, even short circuits between the plates have been noted, with the short circuit current passing through the top dust layers of the over-spilling hopper.

III. Voltage Control in Middle and Output Zones

Majority of particles collected in the middle and the output zones are small particles, with the diameter D < 10 μm. When collected into the dust layer, residing on the collection plates, these small particles result in elevated resistance, which may exceed the resistance of the input-zone dust by an order of magnitude. The root cause for this is plane fact that most of the resistance, encountered by the *electric wind* current, passing through the dust, comes from the need for the charges to pass from one particle to another. Overall effect of highly resistive dust layers include back-corona, phenomenon which includes localized internal arcing with the dust layers and local heating, resulting in a number of craters, erupting the pre-heated dust back into the gas stream. Non-uniform *electric wind* and non-uniform electric field focuses toward the craters, jeopardizing the collection efficiency, annihilating the corona effects of the emission plates, and resulting in a very high re-entrance of the particles.

Solution

ESP relieves the back corona effects by the adaptive intermittent control and the proper rapping. Intermittent power supply provides the relax intervals with no voltage, their duration being several tens of milliseconds. These intervals proved to be an adequate prevention of back-corona effect. The ON dwell interval, wherein the proper voltage is applied between the electrodes ranges from several tens to several hundreds of milliseconds. With an increased resistivity of the ashes, the *electric wind* and electric field, initially homogenous, tends to deteriorate and focus towards hot spots that are being formed within the dust layer. Continued, uninterrupted power supply would give a rise to forming the craters. On the other hand, brief OFF intervals are used to relax the hot spots and insure a homogenous field at the beginning of the next ON pulse.

Although the relaxation OFF state proved useful in fighting the back corona, its extensive use over prolonged intervals of time reduces the average current density and hence, the collection efficiency. Therefore, duration of ON and OFF intervals has to be adjusted on-line, in order to suite to the best possible extent the operating regime and filtering goals.

ETF2005 controller utilizes DSP technology to decode and identify the signs of the back corona within the voltage and current waveforms. The current spectrum during the ON dwells and the voltage waveform during the relax-OFF intervals comprise sufficient information for the on-line adjustments of the intermittent power supply.

A. *Rapping of the Output Zone*

The particles re-entering the gas stream during rapping of the output zones cannot be collected further on, and they make part of the final emission, ending in the chimney.

Solution

The rapping frequency of this zone is reduced to the indispensable minimum. The need for the rapping in this zone is detected through ESP algorithm for detecting the thickness of the dust layers. When the rapping command is generated for the output zone, all and any other rapping processes are postponed, in order to avoid simultaneous rapping of the output zone and other zones. In such way, the adverse consequences of the output zone rapping are minimized.

B. *Rapping of the Emission Electrodes*

Collection efficiency relies on the abundance of ions, generated by negative corona on the emission electrodes. These electrodes get dusty as well, yet to a much lower extent. Though, even a small veil of dust increases the radius of the electrode curvature, reduces the peak values of the electric field, and diminishes the overall corona and current. Therefore, proper rapping of the emission plates proves an essential role.

Solution

Analysis of the voltage and current waveforms provides for the indication of the emission electrodes status. The need for rapping is detected and scheduled. In most cases, emission electrodes are to be rapped more frequently than the collection plates. Rapping of the emission plates contributes only a small amount of particles re-entering the gas stream. Therefore, their rapping can be made more frequent and suited to the actual needs. The rapping does increase the number of sparks per minute. Therefore, whenever possible, the rapping of emission electrodes coincides with the rapping of collection plates.

IV. High Frequency ESP Units

Conventional 50 Hz design had been predominant solution for controlling the particulate emission from large electrostatic precipitators. Although capable to reach removal efficiencies up to 99.8%, 50 Hz design suffers a number of drawbacks, leading to poor energy efficiency, very large size of electrode plates, and it cannot compete with the high frequency HFESP. Resulting voltages and currents obtained with conventional ESP units are presented in Fig. 1. Essentially, the plates are supplied with rectified 50 Hz waveform. Therefore, the voltage pulsates at a pace of 100 Hz, passing quickly the crest value and falling down into dale. Hence, the time interval when the instantaneous voltage is close to the breakdown value, leading to a rich ionization and efficient precipitation, is very short. In brief, the ESP filters only at the peaks of the voltage crest, while operating idle in between the two 10ms spaced crests.

With conventional 50 Hz design, the output DC current is discontinuous, depending on the thyristor firing angle. The input line current is therefore distorted and lagging. As a consequence, the input power factor is very poor, with a high harmonic distortion in the mains supply. Reactive and apparent power are very large, with $\cos(\varphi) < 0.65$, whilst power factor $\lambda = P/S < 0.5$. On the other hand, the HFESP high frequency supply has diode rectifier in input stage with $\cos(\varphi)$ above 0.95 and power factor above 0.75.

During the intermittent operation of conventional 50 Hz system, the ESP pulsations reflect directly to the main 6kV/0.4kV transformer, supplying the whole ESP; as the system does not have any intermediate filters or intermediate DC-link. Low frequency (3−10 Hz) pulsations introduce a flicker, mechanical stress and audible noise. These problems are resolved with HFESP, by adopting a 3-phase rectifier, turning the 3x400 V, 50 Hz main supply into a stable DC-link voltage, followed by a 10−20 kHz IGBT H-bridge.

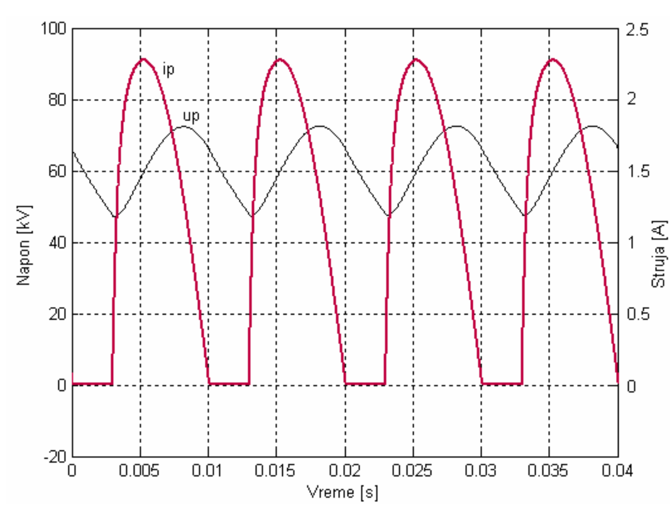

Fig. 1. Typical voltage and current waveforms obtained with a 50 Hz supplied, SCR driven ESP.

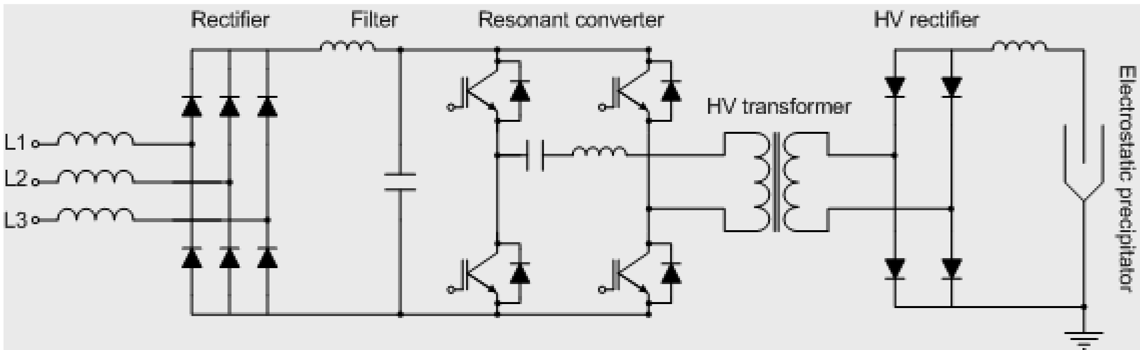

Fig. 2. High frequency ESP supply.

The efficiency of the precipitation can be increased by providing the power supply which keeps the voltage closer to the breakdown threshold over longer time intervals. With f = 10 kHz supply of the transformer, the rectified pulses at the output would be spaced 50 µs. In such case, due to a finite capacitance of the plates and the associated low pass filtering, the voltage across the plate would be almost ripple-free, without any significant crests and deeps. As a consequence, it would be possible to control the plate voltage more accurately, and keep it next to the breakdown level almost at all times.

In Fig. 3, simplified electrical schematic of the high frequency ESP supply is shown. It comprises:

- Three phase diode rectifier,
- IGBT H bridge,
- High frequency – high voltage transformer,
- High voltage, high frequency diode rectifier,
- Digital Voltage, rapping and heating Controller & Integrated PLC.

HFESP (high frequency ESP power supply and control) require a lower size and weight of electrodes, offers significant energy savings, prevents back corona, brings up a very fast reaction to flashover, results in a much higher high power factor, and has a transformer/rectifier set several times smaller and lighter compared to traditional 50 Hz design. Compared to conventional 50 Hz power supply, the HFESP package offers a significant weight and size reduction. For the ratings of 75 kV and 1000 mA, the weight of the complete system is some 300 kg, which can be installed directly on ESP roof. Notice at this point that the 50 Hz transformer only weighs over 1500 kg.

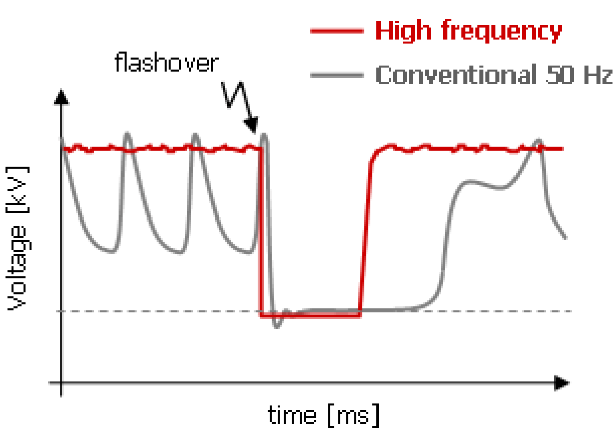

Fig. 3. HFESP reaction to the flashover.

Development and deployment of HFESP units rated 1000 mA and 2000 mA is performed at the Department of Electrical Engineering, University of Belgrade. Key element of any ESP is the proper control, allowing for the proper corona control, sufficient ionization, and the suppression of the back corona effect. Digital Voltage Controller represents the most important component of the HFESP device. It is developed on the bases of the last generation Digital Signal Processors, and comprises the proprietary adaptive algorithm of voltage control, tested at major Serbian thermal power plants and confirmed a superior particle filtering and energy efficiency performance.

Controller has a number of operating modes. One of them is the adaptive-intermittent mode of power supply. Result is energy saving and improved collection efficiency. This algorithm eliminates the back corona risks, and re-entry of collected particles. Due to adaptive algorithm of intermittent power supply, digital Voltage Controller maintains the emission under required 50 mg/Nm^3, reducing at the same time the power losses and the power consumption.

With the power supply no longer dependent on the mains frequency, the response time of the system will be shortened by an order of magnitude. The HFESP reacts in hundreds of microseconds, and it quickly minimizes the adverse effects of flashover, such as the short circuit current spikes, massive ionization, and a significant de-ionization time. As a consequence, the HFESP-controller precipitator can operate much closer to the breakdown voltage, with a very low incidence of flashover, increasing thus the particle filtering. With the HFESP high frequency supply, reaction time is below 500 µs. Conventional 50 Hz supply has the reaction time of 10 ms or more. Result is a significant improvement of precipitator performances in terms of energy saving and improving the collection efficiency.

Very fast microprocessors can provide real time parameter estimation of the DC-current spectrum, which allows back corona detection, estimation of the dust layer thickness, early corona detection and prevention of arcing. Hence, de-ionization intervals are rarely used, and the precipitation efficiency increases. DC-current spectrum content is detected through the parameter spectral estimation, leading to an ease in detecting the corona phases. At the same time, this eliminates the need for the operator to adjust the references manually in cases when the coal/fuel parameters change during the operation.

For the maximum efficiency of particle collection, the ESP needs to operate as close to the breakdown potential as possible. With the highest voltage feasible and the maximum electric field, the collection efficiency improves. The collection efficiency is proportional to the square of the applied voltage.

With conventional 50 Hz system, the breakdown occurs at the crest of rectified sinusoidal voltage half-wave. Thus, amplitude of half-wave should not cross breakdown voltage. The mean voltage is lower (maximum mean value is $2/\pi \cdot U_{max}$). Therefore, the average of the squared voltage at the ESP is roughly twice lower than the breakdown voltage squared. On the other hand, the HFESP can control the voltage with a minimum voltage ripple, keeping it close to the breakdown level where needed. Hence, as a rough estimate, the HFESP offers the high voltage on the electrodes which has the average square value twice larger than the one encountered with a 50 Hz system.

High frequency power supply has a negligible ripple, below 1%, and the mean value of voltage can achieve 98.5% of U_{max}.

V. Conclusion

From the above analysis, we conclude that the HFESP bring considerable advantage in terms of cost, precipitation efficiency, energy efficiency and weight over the conventional ESP systems, based on 50 Hz SCR control. In brief, the HFESP approach results in:

- High collection efficiency
- Significant energy savings
- High power factor
- Much lower size and weight of electrodes
- Suppression of back corona
- Early corona detection, analysis and flashover suppression
- Fast recovery from arcing and a scarce needs for power down intervals
- Flexibility and modularity.

ESP controller implemented at TENT-A offers an improved collection of fine particles, improves the energy efficiency of the ESP, benefits on coordinated control of the ESP voltage, rapping and distributed heating, includes the spectrum based flashover suppression and the back corona elimination, and comprises the adaptation mechanism with respect to the fuel parameters.

Although there has been an increasing awareness of the atmospheric pollution, the tendency to limit uncontrolled emissions from all sources has become larger. Enacted legislation is continuously reviewed and is becoming more stringent.

The new control technology for electrostatic precipitators, developed at the University of Belgrade, minimizes the atmospheric pollution problem and offers a number of side benefits. The package includes the hardware and software bases for this new ESP control technology process.

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