Analysis and Comparison Study of PWM and Phase-Shifted PWM Full-Bridge Inverter Fed High-Voltage High-Frequency Ozone Generator

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Abstract—This paper presents the analysis and the comparison study of a High-voltage High-frequency Ozone Generator using PWM and Phase-Shifted PWM full-bridge inverter as a power supply. The circuits operations of the inverters are fully described. In order to ensure that zero voltage switching (ZVS) mode always operated over a certain range of a frequency variation, a series-compensated resonant inductor is included. The comparison study are ozone quantity and output voltage that supplied by the PWM and Phase-Shifted PWM full-bridge inverter. The ozone generator fed by Phase-Shifted PWM full-bridge inverter, is capability of varying ozone gas production quantity by varying the frequency and phase shift angle of the converter whilst the applied voltage to the electrode is kept constant. However, the ozone generator fed by PWM full-bridge inverter, is capability of varying ozone gas production quantity by varying the frequency of the converter whilst the applied voltage to the electrode is decreased. As a consequence, the absolute ozone quantity affected by the frequency is possibly achieved.

I. INTRODUCTION

In recently year, ozone has been widely used for agent as the oxidant element for bleaching and disinfecting in many applications, particularly for air and water such as deodorization, drinking water purification, color removal etc., since it has an extremely strong oxidizing power, and leaves no residues harmful to the global environment [1, 2]. As an alternative method, silent electric discharge or corona effect operation by applying the high voltage to electrode tubes is widely used in generating ozone for industrial applications. The use of high frequency power supplies for ozone generation offers advantages such as an increase in the power density applied to the ozonizer electrode surface and increase in ozone production for a given surface area, whilst decreasing the necessary peak voltage [6]. The increase in the frequencies up to several kilohertz is possible with power electronic switching devices for instance Power MOSFETs and IGBTs. Consequently, the increase in the efficiency of the ozonizer, the decrease in the equipment volume and easily controlled ozone production can be achieved [4]. Low power ozone generation can be found in [4, 5]. Many converter topologies have been proposed in order to improve efficiency and reduce size [3, 7]. One of those is based on the voltage source type IGBT resonant inverter [3-12]. This technique offers soft switching, reduced losses, and electro interference (EMI) / radio frequency interference (RFI) and power control schemes such as pulse density modulation (PDM) were proposed for improving the ozone gas generating characteristics [3, 6]. However, there are a few works for comparison of the PWM and Phase-Shifted PWM full-bridge inverter fed ozone generator.

Therefore this paper focuses on the analysis and the performance comparison of the high-voltage high-frequency power supply for an ozone generation system. The PWM and Phase-shifted PWM full bridge inverter are used for the power supply. The performance of these power supplies are compared in this paper. The proposed system is able to vary ozone gas production quantity by varying the frequency of the converter.

II. CONFIGURATION OF THE PROPOSED OZONE GENERATOR

The proposed ozone generating system is shown in Fig. 1. It consists of a 1-phase full bridge diode rectifier with a DC smoothing capacitor, a high frequency PWM and phase shift PWM inverter using Power MOSFETs, a high-voltage high-frequency transformer and an electrode set. The details of these components are as follows.

1). Full bridge diode rectifier: This part converts a 220V AC mains supply to an approximately 310V DC voltage associated with the dc capacitor filter with value of 3300 μF.

2). PWM and Phase shift PWM full bridge inverter: This part uses IRFP460 MOSFET package equipped with a free wheeling diode in the body as the switching devices. It converts DC into AC voltages. PWM and Phase-shift PWM signals are controlled by a dsPIC microcontroller. The frequency of the AC output voltage is varied in a certain range to ensure that the zero voltage switching (ZVS) condition can occur for a decrease in switching loss.

![Fig. 1 The proposed system of an Ozone Generator](image-url)
3). High-voltage high-frequency transformer: The EE-80 ferrite core is used. The output voltage is stepped up and fed to electrodes for ionizing gas.

4). Resonant inductor (Ls): This component is used for reducing resonant frequency in a suitable range. The range is considered on the basis of minimized device losses.

5). Electrode set: The electrode set is designed for highly non-uniform electric field generation. The drawing is shown in figure 2 for the front and side views. The dimensions of the electrode set are \( r_1 = 2.45 \text{ cm} \), \( r_2 = 22.5 \text{ cm} \), and \( r_3 = 2.45 \text{ cm} \). The approximate permittivity value of the used dielectric glass \( (\varepsilon_r) \) is between 5 and 10, the approximate permittivity value of the air \( (\varepsilon_r) \) is equal to 1, and the electrode length is equal to 22cm. These dimension and specific permittivity values will be used for calculating the parameter values of the electrode equivalent circuit.

III. CIRCUIT OPERATION OF PWM AND PHASE-SHIFT PWM FULL BRIDGE INVERTER

A. PWM Full-Bridge Inverter

The switching patterns taking into account the dead time effect, output voltage and current waveforms of the PWM full bridge inverter are shown in Fig.3 for a ZVS condition. The dead time \( t_{DT} \) is used to prevent upper and lower switches of the same leg (i.e. \( S_1\rightarrow S_2 \) and \( S_3\rightarrow S_4 \)) from a short circuit failure. In order to achieve ZVS operation, the controlled frequency must be greater than the resonant frequency. As shown in Fig.3 and 4 the circuit operation corresponding to the switching patterns can be divided into 6 modes as follows.

Mode 1(\( t_1\sim t_2 \)): This mode allows the energy fed back to the dc supply from the RLC load which is equivalent to the high frequency transformer and electrode tube. During this interval, both switches \( S_1 \) and \( S_3 \) turn on. The current flows back to the dc supply via \( D_3 \) and \( D_1 \). The output voltage \( V_{AB} \) is \( +V_d \) which is the dc supply voltage. The voltages across \( S_2 \), \( C_2 \) and \( D_2 \) are \( +V_d \) and voltages across \( S_1 \), \( C_1 \) and \( D_1 \) are zero. The assumption is that the voltage across switches during turn-on is negligible. The voltages across \( S_4 \), \( C_4 \) and \( D_4 \) are \( +V_d \) and voltages across \( S_3 \), \( C_3 \) and \( D_3 \) are zero. This mode is so-called an inverting mode.

Mode 2(\( t_2\sim t_3 \)): This mode is a rectifying mode which the DC power supply provides the energy to the load. \( S_1 \) and \( S_3 \) still turn on. The current direction is opposite to that of mode 1. The current flows from the dc supply to the load via both \( S_1 \) and \( S_3 \). The resultant output voltage \( V_{AB} \) is still \( +V_d \). The voltages across \( S_2 \), \( C_2 \), \( D_2 \), \( S_1 \), \( C_1 \), and \( D_1 \) are \( +V_d \) and voltages across \( S_3 \), \( C_3 \), \( S_3 \), \( C_3 \), and \( D_3 \) are zero.
zero. After Mode 6 is complete which is a finally stage of the operation period, the cycle of the operation is repeated.

B. Phase-Shift PWM Full-Bridge Inverter

The switching patterns taking into account the dead time effect, output voltage and current waveforms of the phase shift PWM full bridge inverter are shown in Fig. 5 for a ZVS condition. Signals for switches S₁ and S₂ of the second leg are shifted away from switches S₃ and S₄ of the first leg with the phase shifted angle \( \phi \). The dead time \( t_{DT} \) is used to prevent upper and lower switches of the same leg (i.e. \( S_1 - S_2 \) and \( S_3 - S_4 \)) from a short circuit failure. The output voltage can be varied by changing a value of \( \phi \). In order to achieve ZVS operation, the controlled frequency must be greater than the resonant frequency. As shown in Fig. 5 and 6 the circuit operation corresponding to the switching patterns can be divided into 10 modes as follows.

**Mode 1 \( (t_1 \sim t_2) \):** This mode allows the energy fed back to the dc supply from the RLC load which is equivalent to the high frequency transformer and electrode tube. During this interval, both switches S₁ and S₃ turn on. The current flows back to the dc supply via D₁ and D₃. The output voltage \( V_{AB} \) is \( +V_d \) which is the dc supply voltage. The voltages across \( S_2, C_2 \) and \( D_2 \) are \( +V_d \) and voltages across \( S_1, C_1 \) and \( D_1 \) are zero. The assumption is that the voltage across switches during turn-on is negligible. The voltages across \( S_4, C_4 \) and \( D_4 \) are \( +V_d \) and voltages across \( S_3, C_3 \) and \( D_3 \) are zero. This mode is so-called an inverting mode.

**Mode 2 \( (t_2 \sim t_3) \):** This mode is a rectifying mode which the DC power supply provides the energy to the load. S₁ and S₃ still turn on. The current direction is opposite to that of mode 1. The current flows from the dc supply to the load via both S₁ and S₃. The resultant output voltage \( V_{AB} \) is still \( +V_d \). The voltages across \( S_2, C_2, D_2, S_4, C_4, \) and \( D_4 \) are \( +V_d \) and voltages across \( S_1, C_1, D_1, S_3, C_3, \) and \( D_3 \) are zero.

**Mode 3 \( (t_3 \sim t_4) \):** During this interval, S₁ turns off while as S₃ turns on. Since S₁ is turned off by the signal, the current flows through \( C_1 \). \( C_1 \) is charged from zero to \( +V_d/2 \). At the same time, the voltage across \( C_2 \) is discharged from \( +V_d \) to \( +V_d/2 \) via the load and \( S_1 \) since \( C_2 \) is connected in parallel with the load.

**Mode 4 \( (t_4 \sim t_5) \):** This mode is a free wheeling time interval. Both S₁ and S₃ turn on. The output voltage is zero. Then, the current flows through \( D_2, S_1 \) and the load.

**Mode 5 \( (t_5 \sim t_6) \):** During this mode, S₁, S₂ and S₄ turn off while as S₂ still turns on. Since S₁ is turned off by the signal, the current flows through \( D_2, C_3 \) and the load. \( C_3 \) is charged from zero to \( +V_d/2 \).

Fig 6. Overall operating modes under ZVS operation of the Phase-Shifted PWM Full-bridge Inverter.
from zero to \( +V_d/2 \) via the load and \( C_1 \). \( C_1 \) is discharged from \( +V_d \) to \( +V_d/2 \).

**Mode 9**: This mode is a free wheeling mode. Since \( S_2 \) turns off, \( S_1 \) stills turns on and \( S_1 \) is turned on by the signal, the path of current to the dc supply is cut off. Then the current flows through load, \( D_1 \) and \( S_1 \). The load voltage is zero.

**Mode 10**: In this mode, \( S_3 \) still turns on and \( S_4 \) turns off. The current flows through \( D_1 \), \( C_4 \), and the load. \( C_4 \) is charged from zero to \( +V_d/2 \). After Mode 10 is complete which is a finally stage of the operation period, the cycle of the operation is repeated.

### IV. CIRCUIT ANALYSIS

In order to understand the preliminary characteristics of voltages and currents of the main and load circuits, a mathematical approach is required. This analysis is based on reduced second order differential equations for ease of solving instantaneous voltage and current equations under the below assumptions similar to [4].

1. All the components of the circuit are ideal.
2. Dead time \( t_{dt} \) is negligible.
3. The parameters are referred to the primary side of the transformer.
4. The effect of inductance \( L_m \) can be neglected.

The applied voltage to the transformer and electrode tube is shown in Fig.7. The equivalent circuit for each state can be shown in Fig.8. The parameters for the equivalent circuit are as follows.

- \( V_d \) = DC voltage supply.
- \( v_o \) = Transformer output voltage referred to the primary side.
- \( i_1 \) = Transformer input current.
- \( L_r \) = Transformer parasitic inductance.
- \( R_r \) = Transformer resistance.
- \( C_r \) = Lumped capacitance (electrode tube, and transformer capacitances).
- \( R_e' \) = Equivalent load resistance.

The procedure for the circuit analysis is as follows.

For simplification, time constants, angular frequencies can be defined as follows:

\[
\tau_{rc} = R_e' C_r, \quad \tau_{rl} = \frac{L_r}{R_r}, \quad \omega_r = \frac{1}{\sqrt{L_r C_r}}, \quad \tau_i = \frac{R_r}{R_e'}.
\]

\[
\alpha_r = \frac{1}{2} \left( \frac{1}{\tau_{rc}} + \frac{1}{\tau_{rl}} \right), \quad \omega_r = \sqrt{\omega_r^2 + \frac{1}{\tau_{rl} \tau_{rc}}}, \quad \alpha_r = \sqrt{\omega_r^2 - \alpha_r^2}.
\]

- State 1: interval \( t_0 - t_1 \)

From Fig.8(a), by using KVL and KCL, the circuit equations are as follows:

\[
L_r \frac{di_1}{dt} + R_r i_1 + v_o = V_d
\]  

\[
i_1 - i_2 = C_r \frac{dv_o}{dt}
\]

\[
i_1 = C_r \frac{dv_o}{dt} + \frac{v_o}{R_e'}
\]

\[
i_2 = \frac{v_o}{R_e'}
\]

\[
v_o = V_d - L_r \frac{di_1}{dt} - R_r i_1
\]

\[
i_1 - \frac{v_o}{R_e'} - C_r \frac{dv_o}{dt} = 0
\]

**Fig. 7.** Ideal output voltage of the inverter applied to the transformer and the electrode tube.

**Fig. 8 Equivalent circuits for the second order derivatives in the analysis.**

Let initial conditions be \( v_o(0) = V_{oa} \), and \( i_1(0) = i_0 \).

Rearranging the above equations into a second order differential equation form, the output voltage is expressed as

\[
\frac{d^2 v_o}{dt^2} + \left( \frac{1}{\tau_{rc}} + \frac{1}{\tau_{rl}} \right) \frac{dv_o}{dt} + \left( \frac{1}{\tau_{rl} \tau_{rc}} + \alpha_r^2 \right) v_o = \omega_r^2 V_d
\]  

By solving the above equation, the output voltage can be obtained as

\[
v_o = \frac{V_d}{\tau_i + 1} + \left( \frac{V_o - V_d}{\tau_i + 1} \right) e^{(-\alpha_r \tau_i)} \cos(\omega_r \tau_i)
\]

\[
+ \frac{1}{\omega_r} \left( \alpha_r \left( \frac{V_o - V_d}{\tau_i + 1} \right) + \frac{i_0}{C_r} \frac{V_a}{\tau_{rc}} \right) e^{(-\alpha_r \tau_i)} \sin(\omega_r \tau_i)
\]

Consequently, the second order differential equation of the transformer input current \( i_1 \) is

\[
\frac{d^2 i_1}{dt^2} + \left( \frac{1}{\tau_{rc}} + \frac{1}{\tau_{rl}} \right) \frac{di_1}{dt} + \left( \frac{1}{\tau_{rl} \tau_{rc}} + \alpha_r^2 \right) i_1 = \omega_r^2 \frac{V_d}{R_e'}
\]

By solving the above equation, the transformer input current can be obtained as
\[ i_t = \frac{V_d}{(R_T + R_i)} + \left( I_u - \frac{V_d}{(R_T + R_i^p)} \right) e^{(-\alpha_r \omega_r \omega_n_1)} \cos(\alpha_n_1) \] (10)

\[ i_t = \frac{1}{\alpha_r} \left( I_u - \frac{V_d}{(R_T + R_i^p)} \right) + \frac{V_d - V_o - R_i I_t}{L_T} e^{(\alpha_r \omega_r \omega_n_1)} \sin(\alpha_n_1) \] (12)

- State 2: interval \( t_1 \rightarrow t_2 \)

From Fig.8(b), using Nodal analysis at node \( v_o \) can arrange the equations as follows:

\[ i_1 + i_2 + i_3 = 0 \] (13)

\[ i_2 = -C_r \frac{dv_o}{dt} - \frac{v_o}{R_c} \] (14)

\[ L_T \frac{di_1}{dt} + R_T i_1 = v_o \] (15)

Initial conditions are \( t = t_1 = 0 \), \( v_o(t_1) = V_o^p \), and \( i_1(t_1) = I_{u1} \).

Rearranging the above equations into a second order differential equation form, the output voltage is expressed as:

\[ \frac{d^2 v_o}{dt^2} + \left( \frac{1}{\tau_{Rc}^p} + \frac{1}{\tau_{Rc}^i} \right) \frac{dv_o}{dt} + \left( \frac{1}{\tau_{Rc}^p \tau_{Rc}^i} + \alpha_r^2 \right) v_o = 0 \] (16)

By solving the above equation, the output voltage can be obtained as:

\[ v_o = V_o e^{-\alpha_r \omega_r \omega_n_1} \cos(\alpha_n_1) + \frac{1}{\alpha_n} \left( \alpha_r V_o + \frac{I_t}{C_r} \right) \] (17)

Consequently, the second order differential equation of the transformer input current \( i_1 \) is

\[ \frac{d^2 i_1}{dt^2} + \frac{1}{\tau_{Rc}^p} \frac{di_1}{dt} + \frac{1}{\tau_{Rc}^p \tau_{Rc}^i} i_1 = 0 \] (18)

By solving the above equation, the transformer input current can be obtained as:

\[ i_1 = \frac{I_t}{C_r} e^{-\alpha_r \omega_r \omega_n_1} \cos(\alpha_n_1) + \frac{1}{\alpha_n} \left( \alpha_r I_t + \frac{R_i I_t^2}{L_T} \right) e^{-\alpha_r \omega_r \omega_n_1} \sin(\alpha_n_1) \] (19)

Using above equations and obtained parameters from the measurement and calculation mentioned before, the waveforms of the voltage and current of the transformer can be plotted as shown in Fig.9. These waveforms are merely results of a first stage for analyzing the simplified modeling of the proposed system. The results seem to be reasonable in views of the component characteristic such as the zero voltage switching condition and phase difference angle between the current and voltage. It is implied that the obtained parameters values could be valid. In order to confirm the correctness of these parameter values, the simulation results of the whole system will be illustrated in the next section.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The prototype has been implemented and tested. The resonant frequency is about 45 kHz. The inverter frequency is varied between 45 kHz and 60 kHz. The reason for selecting such certain range of the inverter frequency is the limitation of the transformer current. In order to prove the ZVS operation, the switch voltage and current are shown in Fig.10. It can be obviously seen that when the \( S_1 \) turns on, the voltage across the switch falls to zero immediately. This event occurs before the switch current rises from a negative value through zero to a positive value. Therefore, in practice this negative current will flow slowly through the free wheeling diode built in the body of the power MOSFET, thus reducing switching loss during turn-on time of the power MOSFET. The experimental result is in good agreement with the simulation one. The ozonizer is fed by a pump with a 20 L/min dry-air flow rate.
VI. CONCLUSIONS

The paper has dealt with the performance comparison of an ozone generator using PWM and Phase-shifted PWM full bridge inverter as a power supply. The proposed technique offering high-voltage and high-frequency is capable of generating ozone. The Phase-shifted PWM full bridge inverter allows constant applied electrode voltage whilst the frequency is varied. Without the adjustment of a phase-shifted angle, the applied electrode can be decreased with a frequency increase due to a high frequency effect on a step-up transformer. As a consequence, the absolute ozone productivity is not achieved with the increase in the frequency. In order to overcome this problem, the Phase-shifted PWM full bridge inverter is introduced. Apart from the voltage value, this inverter has proved that the inverter frequency significantly affects the ozone productivity.

REFERENCES