Interconnected operation of the ozone generator with the power supply unit

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Abstract. This article is addressed to the inductivity of the feeder transformer influence on of the plate-type ozone generator operating modes. The equation characterises the ozone generator interconnected operation with the transformer, in discharge and non-discharge modes is represented. Use of the near-resonant mode of operation is proposed with a view to reach maximum output capacity. With that end in view, it is proposed to use the transformer with higher inductance. Oscillograph charts of two modes of operation of the ozone generator are analysed. Current waveform factors are determined by the harmonic analysis method. Experiments proved that current waveform factor increase in value for the account of continuous discharge is conductive to increase of ozone output by 25-30 % and power loss reduction by 10-15 %.

1. Introduction

High-capacity ozone generators are widely used in various branches of industry, in the water preparation, treatment, disinfection and deodorization. High technologies are applied in the ozone generator, which consists of ozone generator, air treatment unit (drying and cleaning), ozone generator power supply unit with regulating equipment, ozone with water (air) mixing unit and accessories. At present, extensive studies of ozone use in various branches of agricultural production are conducted: storage of agricultural production, controlled environment in livestock farm and poultry-farm premises, premises and containers treatment, desinsection and deratization [6, 9, 20]. Distinctive feature of these consumers is regular need in small doses of ozone. Therefore, the generators with plate electrodes are applied therein instead of bulky and expensive traditional ozone generators (with tubular electrodes and forced cooling). Design of such units is plain and consists of: plate-type ozone generator, small-scale compressor and power supply unit (high-voltage transforme). Ozone generator capacity is 100-300 W. Taking into consideration that ozone generator capacity is comparable with the feeder transformer (НОМ -10, 20), the necessity of accounting of transformer parameters influence over the ozone generator operation mode. By now, no data on interconnection operation of the ozone generator with plate electrodes and transformer are available in the literature by now. Accounting of influence of transformer inductivity over duration of discharge and non-discharge periods in the generator inductivity is of especially great scientific-and-practical interest [1, 13, 16].

2. Materials and Methods

Research has been carried out with use of the specialised bench, which consists of the plate-type ozone
generator, air blower (compressor), the laboratory auto-type transformer (ЛАТР) and voltage transformers HOM -10 and HOM - 20. Voltage was measured the low-voltage side - with the voltmeter 250 V, and, on the high-voltage side - with the kilovoltmeter 35 kV. Current was measured at the low-voltage site - with the amperemeter 1 A, and at the high-voltage side - by means of the current divider - with the milliamperemeter 100 mA. Ozone concentration was determined by iodimetric titration, and air flow rate - with the variable area flow meter PC-5. Dynamics of current variation was registered by means of the oscillograph recorder of type C 1-90. Harmonic analysis was carried out by the corresponding procedure. The outcomes are processed by mathematical statistics method [4, 11, 18].

3. Results and Discussion

The classical ozone generator theory, as an electric apparatus, it represented in the work of Yu. V. Filippov. It is based on representation of the ozone generator in the form of equivalent electrical circuit. Prior-to-discharge period is represented in the form of capacities of dielectric barriers connected in series and air gap capacity. During the discharge period, the air gap capacity is replaced with constant electromotive force source owing to gap voltage constancy within the period [1, 2, 10, 17].

Using equivalent electrical circuits Yu. V. Filippov has determined the current and voltage variation laws on components of the ozone generator, and has constructed corresponding time based historical graphs (Figure 1). Here, during the initial period/interval 0, the barrier voltage and discharge area are increased along with increase of the main voltage. During the discharge/interval the air gap discharge and current step occur at reaching the interval \( V_n \) of the burner voltage value. Further, amperage is determined only by the rate of voltage variation on the barriers of the ozone generator. Voltage in the discharge gap remains constant [1].

At the plate-type ozone generator operation in the discharge mode, the transformer inductivity influence over discharge process is increased. Moreover, magnetic losses increase in the transformer - ozone generator circuit. The need of mathematical description of interconnected operation of the ozone generator and power supply unit arises [5, 7, 15].

Operation of actual transformer is characterised by the following set of equations:

\[
U_1 = r_1 i_1 + L_{21} \frac{dt_2}{dt} + M \frac{dt_3}{dt}
\]

\[
U_2 = -r_2 i_2 + L_{22} \frac{dt_2}{dt} + M \frac{dt_3}{dt}
\]

(Figure 1. Schedule changes in current, network voltage, barrier and gap)
Where:
- \( r, r_2 \) - true resistances of primary and secondary windings of the transformer;
- \( L_{11}, L_{22} \) - according to inductance of primary and secondary windings of the transformer;
- \( M \) - mutual induction of windings;
- \( V_1, V_2 \) - according to the primary and secondary windings voltage.

The methodology of A. I. Voldek [2] is used for investigation of the transformer with capacitive load operation. The equations, characterising interconnected operation of the transformer with the ozone generator, have been received upon some system conversions.

\[
U_1 = r_1 i_1 + \frac{x_1}{\omega} \frac{di_1}{dt} + \frac{x_{12}}{\omega} \left( \frac{di_1}{dt} + \frac{di_2'}{dt} \right)
\]

\[
U_2' = -k^2 r_2 i_2' - \frac{x_{12}}{\omega} \frac{di_2'}{dt} + \frac{x_{12}'}{\omega} \left( \frac{di_1}{dt} + \frac{di_2'}{dt} \right)
\]

As operation of the transformer with the commensurable capacity load is considered, the value of magnetic losses should be taken into account. Having designated it as the true resistance \( r_m \), we can calculate the magnetizing circuit impedance.

\[
Z_m = \sqrt{r_m + x_m^2}
\]

Where \( x_m = x_{12}, r_m = x_{12}'/r_{mg} \)

\( r_{mg} \) - resistive loss true resistivity is equal to:

\[
r_{mg} = \frac{U_{12}^2}{P_{mg}} = \frac{E_1^2}{P_{mg}}
\]

Where:
- \( P_{mg} \) - magnetic circuit iron loss.

In consideration of the foregoing, \( x_{12}' \) is replaced in the system (2) with the value of total losses in magnetic circuit \( Z_m \)

\[
U_1 = r_1 i_1 + \frac{x_1}{\omega} \frac{di_1}{dt} + Z_m \left( \frac{di_1}{dt} + \frac{di_2'}{dt} \right)
\]

\[
U_2' = -k^2 r_2 i_2' - \frac{x_{12}}{\omega} \frac{di_2'}{dt} + Z_m \left( \frac{di_1}{dt} + \frac{di_2'}{dt} \right)
\]

System (3) corresponds to the equivalent electrical circuit, shown in the Figure 2.

**Figure 2.** Equivalent electrical circuit of the transformer and ozone generator taking into account magnetic losses

During the prior-to-discharge period, voltage in the ozone generator is expressed through the formula (4):
Accordingly, we shall receive from (4), for the prior-to-discharge period:

\[
U_1 = r_1 i_1 + \frac{x_1}{\omega} \frac{di_1}{dt} + \frac{Z_m}{\omega} \left( \frac{di_1}{dt} + \frac{di_2}{dt} \right)
\]

and during the discharge period (5):

\[
U_2' = \left(\frac{1}{C_{gn}}\right) \int i_2' \, dt
\]

\[
U_2 = \left(\frac{1}{C_{gn}}\right) \int i_2' \, dt + i_2' r_n
\]

The transformer-ozone generator system during the discharge period is described by the equations:

\[
\frac{1}{C_{gn}} \int i_2' \, dt + i_2' r_n = -k^2 r_2 i_2' - \frac{x_{12}}{\omega} \frac{di_2}{dt} + \frac{Z_m}{\omega} \left( \frac{di_1}{dt} + \frac{di_2}{dt} \right)
\]

\[
U_1 = r_1 i_1 + \frac{x_1}{\omega} \frac{di_1}{dt} + \frac{Z_m}{\omega} \left( \frac{di_1}{dt} + \frac{di_2}{dt} \right)
\]

\[
\frac{1}{C_{gn}} \int i_2' \, dt + i_2' r_n = -k^2 r_2 i_2' - \frac{x_{12}}{\omega} \frac{di_2}{dt} + \frac{Z_m}{\omega} \left( \frac{di_1}{dt} + \frac{di_2}{dt} \right)
\]

**Figure 3.** Oscillograph chart of the ozone generator operation with no-current condition.

**Figure 4.** Oscillograph chart of the ozone generator operation in the continuous discharge mode.
The solution of the system of linear equations (6) and (7) is highly complicated. Here, there are 2 modes of operations of the ozonation system: prior-to-discharge and discharge. Moreover, resistance of the air gap and the dielectric barrier are non-linear. To reach the maximum output of ozone, it is proposed in [3] to use the voltage resonance condition at \( X_L = X_C \). However, the dielectric barrier is made of a glass that, in the resonance condition, may lead to current sharp increase and the dielectric barrier disruption. The near-resonant mode is applied in our study. Thus, the current curve form factor should not be less than 0.9 [4,8,19]. Taking into account that transformer inductance may lead to extension of the discharge duration, we have accepted the transformer HOM-20, which inductance is twice more than of the HOM-10, which has been used earlier. The harmonic analysis of oscillograph charts is used for evaluation of the current curve behaviour (Figures 3 and 4).

According to the oscillograph charts received, there are the current curve plateaus in the mode with no-current condition (Fig. 3) that is characteristic for electric induction current (no-discharge). Discharge continuity (fig. 4) is maintained at the expense of additional increased inductance of the transformer HOM-20, which supports the value of the voltage of the discharge gap \( U_n \) at the moment of discharge re-ignition. For the account of increase of the self-induced electromotive force of the feeder transformer, the instantaneous re-ignition of the ozone generator is occurred [10, 14, 16].

The oscillograph chart of the current of the ozone generator in normal operation mode is shown in the Figure 3. Effective current value is \( I = 25.6 \) mA.

The non-sinusoidal current can be represented in the form of the Fourier series for determination of the current curve form factor. Symmetrically with respect to the time axis, we receive:

\[
f(x) = A_1 \sin x + A_2 \cos x + A_3 \sin 3x + A_4 \cos 3x + A_5 \sin 5x + A_6 \cos 5x ...
\]

Where:

\[
A'_k = A_k \cos \varphi_k; \quad A''_k = A_k \sin \varphi_k
\]

For analysis, the half-cycle should be broken down into 28 sections:

\[
A'_k = \frac{2}{n} \sum_{l=1}^{56} l \sin k\alpha = \frac{4}{n} \sum_{l=1}^{28} l \sin k\alpha
\]

\[
A''_k = \frac{4}{n} \sum_{l=1}^{28} l \sin k\alpha
\]

Outcomes are recorded in the Table 1.

| Harmonic number | \( A'_k \) | \( A''_k \) | \( A_k \) | \( \varphi_k \) | \( \alpha_k \) |
|-----------------|-----------|-------------|---------|----------------|-------|
| 1               | 42.18     | -31.99      | 52.90   | -0.7584        | -37°11|
| 3               | 22.58     | 25.99       | 34.40   | 1.1510         | 49°01|
| 5               | -7.85     | 10.44       | 13.10   | -1.3299        | 126°57|
| 7               | -0.40     | -1.54       | 1.59    | 3.8500         | 255°26|

Here:

\[
A_k = \sqrt{(A'_k)^2 + (A''_k)^2}; \quad \varphi_k = \frac{A''_k}{A'_k}
\]

Table 2. Outcome of the current curve in the discharge continuous burning mode

| Harmonic number | \( A'_k \) | \( A''_k \) | \( A_k \) | \( \varphi_k \) | \( \alpha_k \) |
|-----------------|-----------|-------------|---------|----------------|-------|
| 1               | 139.00    | -6.53       | 139.2   | -0.0469        | -2°41|
| 3               | 1.56      | -13.37      | 13.4    | -12.6132       | -85°28|
| 5               | -5.57     | 10.75       | 12.1    | -1.9299        | 118°23|
| 7               | 10.75     | 9.49        | 14.3    | 0.8827         | 41°26|
By analogy, the harmonic analysis is carried out for the current curve in the discharge continuous burning mode, and the outcomes are recorded in the Table 2.

Effective current values in first and second variants are equal to 25.6 and 35.8 mA, accordingly.

Current scale is determined by the procedure provided in /5/.

Let’s compute the ordinate mean square value:

\[ l_{msq,l} = \sqrt{\frac{62951}{28}} = 47.2 \text{ mm} \]

Per 1 mm of the ordinate, we shall receive:

\[ \Delta I_l = \frac{I_l}{l_{msq,l}} = \frac{25.6}{47.3} = 0.54 \text{ mA} \]

The crest factor is:

\[ K_{a,l} = \frac{I_{nl}}{I_l} = \frac{39.4}{25.6} = 1.54 \]

Based on the data in the Table 3, we shall receive:

\[ v_l = \frac{I}{\sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2}} = \frac{20.36}{20.26 + 20^2 + 13.17^2 + 5.01^2 + 0.61^2} = 0.82 \]

\[ V_l = 0.98 \]

| Harmonica | Scale, mA/mm | Crest factor, Ka | Current amplitude, mm | Effective current value, mA |
|-----------|--------------|------------------|-----------------------|---------------------------|
| Actual current | 0.54 | 1.54 | 39.40 | 25.60 |
| 1 | 0.36 | 1.47 | 52.63 | 35.80 |
| 2 | 0.54 | 1.41 | 28.57 | 20.26 |
| 3 | 0.36 | 1.47 | 50.10 | 35.53 |
| 5 | 0.36 | 1.47 | 7.07 | 5.01 |
| 7 | 0.36 | 1.47 | 0.86 | 0.61 |
|  |  |  | 5.15 | 3.65 |

Note: In the numerator - initial mode, In the denominator - continuous discharge burning mode.

Value of form factors of the current curve are received from the ratio of the first current harmonic to the sum of squares of all other odd harmonics. At constant cos \( \phi \), it leads to increase of the power factor of the ozone generator. Thus, energy losses are decreased by 10-15 %, and ozone output is increased by 25-30 %.

4. Conclusions

Set of equations, which describe interconnected operation of the ozone generator with the power supply unit, are represented. Taking into account that the ozone generator is characterised by 2 modes: discharge and non-discharge, two set of equations are provided accordingly. However, resistances of the air gap and of the dielectric barrier are non-linear. Moreover, it should be taken into account that capacity of the plate-type ozone generator is commensurable with the capacity of the feeder transformer. It may cause the transformer' iron saturation and non-linear mode of operation thereof, accordingly.
The solution of the received sets of equations is rather complicated and bulky. Taking into consideration the above, use of these sets of equations appears to be interesting for consideration of dynamics of interconnected operation and the ozone generator and power supply unit design development. Increase of ozone output and improvement of power indices of the plate-type ozone generator appear to be interesting for scientific-and-practical purposes. It is proposed to use near-resonant mode of operation of the ozone generator. Taking into consideration that transformer inductance may lead to the discharge period extension, the transformer НОМ-20, which inductance is twice more than the same of the НОМ-10 used earlier, has been used in the study.

With a view of evaluation of the current waveform behaviour, the harmonic analysis has been used. Evaluation criterion is change of the value of the form factor of the current curve, which has increased from 0.82 to 0.98. At constant cos φ, it leads to increase of the power factor of the ozone generator. Energy losses on 10-15 % Thus, energy losses are decreased by 10-15 %, and ozone output is increased by 25-30 %.

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