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Pulsed Plasma Process for Flue Gas Removal from an Industrial Incinerator by Using a Peak 200-kV, 10-kA Pulse Modulator

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The electrical discharge process, especially the pulsed plasma discharge process can be applied to the removal of pollutant gases from industrial plants such as power generation plants and incinerators. Up to now, most of the study has been performed in a laboratory scale with short-term tests due to the lack of a reliable pulse modulator with a high average power. The pulsed corona discharge method shows encouraging results for the removal of NO_x and SO_2 gases based on small-scale experiments. A 120-kW high average power modulator for industrial applications of the pulsed corona process to remove flue gas has been designed and manufactured. It is one of the largest scale modulator systems in the world for treating NO_x and SO_2 simultaneously. Its design specifications are as follows: an average power of 120 kW, a peak voltage of 200 kV with a full width at half maximum (FWHM) of 500 nsec, a peak current of 10 kA, and a pulse repetition rate of 300 Hz. It is required to have long lifetime and high reliability for commercial plant application because the downtime for maintenance affects plant availability. A high-power, fast semiconductor switch, a magnetic-pulse-compression (MPC) switch, and a fast-pulse transformer are essential components to meet these requirements. The 120-kW high average power modulator has been installed and tested at an industrial incinerator plant with a gas flow of 50,000 Nm^3/Hr. This modulator was operated with pulses of up to 150 kV with 500-nsec (FWHM) pulse widths at a 240-Hz repetition rate in a plasma reactor. This paper presents the design details and operational test results. Especially, the dynamic operating characteristics of the MPC modulator combined with the non-thermal plasma reactor were measured, and the SO_2 and NO_x removal characteristics were analyzed.

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I. INTRODUCTION

Application of pulse-power technology to environmental problems shows the possibility of meeting strict environmental standards on a more economical and smaller scale. The corona discharge system has been studied for its potential application to reduce NO_x and SO_x emissions [1]. The pulsed corona discharge process has produced encouraging results for the removal of NO_x and SO_2 in flue gas based on small-scale experiments [2–4]. In our previous experiments for the simultaneous removal of SO_2 and NO_x in the flue gas from an iron-ore sinter plant, we demonstrated and evaluated the possibility of using this process [5]. One of the early experiment by Neau *et al.* used an ∼250-kV high voltage with very fast-rising, repetitive, short pulses (200 ns to 500 ns) [6]. These parameters cannot be readily achieved with standard pulse generators using switches, such as thyratrons or spark gaps. Magnetic Pulse Compression (MPC) is the only solution to obtain repetitive, short, high-power pulses. The MPC scheme using a saturable reactor together with pulse capacitors is a useful technology for shaping input pulses into narrow output pulses of much higher power. Our approach is based on the use of saturable reactors as magnetic switches in pulse-compression networks. The issues of system lifetime and reliability are major difficulties for practical industrial applications. The combination of a high-power, solid-state switch with an MPC is a suitable scheme to meet these requirements. A modulator with an MPC circuit can meet the long-lifetime and high-reliability requirements.

Recently, an average 120-kW modulator for simultaneous removal of SO_2 and NO_x was constructed and tested with a plasma reactor for a medium-size industrial incin-

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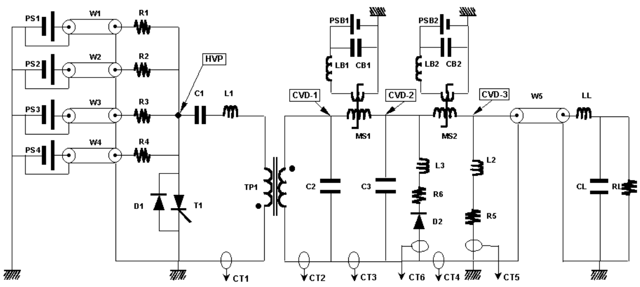

Fig. 1. Simplified equivalent circuit diagram of the MPC modulator.

erator plant. This system utilizes a two-stage magnetic pulse compressor, which can generate 150-kV pulses with 500-nsec (FWHM) pulse widths and a 300-Hz repetition rate. The plasma reactor has wire-plate electrodes and can treat a gas at 50,000 Nm^3/Hr. In the initial commissioning stage, we obtained an average output power of 70 kW at a repetition rate of 270 Hz by optimizing the compression ratio at each stage. The energy transfer efficiency of the MPC was 64.3 %. The ultimate object of this project is the realization of this process on a large scale. The detailed objectives are to generate an intense, pulsed streamer discharge by applying a higher than 150 kV voltage pulse, to reduce the power consumption required for SO_2 and NO_x removal, and to develop a reliable pulse voltage generator using an MPC. This paper describes the initial test results and the operational characteristics of the MPC modulator for an industrial incinerator.

II. SYSTEM DESCRIPTION

The simplified equivalent circuit diagram for the two-stage magnetic-pulse-compression modulator is shown in Fig. 1. It can be subdivided in several main sections, such as the DC power supply, the semiconductor switch assembly, the pulse transformer, the magnetic switching section (MS1, MS2), and the load (C_L, and R_L).

A high-voltage inverter power supply (Dong-A High-Tech) with an average power of 33 kW was developed. It provides DC high-voltage generation with 0.5 % fine regulation of the charging voltage on the capacitor C_1 and has the feature of command charging. It makes the system simple, reliable, and compact. The energy stored in C_1 is transferred to C_2 by using a semiconductor switch (T_1, and D_1) and is compressed by the MS1 and the MS2 magnetic switches sequentially. The semiconductor switch (ABB; 5SPR-26L4508-8-WC) is designed to generate pulse widths of 7 μs and peak currents of 12.6 kA at 20 kV and 300 pps. It was built with a fast thyristor based on a solid-state switch stack and consists of 8 static induction (SI)-thyristors stacked in series to generate high-power pulses. It takes advantages of a long

Table 1. Design parameters of the 2-stage MPC modulator.

Average power (kW)	120
Peak power (MW)	2000
Peak output voltage (kV)	200
Peak current (kA)	10
Pulse length (nsec, FWHM)	500
Pulse energy (J)	400-600
Rise time (nsec, 10 $\sim$ 90 %)	250
Pulse repetition rate (Hz)	300
Efficiency (%)	70
Life time (pulses)	3×10^9

Table 2. Design values of the two magnetic switches.

Parameters	MS-1	MS-2
Core flux density swing (T)	3.6	3.6
Core sectional area (cm^2)	152.4	152.4
Packing factor	0.63	0.63
Coil turns	16	4
Coil sectional area (cm^2)	366	366
Mean flux path length (cm)	94.25	94.25
Peak voltage (kV)	200	200
Volt-second (mV-sec)	1400	360
Core loss at 300 Hz (kW)	2.2	4.5

lifetime, a high reliability, and a miniaturization of components. The pulse transformer with a 1:8 turn ratio was designed using high grain-oriented silicon steel cores. During the charging of C_2, MS1 acts as an open switch until the core saturates. When the core of MS1 saturates, the circuit inductance drops down to a very small value that is equivalent to a closed switch. Then, the current flows through MS1 and charges C_3. When the core of MS2 saturates, the energy stored in C_3 is delivered to the load. Since the designed pulse generator requires a maximum peak output voltage at the corona reactor of over approximately 200 kV, the use of a pulse transformer with a 1:8 turn ratio will require only a 25-kV DC power supply and the corresponding insulation requirement in the primary circuit. The low-power DC current sources (75 V, 10 A) connected to MS1 & MS2 bias the magnetic switches and control the flux swing (ΔB) for the given core volume.

Table 1 summarizes the design parameters of the MPC modulator. The MPC circuit is designed according to the principle of Druckmann *et al.* [7], and the detailed procedures are described in the previous paper [8]. The modulator with an average power of 120-kW can generate a maximum 2-GW peak power with a 500-nsec (FWHM) pulse width. The design values of the two magnetic switches are listed in Table 2. The magnetic switch for each stage was designed using a 2605CO Metglas amorphous core (15-μm-thick, 2″-wide sheet).

Three toroidal-type cores in parallel are utilized to wind the main coils. The MS1 switch has coil windings of 16 turns. The MS2 switch with coil windings of 4 turns has three cores which are identical to the core used in the MS1 switch. The coils on MS1 and MS2 are wound with Litz wire to keep the current distributions in the cross sections of the coil wire uniform for low losses. The high-voltage components, such as the pulse transformer, the HV capacitor, and the MS switch, are immersed in transformer oil which is continuously circulated through a heat exchanger. Thermal management of losses was one of the key technical issues considered in the switch designs. Cooling channels were designed into the switches to keep temperatures within acceptable ranges.

The corona reactor can be expressed as a capacitor before the corona onset and can be represented by a nonlinear resistor in parallel with a varying capacitor [9,10]. The geometric capacitance of the reactor before the corona onset is 10 nF. In Fig. 1, L_L is the wiring inductance between the MPC modulator and the reactor load. C_L is the varying capacitance of the reactor, and R_L is the nonlinear resistance during corona development. R_1-R_4, and D_1 protect the DC high-voltage power supply from the inverse voltage. R_6 and D_2 absorb the reflected energy from the load in the case of arcing in the reactor. If the streamer corona is to be kept from transforming to an arc, the duration of the high-voltage pulse must be restricted to less than 1 μs [11]. We can make the pulse width short by connecting a resistor to the reactor in parallel. The resistor, R_5 (200 Ω), connected to the reactor in parallel has the function of reducing the voltage level after a narrow pulse current is extinguished. The inductor L_2 added to the resistor R_5 is intended for utilizing the energy effectively by minimizing loss at R_5. The inductor can restrict the current flowing through R5 until it is saturated. According to our calculation, L_2 should be about 300 μH.

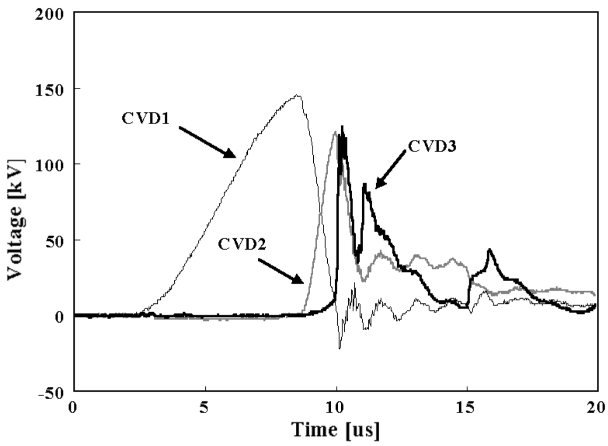

Fig. 2. Voltage waveform with commercial plasma reactor.

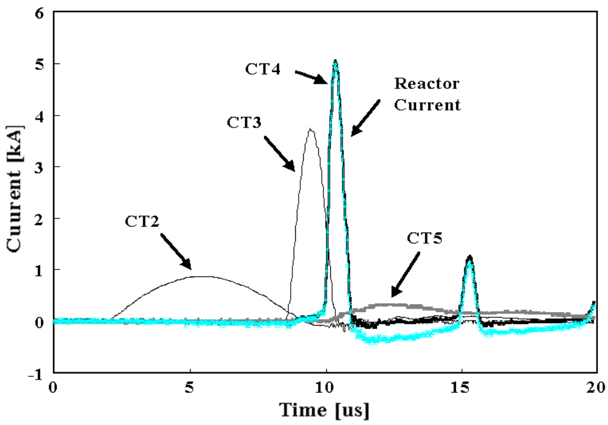

Fig. 3. Current waveform with commercial plasma reactor.

III. MPC MODULATOR TEST

The modulator was tested with the commercial plasma reactor load for an industrial incinerator plant to analyze its performance. Figure 2 shows the voltages measured at CVD1, CVD2, and CVD3 indicated in Fig. 1, and Figure 3 shows the corresponding current waveforms measured at CT2, CT3, CT4, and CT5, as well as the calculated reactor current.

The reactor current corresponds to the difference between the MS2 switch current (CT4) and the tail current (CT5). The pulse compression procedure is well represented in Fig. 2 and Fig. 3. The capacitor C_1 was charged to a voltage of 18.2 kV by using a high voltage inverter power supply. After the semiconductor switch (T_1) is closed, C_1 discharges upon C_2 with a charging time of approximately 6.96 μs, and the pulse transformer with a 1:8 turn ratio steps up the voltage to 145 kV. During this time, the first magnetic switch (MS1) holds off the current by presenting a large inductance to the circuit. It then saturates, allowing the energy to flow to C_3, which has about a 1.8-μs charge time. After the saturation of the second magnetic switch (MS2), the energy flows to the reactor load. The final load-voltage and MS2 current waveforms are those measured at CVD3 and CT4. The peak voltage and current reach up to 119 kV and 5.01 kA respectively, and correspond to a peak power level of 596 MW. The pulse width (FWHM) is about 700 ns, and the voltage rise time is about 680 ns. The 6.96-μs initial pulse generated by the semiconductor switch is compressed down to 700 nsec at CVD3. When a high voltage is applied to the discharging electrode, first, a capacitive current flows to charge the reactor. When the voltage reaches the corona onset value, a corona discharge occurs, and a corona current flows after a statistical time lag. At this time, we can observe a voltage drop caused by a reduction in the gas resistance between the discharging electrode and the grounded plate.

At a high repetition rate, even small increases in the

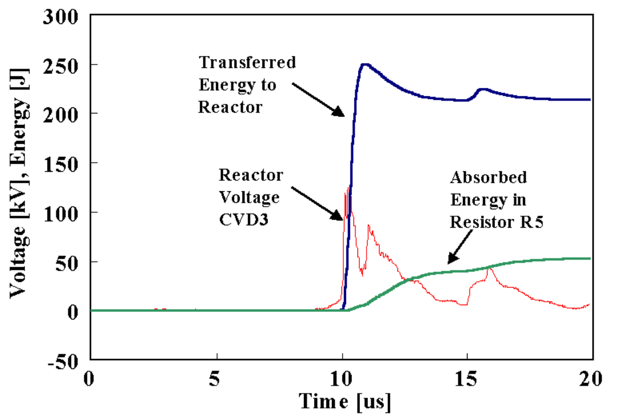

Fig. 4. Reactor and tail energy and voltage waveform with a commercial plasma reactor.

Table 3. Test results of MPC switches.

Parameters	MPC-1	MPC-2
Peak voltage (kV)	120	119
Peak current (kA)	3.8	4.95
Saturation time (μs)	1.8	0.94
Lsat (μH)	19	1.2
Peak H_c (kA/m)	63	22
Average ΔB (T)	3.45	1.65

energy efficiency are very important. The energy efficiency in the magnetic-pulse-compression loop is defined as the ratio between the accumulated energy in the final capacitor and the initial energy in the first capacitor bank. Figure 4 shows the energy transferred to the plasma reactor and dissipated at the tail resistor R_5 connected to the reactor in parallel. The energy delivered per pulse was found to be about 213.5 J by integrating the product of the voltage and the current waveforms. The loss at the parallel resistor was approximately 52.7 J due to a restriction of the current flowing through this resistor by the inductor (L_2).

When the capacitor C_1 is charged to a voltage of V_C, the stored energy can be expressed as E = 0.5 C_1 V_C^2. Since the value of C_1 is 2 μF and that of V_C is 18.2 kV, the energy stored is equal to 332 J. Therefore, the energy-transfer efficiency of the MPC modulator becomes 64.3 % (213.5 J/332 J). The energy-transfer efficiency of the main switch was calculated as 85 %. The loss at the parallel tail resistor was 15.8 %. The other loss dissipated in the MS switches, the series equivalent resistor, etc. was estimated to 4.9 %. Actually, the high-voltage inverter power supply also has some loss in power conversion. Considering this loss, the overall energy-transfer efficiency from the wall plug to the reactor load was around 64 %.

The B-H curve of each magnetic switch can be obtained using the voltage and current waveforms. Figure 5 shows the B-H curves of the MS1 & MS2 switches.

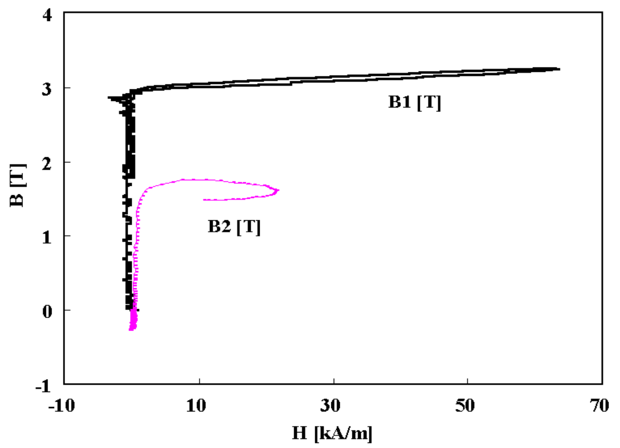

Fig. 5. B-H curves of the MS1 & the MS2 switches.

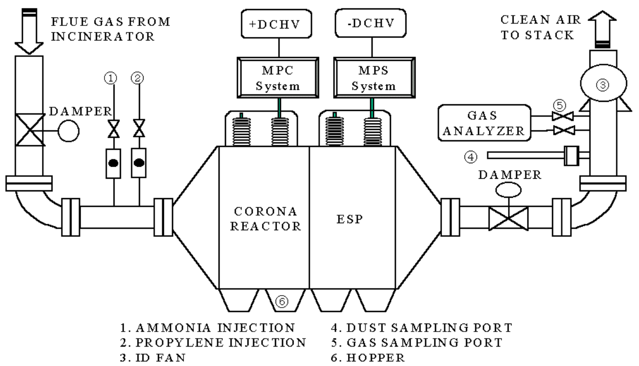

Fig. 6. Schematic of the corona discharge reactor and the electrostatic precipitator for an industrial incinerator plant.

Test results for each switch are summarized in Table 3. The average magnetic flux density swing, ΔB, is 3.45 T for MPC switch 1 and 1.65 T for MPC switch 2. At the same magnetic core saturation level of 3.6 T, the ΔB's are different due to the different insulation gap between winding and core, and the different winding turns. The peak coercive field strengths, H_c, are larger than 63 kA/m and 22 kA/m, respectively, so they are enough to guarantee full saturation of cores. The saturated inductance for MS1, $L_{1,sat}$, is 19 μH, and the saturated inductance for MPC-2, $L_{2,sat}$, is 1.2 μH. These values do not include the stray inductance of the inter-connecting wiring between the magnetic switches and other circuit components. A little bit earlier saturation is better to get higher pulse efficiency, so the saturation time of the switch core is adjusted to be smaller than the transfer time of the switch located at the front section.

IV. DE-NO$_x$/DE-SO$_x$ EXPERIMENT

The MPC modulator was operated with a corona discharge processing reactor. Figure 6 depicts the schematic

Table 4. Main parameters of pulsed corona reactor.

Gas flow rate (Nm^3/hr)	50,000
Gas velocity (m/sec)	1.2-1.4
Gas temperature (°C)	193
GP (Gas Passage) number	11
GP size, W × H × L (m^3)	3.2 × 6.2 × 4.5
Total wire length (m)	480
Wire diameter (mm)	10
Distance between plates (cm)	300

of the pulsed corona reactor and electrostatic precipitator installed at an industrial incinerator plant. The reactor is composed of two series reactors. The first is the pulsed corona reactor (PCR) to remove SO_2 and NO_x, and the second is the electrostatic precipitator (ESP) to collect products such as ammonium sulfate and ammonium nitrate. The PCR and ESP use a positive pulsed voltage and a negative DC voltage, respectively.

The main parameters of the corona reactor are shown in Table 4. This reactor is designed to be able to treat a flue gas flowing at 50,000 Nm^3/Hr from the incinerator. The reactor structure is identical to a typical electrostatic precipitator. The PCR has eleven gas passages composed of twelve discharging electrodes per frame and eleven collecting plates. The diameter of the discharging wire is 10 mm. The height and the length of each collecting frame are 4096 mm and 3964 mm, respectively, and the spacing between the grounded plates is 300 mm. The calculated geometric capacitance of the reactor is approximately 10 nF.

The positive high-voltage pulse applied to the discharging electrode induces a streamer corona discharge that rapidly grows toward the grounded plate. The voltage required to produce the pulsed plasma depends on the two electrodes and the pulse duration. The energy in the plasma is used to produce radicals that decompose the pollution molecules [12]. Free electrons gain energy from an imposed electric field, and during their drift, they lose energy through collisions with neutral gas molecules, such as O_2, N_2, and H_2O. Chemically active species, such as O, OH, HO_2, and O_3, can be formed from the electron-molecule collisions, and they can convert SO_2 and NO_x into sulfuric acid and nitric acid [9, 13]. The sulfuric acid and the nitric acid can be neutralized by the ammonia usually used in the pulse corona discharge process. In such a case, ammonium sulfate and ammonium nitrate, respectively, are obtained as the final products of SO_2 and NO_x removal.

Figure 7 shows the SO_2 and the NO_x removal characteristics. The concentrations of SO_2 and NO_x (sum of NO and NO_2) in the flue gas at the inlet and the outlet of the reactor were analyzed by using a gas analyzer. The actual flow rate of the flue gas was 42,000 Nm^3/h at 170 °C. The energy density, defined as the ratio of the power to the flue gas flow rate, was 1.4 Wh/Nm^3

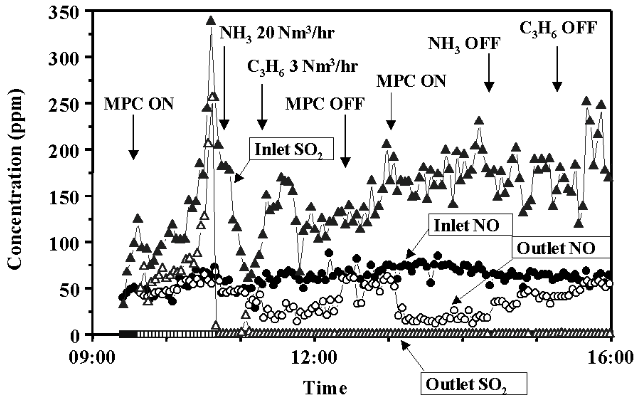

Fig. 7. SO_2 and NO_x removal characteristics for various ammonia (NH_3) and propylene (C_3H_6) concentrations.

on the basis of the discharging power. To improve the removal efficiencies for the SO_2 and NO_x, we used ammonia (NH_3) and propylene (C_3H_6) as chemical additives. The role of C_3H_6 in NO_x removal is well described in a previous study [14]. C_3H_6 was found to be very effective in enhancing NO_x removal. The concentrations of NH_3 and C_3H_6 used as additives were 370 ppm and 55 ppm, respectively. In this experimental condition, the input SO_x concentration of 100-120 ppm was decreased to 0 ppm, which is equivalent to an SO_x removal efficiency of about 99 % on the basis of the initial concentration. An input NO_x concentration of 70-75 ppm was decreased to 20 ppm, which corresponds to a NO_x removal efficiency of 70 %. The NO removal efficiency is greatly improved by using the proper amount of a C_3H_6 additive. A constant NH_3 injection may cause problems of slippage or degradation of the removal efficiency because the SO_x and the NO_x concentrations are changing during the actual process. In normal operation, the concentrations of the additives (NH_3 and C_3H_6) will be automatically regulated, following actual SO_x and NO_x concentrations, to avoid problems.

V. CONCULSIONS

A MPC modulator with an average power of 120 kW has been constructed and operated with a pulsed corona discharge process reactor for the removal of SO_2 and NO_x in the flue gas of an incinerator plant. We employed a two-stage magnetic pulse compressor circuit to produce positive high voltage pulses. The tested peak voltage and current measured at the corona reactor were approximately 119 kV and 5.01 kA, respectively, equivalent to a peak power of 596 MW, which is limited by the sparking in the reactor. The test result showed that the core was well saturated and the corresponding switching function is obtained. A pulse efficiency of 64.3 % was achieved with a pulsed corona reactor load.

The SO_2 and the NO_x removal characteristics were analyzed. To enhance the removal efficiencies for SO_2 and NO_x, we found the role of chemical additives, such as ammonia (NH_3) and propylene (C_3H_6), to be very important. In a preliminary experiment, we obtained the following results: an input SO_x concentration of 100-120 ppm was decreased to 0 ppm by using NH_3 addition, and an input NO_x concentration of 70-75 ppm was decreased to 20 ppm by using C_3H_6 addition. This result corresponds to removal efficiencies of about 99 % for SO_x and 70 % for NO_x on the basis of the initial concentrations. The NO removal efficiency is greatly improved by using a proper amount of the C_3H_6 additive. Ammonia injection was very effective in enhancing SO_x removal. Although an increase in the C_3H_6 concentration gives rise to enhanced NO_x removal, it should be limited to less than 28 ppm per Wh/Nm^3 because of the C_3H_6 slip. Our goal in the test operation during the year 2003 was to demonstrate and improve the reliability of the main HV components and the MPC system for industrial application, together with a research effort to improve the pulse efficiency through an understanding of the nonlinear characteristics of the corona process parameters such as the removal efficiencies of SO_2, NO_x, CO, HCL, and dust.

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