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# Control of an ozone generator—theory and practice

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**Abstract.** The process of ozone generating using 'silent' or 'barrier' discharges is described and analysed. Based upon conclusions from the analysis, a voltage control circuit is described which utilizes two IGBTs as switching devices with associated control circuitry. The circuit so developed has been used to control the output from a 50 g h$^{-1}$ commercial ozone generator.

**Keywords:** ozone generation and control, power electronics, high-voltage engineering

## 1. Introduction

Ozone, the triatomic form of oxygen, is finding increasing application in a large number of industries as a bactericide and a bleaching agent. Ozone, when used in the treatment of potable water, is reported as being 100 to 1000 times more effective at eradicating *E. coli* than the traditional, less environmentally friendly, disinfectants such as chlorine and chlorine dioxide. Potentially dangerous contaminants such as cryptosporidium and coliform bacteria which can cause severe intestinal illnesses are also effectively dealt with. However, ozone is highly unstable, readily reverting, particularly in the presence of organic compounds, to the benign form oxygen, and therefore the gas cannot be easily stored; consequently it is normally generated at point of use. This instability, though in one sense inconvenient, is essentially why the gas is environmentally preferable.

The most common method of ozone generation is to produce an AC corona discharge in a gap bounded by metallic electrodes and containing at least one solid dielectric barrier. This procedure was first proposed by Siemens in 1857 [1] and has been considerably studied [2–5] particularly in recent years in a quest for a higher generation efficiency. A cylindrical geometry is normally used although planar electrode systems have been developed. A typical arrangement is shown in figure 1. The gas gap is usually around a few millimetres and the feed gas, air or oxygen, is passed longitudinally along the gap.

One of the requirements of any ozone generator is a facility for varying the ozone concentration in the exit gas. To fully understand how this may be achieved in practice, it is necessary to consider, in some detail, how the ozone generator operates and the various parameters which affect the ozone generation rate.

## 2. Analysis

Consider a simple parallel plate arrangement as shown in figure 1 and let the dimensions of the gas gap and the dielectric layer be $d_g$ and $d_d$ and their relative permittivities be 1 and $\varepsilon$ respectively. If the voltage applied to the gas/dielectric combination is $V$ then the electric fields in the gas gap and dielectric layer $E_g$ and $E_d$ are $V/k_g$ and $V/k_d$ respectively, where

$$k_g = [d_g + (d_d/\varepsilon)] \qquad k_d = (d_d + \varepsilon d_g).$$

To indicate practical values for $k_g$ and $k_d$, consider a typical ozone generator in which the gas gap and dielectric layer are both around 1.5 mm and the dielectric material, often made of glass, may have a relative permittivity of 3. Thus $k_g$ is around 2 mm and $k_d$ around 6 mm giving, for an applied voltage of say 5 kV, an electric field of 2.5 kV mm$^{-1}$ in the gas gap and 0.85 kV mm$^{-1}$ in the dielectric.

The above analysis, which represents simple capacitive division, is perfectly valid provided there is no electrical discharge activity in the gas gap. If the applied voltage $V$ is increased, then when the electric field in the gas gap $E_g$ achieves the breakdown field $E_i$ (around 3 kV mm$^{-1}$ for air or oxygen), discharges in the gas will occur. These are often referred to as 'silent' or 'barrier' discharges and each has a channel diameter of 200–500 $\mu$m and involves a total charge of around $10^{-10}$ C [2]. These discharges deposit electric charge onto the surface of the dielectric which is of the same polarity as that of the electrode on the other side of the gas gap. Thus, if the voltage in figure 1 were positive, then, when discharging commenced, positive charge would be deposited onto the surface of the dielectric in contact with the gas. The mobility of charge on most dielectric surfaces is low and thus, for practical purposes,

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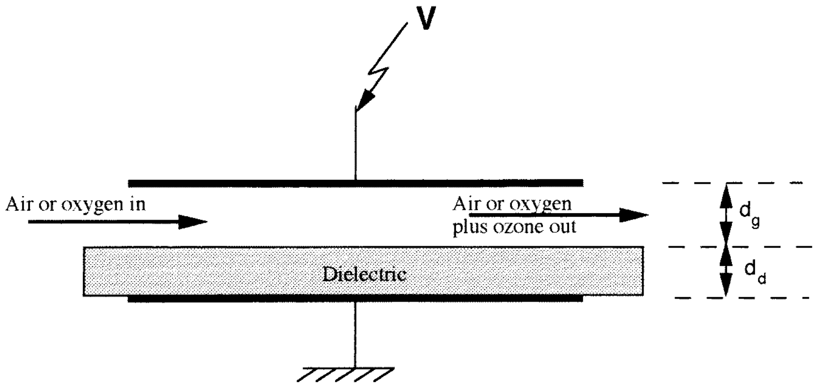

**Figure 1.** Schematic arrangement of a corona discharge ozone generator.

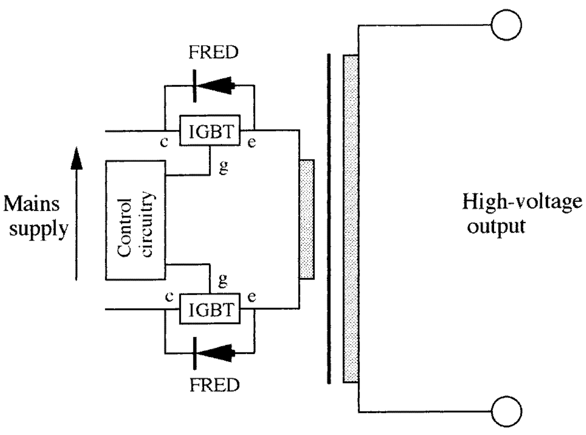

**Figure 2.** Switching circuitry.

during the time scale associated with even low-frequency voltage applications (power frequency), the charge may be considered trapped and totally immobile. The charge sets up an electric field which opposes the field in the gas gap and, clearly, discharging in the gas gap at any position will continue until such time as the gas gap field at that position has been reduced back to just below the breakdown value. Complete cessation of discharging will occur when the entire dielectric surface is covered with the required density of charge.

If the charge density on the dielectric surface is $\rho$ (C m$^{-2}$), then the electrostatic flux density $D$ in both the gas gap and the dielectric is similarly $\rho$ (C m$^{-2}$) and the resultant electric fields in the gas gap and dielectric due to this accumulation of charge are $\rho/\varepsilon_0$ and $\rho/\varepsilon\varepsilon_0$ respectively. The gas gap field, as explained above, opposes the applied field giving a resultant gas gap field $E_g$ of $(V/k_g - \rho/\varepsilon_0)$. Therefore the criterion for stability (discharge extinction) is

$$(V/k_g - \rho/\varepsilon_0) = E_i \tag{1}$$

thus

$$\rho = \varepsilon_0(V/k_g - E_i). \tag{2}$$

Ozone is generated in an electrical discharge by firstly dissociation of $O_2$ to form atomic oxygen (O) and then later three-body collisional recombination of atomic and molecular oxygen to form ozone. The dissociation stage is caused by collisions of energetic electrons with molecular oxygen and thus it is reasonable to assume that the number of ozone molecules produced in any time interval will be directly related to the number of electrons generated in the discharge during that time interval. The number of electrons, in turn, will be reflected as the total charge $Q$ collected by the dielectric. Thus the number of ozone molecules produced $N_o$ will be

$$N_o = KQ \tag{3}$$

where $K$ is an empirical constant.

The surface charge density on the dielectric is

$$\rho = Q/A \tag{4}$$

where $A$ is the total area of the dielectric surface. Thus combining equations (2), (3) and (4) we have

$$\begin{aligned} N_o &= KA\varepsilon_0(V/k_g - E_i) \\ &= K'A(V/k_g - E_i). \end{aligned} \tag{5}$$

To realize the practical significance of equation (5), if we consider a ramp voltage applied to an electrode set-up such as that described, then, as the applied voltage is increased, no discharging takes place until the breakdown field is created in the gas gap. With further increases in the applied voltage, discharging takes place but at all times is self regulating by the effect of the charge accumulation on the dielectric surface. Thus the electric field in the gas gap is limited to the breakdown field and the total number of ozone molecules generated up to any time $t$ corresponding to a voltage $V$ will be governed by equation (5). Obviously the difference between the applied voltage and the voltage across the gas gap is the voltage impressed upon the dielectric layer and this represents a practical limitation to any ozone generator since the dielectric will fail if stressed too highly.

It is important to recognize that discharging in the gas gap takes place only when the applied voltage is increasing. If the applied voltage ceases to increase, then discharging ceases and the generation of ozone ceases.

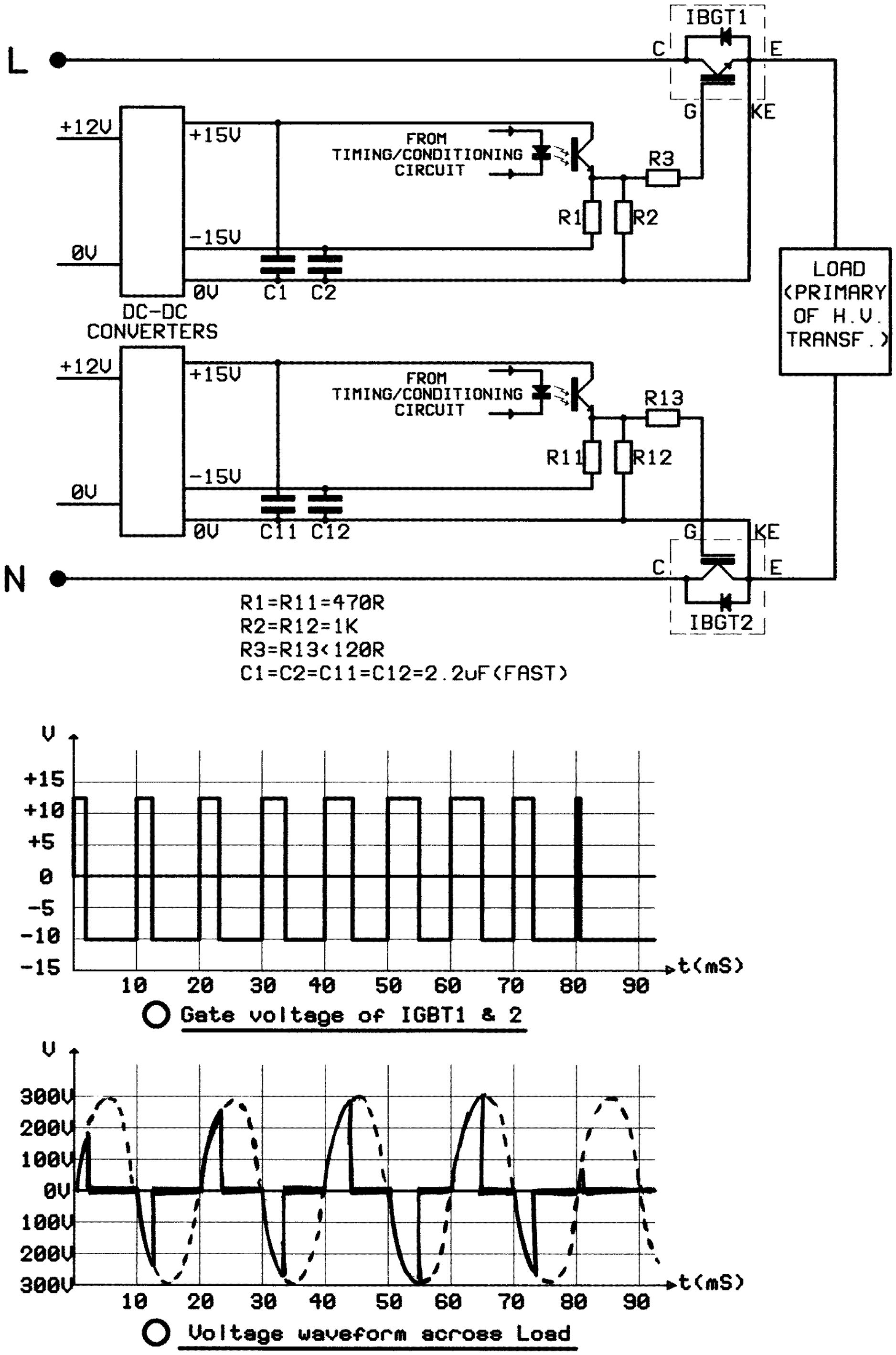

**Figure 3.** Double opto-isolator circuitry and associated waveforms of IGBT gate voltage and output voltage.

Considering now what occurs when the applied voltage is in the form of an alternating sinusoid, the same argument holds and ozone will be generated while the voltage is increasing. Again the field in the gas gap will be limited to the breakdown field and discharging will cease when the voltage ceases to increase (i.e. at voltage peak). Then the number of ozone molecules generated between the start of the discharge and the attainment of voltage peak ($V_{max}$) will again be derived from equation (5) as

$$N_o = K'A(V_{max}/k_g - E_i). \qquad (6)$$

When the applied voltage then starts to decrease, the charge on the dielectric surface produced by the earlier discharges persists and the field in the gas gap is reduced at all stages by this constant field which can be derived from equation (1) as $(V_{max}/k_g - E_i)$. Thus the field in the gas

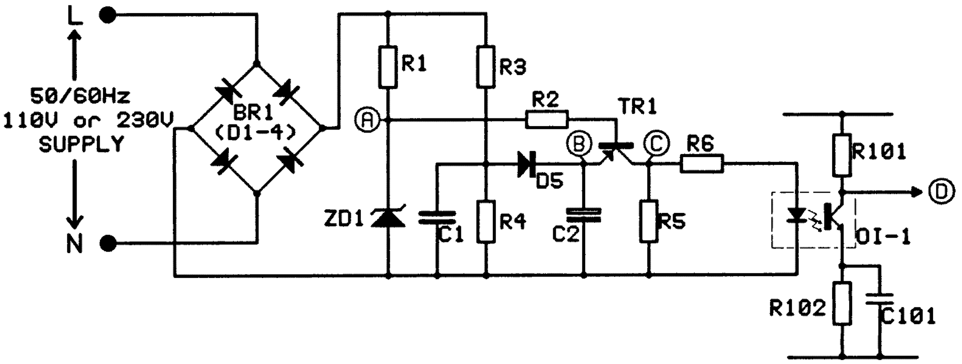

**Figure 4.** 'Zero crossing' detector circuitry.

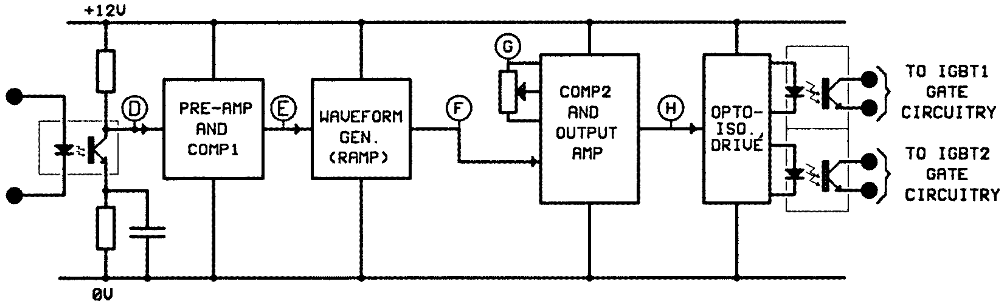

**Figure 5.** Signal conditioning circuitry.

gap $E_g$ for any instantaneous voltage $V$ will be given by

$$E_g = V/k_g - (V_{max}/k_g - E_i). \tag{7}$$

It can be seen from equation (7) that the field in the gas gap can actually become negative before voltage zero and, in fact, depending upon the relative magnitudes of $V_{max}/k_g$ and $E_i$, can even achieve the breakdown field, heralding the onset of discharges in the opposite direction, before voltage zero. When discharging commences in the opposite direction, the charge on the dielectric surface is rapidly neutralized and replaced with charge of the opposite sign and the process described above is repeated.

It can be seen then that the number of ozone molecules produced each half cycle is given by equation (6) and thus the generation rate per second is $fK'A(V_{max}/k_g - E_i)$. Replacing the empirical constant $K'$ by another arbitrary empirical constant $G$ we can then say that the generation rate $R$ of ozone in units of g $h^{-1}$ (which is the normally adopted unit) can be expressed as

$$R = GfA(V_{max}/k_g - E_i)$$

and substituting for $k_g$ in terms of the characteristics of the generator, we then have

$$R = GfA\{V_{max}/[d_g + (d_d/\varepsilon)] - E_i\}. \tag{8}$$

Equation (8) is thus a generalized equation describing how the ozone generation rate varies with variation in all the generator and supply voltage characteristics. It shows, for example, that the generation rate may be varied by variation of the frequency of the supply voltage and this method is indeed adopted in some medium- and high-frequency generators. When the supply frequency is constrained to power frequency however, the method of control is to vary the applied voltage. What is very clear from the foregoing derivation of equation (8), however, is that the actual waveform of the supply voltage is quite unimportant. What is important is simply the peak value and this observation is fundamental to the design of the voltage controller described in the following.

## 3. The voltage controller

Traditionally the ozone output in machines operating at power frequency is controlled by supplying the primary of the HV transformer via a variac which may or may not be motor driven to achieve automatic control. Apart from the expense involved, when a constant ozone concentration is required and the function of the variac is to automatically maintain that pre-selected concentration against other slightly varying parameters, then the variac is often constrained to operate over a very small range of its winding and undesirable wear can occur. This can result in failure of the variac. The philosophy behind the design of an alternative method of control is to replace such a variac by switching circuitry employing power-electronic components.

The standard 'solid state variacs' available commercially operate essentially in the same fashion as a simple

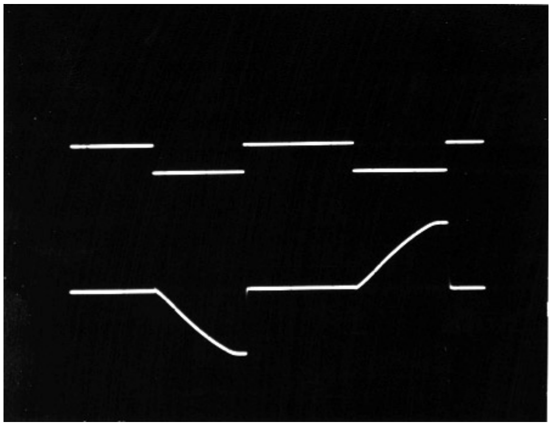

**Figure 6.** Oscillogram of IGBT gate voltage (inverted) and HV transformer output.

light dimmer or controller for small AC machines. Variation of the mean and rms voltage is achieved by switching the AC waveform 'on' at some time after voltage zero and switching 'off' at the following voltage zero using thyristors. Thus, provided switch-on occurs before voltage peak, the peak voltage is quite independent of the switch-on time and so, although varying the switch-on time will certainly vary the average or rms voltage, it will have no effect whatsoever upon the peak voltage. Thus attempts to use this form of controller have resulted in not only a lack of control of the ozone generation rate but also, since the ozone generator is predominantly capacitive, failure of the switching thyristors due to the large capacitive charging current at switch-on.

Clearly, from the above analysis, what is required is a device in which the voltage is switched on at voltage zero and switched off at a variable time on the voltage rise. Maximum ozone generation will then occur when switch-off coincides with the peak voltage of the AC waveform (i.e. 5 ms).

Switching off during conduction cannot be achieved using thyristors, and gate turn off devices, in general, require unacceptably large control currents. The most attractive device for the present application is the insulated gate bipolar transistor (IGBT) which can easily be switched out of conduction and, since the input is effectively a FET, is voltage as opposed to current driven. The circuit which has been designed to fulfil the above function relies on two IGBTs each with in-built fast recovery epitaxial diodes (FREDs) arranged as shown in figure 2.

The function of the control circuitry is to detect voltage zero and apply a positive signal for a given time duration to the gate of the respective IGBT. In reality the same signal can be applied to both IGBTs since one of them will always be reverse biased and will not conduct. However, since one IGBT will always be operating at line voltage, and the other at neutral (zero) voltage, the gate switching has to be effected via a double opto-isolator as shown in figure 3. Figure 3 also shows a waveform of the gate voltage applied to the IGBTs as that voltage duration varies in the range zero to 10 ms, and the resultant output voltage to the HV transformer primary. In the circuit of figure 3 it must also be borne in mind that when each IGBT is switched into and out of conduction a significant short duration current is required to charge the Miller capacitance within the IGBT. Therefore, to effect rapid switching, the capacitors $C_1$, $C_2$, $C_{11}$ and $C_{12}$ in figure 3 must be fast discharge types such as polyester or ceramic.

The voltage zero detector circuit is as shown in figure 4. Standard IC voltage zero detector chips are available commercially but these tend to be very sensitive to voltage and require considerable circuit modification if the voltage is changed. The advantage of the system developed in the present work is that it operates successfully over a wide range of input voltages without the need for adjustment of component values. It operates by firstly full-wave rectifying the mains voltage and applying the output to a zener diode/resistor combination. The voltage across the zener diode, which is essentially a flat-topped pulse with a short-duration fall to zero each 10 ms, is then applied to the base of a transistor, the emitter of which is supplied from the smoothed and divided output from the primary rectifying stage. Thus the transistor conducts only for a very short period around voltage zero and its collector voltage is then applied to a photodiode in an opto-isolator which acts as a buffer between the zero detector stage and the conditioning circuit.

The conditioning circuit is shown in figure 5. The output from the opto-isolate (D) which is a negative-going spike superimposed upon the 12 V line voltage, is fed to a preamplifier and comparator, the output from which (E) is designed to be a 100 $\mu$s pulse of 12 V occurring at each voltage zero. This signal triggers a ramp generator the output from which (F) is compared in a second comparator with a DC control voltage whose limits are arranged to correspond to an output from the comparator varying between zero and 5 ms. This output pulse (H) is then applied to the double opto-isolator shown in figure 3.

One further very important requirement must be mentioned. The positive/negative 15 V rails from which the IGBT gate voltages are derived (figure 3) must be energized before the application of a power-frequency voltage to the IGBTs. Otherwise the IGBT could be initially supplied whilst it was in the potentially conducting state. Depending then upon the point on the wave at which switch-on occurred, an unacceptably high charging current could result. Therefore in the designed circuit, it is arranged that a control voltage is first applied to the controller. This effectively energizes the 15 V rails and ensures that both IGBTs are clamped off. After some time delay, the main voltage is applied. In practice, this proved to be no inconvenience since the ozone units to be controlled operated upon a basis of a primary voltage being established some seconds before full switch-on. This primary voltage was then adopted as the input to the control circuitry.

Figure 6 shows simultaneous traces of the voltage applied to the photodiode of the opto-isolator shown in figure 3 (negative-going) and the open-circuit output from the HV transformer. In practice when the output is applied to the ozone generator, considerable smoothing of the waveform is observed due to inductive effects. Standard R/C snubbers are connected across each IGBT.

## 4. Field trial

The circuit described has been used to control the output from a commercial 2 kV A ozone generator generating at up to 50 g $h^{-1}$. The degree of control achieved was superior in terms of sensitivity to that found using the standard variac method, particularly at very small generation rates. It was found possible, using this form of controller, to maintain a stable ozone concentration, as measured on a conventional UV absorption meter, to within the sensitivity of the meter (i.e. 0.1 g $m^{-3}$).

A further spin-off advantage of this type of controller which was not intended as part of the design philosophy but was recognized when the device was put on test is that, provided the output voltage is not allowed to extend beyond the peak value (5 ms), no transformer inrush current can be produced at switch-on which is constrained to be at voltage zero and so soft starting is not necessary.

In many ozone generation systems, it is necessary to produce a pre-set ozone concentration in the exit gas against the naturally occurring variables such as supply voltage peak, frequency and gas flow rate. Using the variac control method previously described, this is achieved by setting an upper and lower limit from a 4–20 mA REDOX monitor and allowing the motor-driven variac to hunt between the two extremes with appropriate delays built into the control circuitry. In reality this is quite a crude control method and it is clear that, using the present circuit, the REDOX output could be used directly through a current/voltage converter to provide the input to a further comparator, the output from which could supply the variable voltage required in comparator 2 in figure 5. In this way simultaneous and precise control would be achieved.

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