HIGH VOLTAGE NANOSECOND PULSE DISCHARGE SYSTEM FOR REMOVING SO2 AND NOx IN FLUE GAS

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Abstract

This paper is aimed at an investigation of high voltage nanosecond pulse system used in pulse corona discharge for removing SO_2 and NO_x in flue gas from the point of veiw of applied bases. Simultaneously the scientific basis for parametric design of an efficient and reliable nanosecond pulse discharge system with smaller size、 lower cost and more pridicatable performance are described.

1. Introduction

Acid rain is one of three environmental protection problems in the world. But a economic and effective measures solved are not found so far. It is due to SO_2 and NO_x exhausted to atmosphere with flue gas by a combustion of fossil fuel . However, with the increase in demand of electric energy in economic development a exhaust of SO_2 and NO_x has been increasting year after year. According to a incomplete figures, about 160 – 180 million tons of SO_2 were exhausted to atmosphere all over the world each year. Today's "wet" scrubber used windly in the world remains several disadvantages such as higher cost, large size, complex nature of technology and big problem of disposing of the waste products. And it is not capable of removing NO_x from the flue gas. To overcome the disadvantages above mentioned, an advanced post – combustion SO_2 and NO_x controls which is called pulse corona discharge method (PCDM) has been engiging in by seveval countries recent years. This paper is aimed at an investigation of high voltage nanosecond pulse system used in pluse corona discharge for removing SO_2 and NO_x in flue gas from point of view of applied bases. At present an advanced serubber has been being developed. This kind of devices offers a series of advantages such as making the system more economical、 more reliable、 cost less、 consume less of energy and smaller size.

In nonuniform electric fiels E, a corona discharge near the area surrounding electrode with smaller radium is appeared when E comes up to a threshold value. During this process , free electrons are accelerated by E.[1] According to the calculation, electron's velocity is $[2eE\lambda/me]^{1/2}$ within a free path λ, namely electron's energy is 5 − 15ev. When molecules of flue gas are striked by these electrons a large amount of oxidizing oradicals (O、OH、HO_2etc.) can be obtained. They cause plasma chamical reactions with molecules of SO_2 and NO_x. Sulfur trioxide and nitrogen dioxide, in turn, combine with ammonia to form solid sulfates and nitrates which can be separated from the flue gas. When plasma reaction mentioned above is realized by pulse corona discharge, the energy consumption can be decreased greatly. For this reason, it will come true into practice. In theory, when operating time of pulse voltage is so short only that it is passible to gain enough euergy for free electrons not that for ions (because of small mobility) . In that case the output energy of power supply is just for electrons aeceleration. Therefore this method offer a nonequilibrium corona discharge plasma source by which electrons with 5 − 15ev can be obtained.

2. The formation of nanosecond pulse

In general situation equivalent electric circuit of gigh voltage nanosecond pulde discharge system is shown in fig. 1 in which R_1 is total resistances of circuit including resistance of spark gap Switch R (i, t), turning resistance Rc、damping resistance R_g and connect resistance R_w.

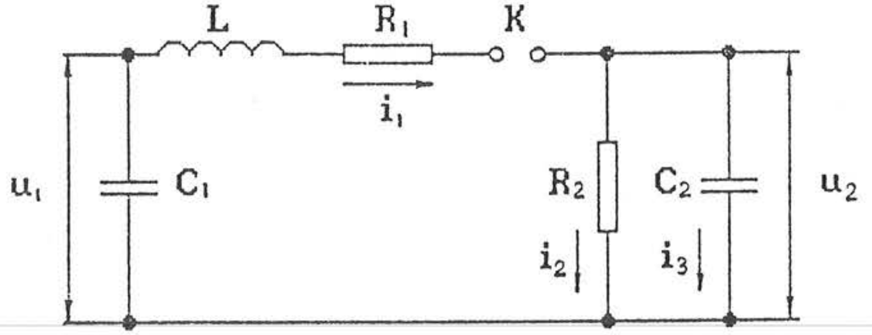

Fig. 1 Equivalent electric circuit of ns pulse discharge system

L —— Circuit total inductance
C_2—— Load capacitance
u_2 —— Load Voltage

c_1 —— Charging capacitance
u_1 —— Charging Voltage
R_1 —— Circuit total resistance

According to circuit theory, the following equations group can be obtained:[2]

$$u_1 = \frac{Ldi_1}{dt} + R_1 i_1 + u_2 \qquad (1)$$

$$i_1 = i_2 + i_3 \qquad (2)$$

$$i_1 = c_1 \frac{du_1}{dt} \qquad (3)$$

$$i_2 = \frac{u_2}{R_2} \qquad (4)$$

$$i_3 = c_2 \frac{du_2}{dt} \qquad (5)$$

solving (1) - (5)

$$\frac{d^2 i_2}{dt^2} + \alpha \frac{di_2}{dt} + \beta i_2 + \gamma \int i_2 dt = 0 \quad (6)$$

$$\frac{d^2 u_2}{dt^2} + \alpha \frac{du_2}{dt} + \beta u_2 + \gamma \int u_2 dt = 0 \quad (7)$$

where $\alpha = \frac{R_1}{L} + \frac{1}{R_2 C_2}$

$$\beta = \frac{1}{L}\left(\frac{R_1 + R_2}{R_2 C_2} - \frac{1}{C_1}\right)$$

$$\gamma = \frac{1}{R_2 C_1 C_2 L}$$

For a nanosecond pulse discharge System, the nonlinear property of resistance of spark gap switch can not be ignored generally. And from yielding radicals, R_c, R_g, R_w < < ; C_2< < can be considered. Substituting R (i, t) into expression (6) and transforming: 3

$$L\frac{di}{dt} + \frac{i}{\sqrt{\frac{2a}{pd^2}\int_0^t i^2 dt}} + R_2 i = u_1 \qquad (8)$$

$$\text{with} \quad \eta = \frac{u_2}{u_1} = \frac{R_2 i}{u_1}$$

$$\tau = \frac{t}{\theta}$$

$$\theta = \frac{2pd^2}{a u_1^2}$$

$$\Lambda = \frac{L}{R_2 \theta}$$

θ —— time constant of spark

Substituting above equations into expression (8),

$$\left(1 + \frac{1}{2\sqrt{\int_0^\tau \eta^2 d\tau}}\right)\eta + \Lambda\frac{d\eta}{d\tau} = 1 \qquad (9)$$

Solving (9), $\eta = f(\tau)$ is obtained (fig. 2) . The corresponding η value is obtained from fig. 2 by givenparameters. When pulse voltage u_2 is given, charging voltage u_1 can be obtained. It is clear that in order to enhance efficincy of power supply η value should be increased as far as passible.

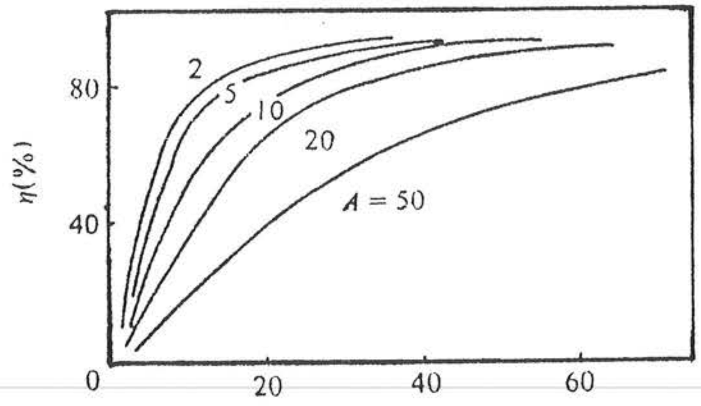

Fig. 2 Relationships between η and τ

When $0 < A \leq 20$, pluse front is given by

$$t_H = \frac{128}{27} \theta \frac{[1 - (2B)^{-1/3}]^{3/2}}{1 - \psi(A)}$$

where $B = \frac{R_2 C_1}{\theta}$

$$\psi(A) = 0.157A - 1.08 \cdot 10^{-2} A^2 + 1.7 \cdot 10^{-4} A^3$$

If $R_2 >> 2\sqrt{\frac{L}{C_2}}$, pulsewidth t_w yields:

$$t_w = 0.7 R_2 C_1$$

On the assumption that inductance of discharge circuit is neglected , the expression of $\eta = f(B)$ may be obtained by simplfication of equation (7), namely

$$\eta = \left(1 - \frac{1}{\sqrt[3]{1 + 2B}}\right)^{3/2} \sqrt{\frac{1 + 2B}{2B}}$$

The results are shown in fig. 3. In this case, the pulse front t_H is given by

$$t_H = \frac{128}{27} \theta \, [1 - (2B)^{1/3}]^{3/2}$$

The half amplitude pulsewidth t_w are:

$$t_w = 2.2\theta + 1.3 R_2 C_1 \, (B \leq 20)$$

$$t_w = 0.7 R_2 C_1 \, (B > 20)$$

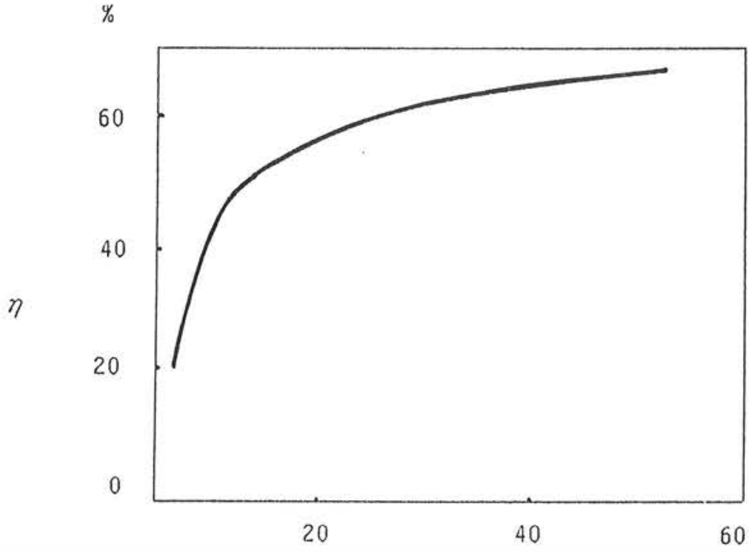

Fig. 3 Relationship between η and B

3. The electrical properties of components in discharge circuit.

(1)Resistance

$R_1$is equivalent resistance in which R_c is for turning pulse front; R_g – for sharpening pulse top distortion. When designing discharge System, selected resistances should be satisfied with following request:

- At the range of operation parameters given, the parasitic values of L_R and C_R should be made small as far as possible. When as long as L_R is much smaller than the inductances of whole discharge System, resistances in system can be considered pure resistances under circumstances of pulse current (because $u_R = Ri + L_R\frac{di}{dt}$) . After resistances values have been given by request of operating parameters, in order to reduce L_R, a linear size of resistances should be decreased as far as possible. But, in practice, the linear size can not be reduced unlimitedly. Generally, therefore, L_R value can not be ignored, particularly at high repetition frequency in nanosecond pulse discharge system. Usually metalfilm and carbon resistances are better than winding resistances.
- The sufficient thermal stability is needed during operating cycles. In order to gain higher output efficiency and remain constant pulse wave, a smaller temperature coefficient of resistance is also needed at high repetition frequency. If it is not enough for natural thermal disipation, the forced cooling form can be used.
- Skin – effect of resistance used in the system should be made smaller even more. On the basis of calculations, permeated depth of AC current in conductors is given by

$$\delta = |\rho / \pi \mu_0 f|^{1/2}$$

here ρ —— resistivity of conductor

μ_0 —— vacuum permeability

f —— frequency of current

The previous expression is obtained on the assumption that current density at depth δ is equal to 1/e times those of conductor's surface. It, therefore, can be seen that the former is about 40% of the latter. Generally, it has been considered that there is no significance in doing that the cross section of conductor keeps big size. Because of high frequency at pulse front, skin effect is intensified. This is to say that value of δ goes down and resistance goes up. After pulse front the situation is quite different. It is thus obvious that the resistance is not constant during pulse period and it is a function of frequency. Consequently, a big size of single conductor is not suitable. The better way is to use multistand conductors. At high frequency, the parasitic inductances and capacitances of conductors play an important part in discharge parameters. In this case, equivalent circuit of pulse discharge system is much similar to long travelling line with energy consumption. In practice, inductance L_0 and capacitance C_0 of unit conductor can be obtained according to shape coefficient K of resistances. If a cross section of conductors is circle , above values are given by

$$K = \frac{l}{\pi D}$$

$$C_0 = 10^{\frac{0.8}{K} - 2} \qquad (\mu\mu \mathrm{Fcm})$$

$$L_0 = 2(\ln 4\pi K - 1) \qquad (\mathrm{m}\mu \mathrm{H/cm})$$

here l —— length of conductor
D —— diameter of conductor

(2)Spark Gap Switch

There are several kinds of fast repetition frequency switches for nanosecond pulse discharge systems in which spark gap switch is still a common one in use at present. It has a short drop time of spark resistance, high withstand voltage and low inductance at high pressure. Especially three electrode trigging spark gap switch is most useful because this kind of spark gap switch has higher trigging stablity and the time delay between trigging pulse and main discharge gap operation is much small. It is most important point for a sprak gap switch with a order of ns that it has breakdown time t_K of the order of ns and small trigging dispersity.[4] The value of t_K represents the interval of spark gap voltage from ordirnary value to zero. From the point of view of discharge mechanism, t_K most depends on the time needed for development of electron avalanches in main discharge channel. In fact, the operation of spark gap switch is a gas discharge process. According to the Streamer Gaseous Discharge Theory (SGDT), the velocity of streamer development is much faster than the those of electron avalanches, For this reason, t_K can be considered as the interval needed from apperance of electron avalanches to the formation of streamer. After the formation of streamer, the resistances of spark is going down fast and spark gap becomes conducting channel rapidly. During this time the transitional properties of spark gap switch can be characterized by the relationship between channel resistance and t_K. From theoretical calculation, we have $t_K = K\theta$, from previous paragraph, the value of t_K is given by

$$t_K = 2K\left(\frac{E}{p}\right)^{-2} \cdot (aP)^{-1}$$

Thus it can be seen that to reduce t_K and develop raliability of spark gap switch the following measure should be taken:

- Increasing in value of p, namely the spark gap is kept in high pressure. This is better way for nanosecond pulse spark gap switch.
- Selecting a gas medium with big characteristic constant value of a , which only depends on gas property itself. The values of a for common gases are as follows:

Air	0. 08 − 0. 10	$(cm^2 \cdot MPa/V^2 \cdot S)$
N_2	0. 055 − 0. 065	$(cm^2 \cdot MPa/V^2 \cdot S)$
A_r	2. 0 − 3. 0	$(cm^2 \cdot MPa/V^2 \cdot S)$

The test shows that at the condition of Ar, when the pressure is 0. 1MPa, t_K goes down to the order of ns (d = 1mm). For the gases which do not have experimental results , a value can be evaluated by following expression:

$$a = \frac{e\beta e}{(3/2)KT_e + eu_i}$$

here u_i —— internal energy of ions

Te—— electron's temperature

βe — coefficient depended on electron's mobility and free path

e —— electron charge

K —— Boltzmann constant

- To reduce the start pulse voltage at trigging electrode for decreasing in trigging dispersity and increasing in trigging stability, high ε coating may be attached at trigging electrode such as barium titanate ($\varepsilon > 1000$). In this way the start pulse voltage can be almost applied to the interval between trigging electrode and main electrode because the voltage contribution is inversely proportional to the value of ε .

Under the action of nanosecond pulse voltage , spark channel can be considered as nonequilibrium electron gas, that is to say that the energies of external electric field just result in state variation of electrons and not change the state of ions. In general cases, the internal energy of spark channel should be included following parts:

- kinetic energy of atoms. ions and electrons.
- ionization energy of neutral particles .
- dissociation energy

For nonequilibrium electron gas, as transferring velocity of electron energy to heavy particles is so slow that kinetic energy can be considered to be no change during observation time. Consequently the internal energy of spark channel almost consume to ionization and excitation of particles and heating of electrons. In this condition, the internal energy of spark channel w is proportional to the value of n_e ($n_e = k_2 w$). As no energy changes between spark channel and space during nanosecond pulse discharge (without conductive and radiative energy consumption), the following expression is given by

$$iE = \frac{dw}{dt} \qquad (10)$$

To gain nonlinear resistance of spark channel R (i, t), if mobility, free path of electrons and conductivity of unit spark channel are assumed to be 、λ and σ respectively, the following expressions are given by

$$b_e = \beta_e \lambda$$

$$i = \pi r^2 n_e e b_e E$$

here $\lambda = D/p$

D —— constant

r —— spark radius

$$E = \frac{p\ i}{a\ w} \qquad (11)$$

$$\sigma = \frac{a}{p} w \qquad (12)$$

Substituting (10), (11) into (12):

$$\sigma = \sqrt{\frac{2a_1}{p}\int_0^t i^2 dt}$$

$$R(i, t) = \frac{d}{\sqrt{\frac{2a}{p}\int_0^t i^2 dt}}$$

here $a_1 = \frac{a}{(\pi r^2)^2}$

d —— gap width

(3)Capacitance

In high voltage nanosecond pulse discharge system the inductance and capacitance should be made much smaller as far as possible. Generally speaking, for the rectangle shape wire, the inductance is expressed as $L_c = \frac{l\mu_0}{3b}(3c + 2h)$. Usually wire length $l >> c, b, h$ (thickness, width and interval respectively), therefore, L_c most depends on l. Consequently, capacitors are reqursed to have small size, otherwise longer connect wire will be put in . In the light of specific conditions, the special capacitors with free inductance or low inductance may be used. In addition, if a suitable arrangement of components in circuit is installed, the total inductance can also be further reduced at the conditions of given parameters.

4. Conclusion

The main conclusions are as follows:

(1) Peak value, the front and width of nanosecond pulse most depend on pulse forming circuit parameters (R, L, C) and θ (Time constant of discharg circuit) substantially.

(2) The smaller θ, the better we can get higher pulse amplitude, gradient and narrow pulse width.

(3) When the spark gap switch operates at higher pressure, the satisfactory performance in discharge system can be obtained.

(4) When the inductance in discharge circuit is small , pulse front depends inversely as the working pressure of spark gap switch (remain constant pd) .

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