

TRANSFORMERLESS RESONANT CONVERTER DRIVING  
MULTIPLE OZONE CHAMBERS FOR HIGH FLOW RATES

MUHAMMAD AMJAD

UNIVERSITI TEKNOLOGI MALAYSIA

TRANSFORMERLESS RESONANT CONVERTER DRIVING  
MULTIPLE OZONE CHAMBERS FOR HIGH FLOW RATES

MUHAMMAD AMJAD

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

JUNE 2013

## ABSTRACT

Ozone gas ( $O_3$ ) is increasingly used as a bleaching agent due to its strong oxidising properties and less harmful to the environment. The most feasible method to generate  $O_3$  is to connect high-voltage of several kV, high-frequency of about tens of kHz power supply across a Dielectric Barrier Discharge (DBD) chamber. Commonly, a resonant power supply with the ferrite transformer is used. However, the presence of the transformer increases the cost and footprint, while reduces the efficiency of the ozone generator. To overcome these deficiencies, this work proposes a design and implementation of an ozone power supply based on transformerless resonant converter. A standard full-bridge inverter is coupled to a resonant tank circuit, i.e.  $LC$  and  $LCL$  to achieve the required high voltage. The  $LCL$  exhibits a double resonance phenomenon resulting in very high voltage gain (above 150). Consequently, the power supply is capable of delivering sufficient potential to the chamber, even if the source voltage is below 20 V. Experimental measurements show that the efficiency of the proposed generator is 92%, while the maximum ozone concentration achieved  $8.0 \text{ g/m}^3$  at a flow rate of 1.0 L/min. This performance is much higher than the existing transformer based resonant converters. This thesis also introduces the concept of ozone generation using multiple chambers. The objective is to maintain a high  $O_3$  concentration at high flow rates. To realise the idea, the same  $LCL$  transformerless ozone generator is used to drive three ozone chambers in parallel. The results indicate that the achieved ozone concentration is three times higher than the output of a single chamber. Furthermore, a closed loop regulation to maintain a stable and constant chamber's output voltage is designed. Another contribution of this work is the introduction of a simple and effective method to characterise the DBD chamber parameters. Traditionally, Lissajous figures are employed to estimate the values of the chamber's resistor and capacitor. However, this method proves unsatisfactory at high frequencies. Using the proposed method, the chamber parameters can be determined accurately at various frequencies.

## ABSTRAK

Gas Ozon ( $O_3$ ) semakin digunakan sebagai agen peluntur disebabkan ciri-ciri pengoksidaannya yang kuat dan kurang memberi kesan merbahaya kepada persekitaran. Kaedah yang paling sesuai bagi menghasilkan  $O_3$  ialah dengan menghubungkan beberapa kV voltan tinggi, frekuensi tinggi dengan berpuluh-puluh kuasa kHz melalui ruang yang tertutup *Dielectric Barrier Discharge* (DBD). Kebiasaannya, satu perbekalan kuasa resonan dengan transformer ferit digunakan. Tetapi, penggunaan transformer ini meningkatkan kos dan kesan tapak kaki serta mengurangkan keberkesanan janakuasa ozon. Untuk mengatasi kelemahan-kelemahan tersebut, kajian ini mencadangkan satu reka bentuk dan pelaksanaan perbekalan kuasa ozon berdasarkan penukar resonan tanpa transformer. Penyongsangan *full-bridge* standard dipasangkan kepada satu litar tangki resonan, i.e. *LC* dan *LCL* bagi mendapatkan voltan tinggi yang diperlukan. *LCL* menunjukkan fenomena resonan berpasangan yang menghasilkan voltan tinggi (melebihi 150). Maka, bekalan kuasa mampu memberi potensi yang cukup kepada ruang yang tertutup walaupun punca voltan kurang daripada 20 V. Pengukuran eksperimen menunjukkan keberkesanan janakuasa yang dicadangkan sebanyak 92%, sementara penumpuan ozon maksima mencapai  $8.0 \text{ g/m}^3$  pada kadar pengaliran  $1.0 \text{ L/min}$ . Prestasi ini lebih tinggi berbanding penukar-penukar transformer berasaskan resonan sedia ada. Tesis juga memperkenalkan konsep penjanaan ozon menggunakan ruang-ruang tertutup pelbagai. Tujuannya ialah mengekalkan penumpuan  $O_3$  yang tinggi pada kadar pengaliran yang tinggi. Bagi merialisasikan idea ini, penjanakuasa ozon *LCL* tanpa transformer diguna untuk menjadikan tiga ruang tertutup ozon selari. Keputusan telah membuktikan penumpuan ozon adalah tiga kali lebih tinggi berbanding keluaran satu ruang tertutup. Disamping itu satu peraturan gegelung direka bentuk bagi mengekalkan kestabilan pengeluaran voltan daripada ruang tertutup. Kajian turut memperkenalkan satu cara yang mudah dan efektif untuk menyifatkan had ruang tertutup DBD. Secara tradisinya, rajah Lissajous digunakan bagi menganggar nilai-nilai penahan dan pemuatan ruang tertutup. Namun, kaedah ini ternyata kurang berkesan pada frekuensi tinggi. Had-had ruang tertutup boleh ditentukan dengan tepat pada frekuensi berlainan dengan kaedah yang disyorkan.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xii
	<b>LIST OF FIGURES</b>	xiii
	<b>LIST OF ABBREVIATIONS</b>	xx
	<b>LIST OF SYMBOLS</b>	xxi
	<b>LIST OF APPENDICES</b>	xxiv
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background	1
	1.2 Objective, Scope and Importance of Research	4
	1.2.1 Objective of Research	4
	1.2.2 Scope of Research	4
	1.2.3 Importance of Research	6
	1.3 Organization of Thesis	6
<b>2</b>	<b>REVIEW OF POWER SUPPLIES FOR OZONE GENERATION</b>	<b>8</b>
	2.1 Introduction	8
	2.2 Fundamentals of Ozone Generation	9
	2.3 Overview of ozone Chambers	12

2.3.1	Corona Discharge Chamber	12
2.3.2	Pulse Streamer Discharge Chamber	13
2.3.3	Dielectric Barrier Discharge Chamber	14
2.4	Overview of Power Supplies for Ozone Generation Systems	17
2.4.1	DC Power Supplies	18
2.4.2	Pulse Power Supplies	19
2.4.3	Line Frequency Power Supplies	20
2.4.4	High Frequency Resonant Power Supplies based on Ferrite Core Transformers	21
2.4.4.1	Power Supply based on Full- Bridge Inverter	21
2.4.4.2	Power Supply based on Push- Pull Inverter	23
2.4.4.3	Power Supply based on Class E Inverter	23
2.4.5	Power Supply based on Piezoelectric- Transformer	25
2.5	The Proposed High Frequency Transformerless Power Supply Ozone Generation Systems	26
2.6	Summary	28

<b>3</b>	<b>OZONE CHAMBER MODELLING AND PARAMETER DETERMINATION</b>	<b>29</b>
3.1	Introduction	29
3.2	Models of DBD Ozone Chamber	30
3.2.1	Nonlinear Model	30
3.2.2	Linear Model	33
3.2.3	Limitations of Parameter Determination using Lissajous Plots	35
3.3	Ozone Chamber Configuration	36
3.4	Principle of the Proposed Chamber Parameter	

	Characterisation Method	38
3.5	Measurement Setup for Ozone Chamber	
	Parameter Determination	40
3.5.1	PWM Full-bridge Inverter and Gate	
	Drive Circuit	41
3.5.2	Variable Inductor	42
3.6	Experimental Results to Obtain Chamber	
	Parameter	44
3.7	Summary	47
<b>4</b>	<b>TRANSFORMERLESS <i>LC</i> RESONANT CONVERTER</b>	<b>48</b>
4.1	Introduction	48
4.2	Selection of Resonant Circuit Topology for	
	High-voltage Gain across the DBD Chamber	49
4.2.1	Series-Loaded Resonant Circuit	49
4.2.2	Parallel-Loaded Resonant Circuit	51
4.2.3	Series-Parallel-Loaded Resonant Circuit	52
4.3	Transformerless Converter using <i>LC</i> Resonant	
	Circuit	53
4.3.1	Analysis of <i>LC</i> Resonant Circuit and	
	Ozone Chamber Circuit	54
4.3.2	<i>LC</i> Resonant Circuit Design	55
4.4	Realisation of the Full-Bridge Converter using	
	<i>LC</i> Resonant Circuit	58
4.4.1	Circuit Operation	58
4.4.2	Simulation of Full-Bridge Converter	
	using <i>LC</i> Resonant Circuit	62
4.4.3	Practical Implementation of Full-Bridge	
	Converter using <i>LC</i> Resonant Circuit	64
4.5	Zero-voltage Zero-current Switching	67
4.6	Power Computation for Full-Bridge Converter	
	using <i>LC</i> Resonant Circuit	69

4.7	Ozone Production of Full-Bridge Converter using <i>LC</i> Resonant Circuit	75
4.8	Summary	76
<b>5</b>	<b>TRANSFORMERLESS <i>LCL</i> RESONANT CONVERTER</b>	<b>77</b>
5.1	Introduction	77
5.2	Analysis of <i>LCL</i> Resonant Circuit	78
5.2.1	Frequency Domain Analysis	78
5.2.2	Time Domain Analysis	81
5.3	Ozone Chamber Parameters and <i>LCL</i> Values Determination	84
5.4	Simulation of Full-Bridge Converter using <i>LCL</i> Resonant Circuit	87
5.5	Practical Implementation of Full-Bridge Converter using <i>LCL</i> Resonant Circuit	89
5.6	Power Computation of Full-Bridge Converter using <i>LCL</i> Resonant Circuit	92
5.7	Ozone Production of Full-Bridge Converter using <i>LCL</i> Resonant Circuit	95
5.8	Efficiency, Cost and Size Comparison of Proposed <i>LCL</i> Resonant Circuit with Previous Transformer-based Power Supplies	96
5.9	Summary	98
<b>6</b>	<b>MULTIPLE OZONE CHAMBERS FOR HIGHER FLOW RATES</b>	<b>99</b>
6.1	Introduction	99
6.2	Related Techniques Specific to Higher Flow Rates	100
6.3	Multiple Parallel Ozone Chambers Parameters Determination	102
6.4	The <i>LCL</i> Resonant Circuit Analysis with	

	Multiple Parallel Ozone Chambers	103
6.5	The <i>LCL</i> Resonant Circuit Values Determination	108
6.6	Frequency Response of <i>LCL</i> Resonant Circuit with Parameter Variation and Addition/Removal of Ozone Chambers	109
6.7	Schematic Arrangements of Proposed Ozone Generation System	110
6.8	The Control Circuit to Regulate Ozone Chambers Output Voltage	111
6.9	Simulation of Full-Bridge Converter with <i>LCL</i> Resonant Circuit and Multiple Parallel Ozone Chambers	116
6.10	Practical Implementation of Full-Bridge Converter with <i>LCL</i> Resonant Circuit and Multiple Parallel Ozone Chambers	118
6.11	Power Computation of Full-Bridge Converter with <i>LCL</i> Resonant Circuit and Multiple Parallel Ozone Chambers	120
6.12	Ozone Production at High Flow Rates with Multiple Parallel Chambers	123
6.13	Summary	126
<b>7</b>	<b>CONCLUSION AND FUTURE WORK</b>	<b>128</b>
7.1	Summary of Work	128
7.2	Contribution of Thesis	130
7.3	Suggestion for Future Work	131
	<b>REFERENCES</b>	<b>132</b>
	Appendices A - B	143-147

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
3.1	Experimental results of the ozone chamber parameters	44
4.1	Components of <i>LC</i> circuit and ozone chamber	63
4.2	Internal resistance values of full-bridge converter with <i>LC</i> resonant circuit	72
5.1	Components of <i>LCL</i> circuit and ozone chamber	87
5.2	Values of internal resistance in full-bridge converter with <i>LCL</i> circuit	93
6.1	Resonant frequency variation with different chambers	114
6.2	Combinations of resonant circuit values variation	115
6.3	Components of <i>LCL</i> circuit and ozone chamber	116
6.4	Values of internal resistance of full-bridge converter and <i>LCL</i> circuit	121
6.5	Ozone required for different applications	126

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Potential energy level of oxygen	10
2.2	Corona discharge chamber	13
2.3	Pulsed streamer discharge chamber	14
2.4	DBD chamber configuration (a) planar with two dielectric layers (b) planar chamber with one dielectric layer placed at the centre of the electrodes, (c) planar chamber with one dielectric layer covering the ground electrode, (d) cylindrical chamber with one dielectric layer.	15
2.5	Symbolic representation of microdischarge activity	16
2.6	Tree diagram showing the overview of power supplies for ozone generation systems	17
2.7	DC power supply utilising rectifier with (a) a single diode (half wave) (b) two diodes (full wave)	18
2.8	(a) Villard circuit (b) Greinacher circuit	19
2.9	Power supply for PSD chamber using (a) Pulse transformer generator (b) Magnetic pulse compressor	20
2.10	Configuration of 50/60 Hz AC power supply	20
2.11	Voltage-fed full-bridge resonant inverter	22
2.12	Current-fed full-bridge resonant inverter	22
2.13	Push-pull resonant inverter	23
2.14	Class E resonant inverter	24
2.15	Class E resonant inverter with $LC$ tank	24

2.16	Current-fed half-bridge resonant inverter	25
2.17	Voltage-fed half bridge resonant inverter	26
3.1	Nonlinear model of ozone chamber	31
3.2	Experimental setup for chamber parameter determination	32
3.3	The $Q$ – $V$ Lissajous figure of the ozone chamber	33
3.4	Models of the ozone chamber: (a) nonlinear model, (b)(c) derivation of linear model for high frequency operation	34
3.5	Experimental measurements of $V$ – $I$ and $V$ – $Q$ Lissajous plots at 15 kHz	34
3.6	Experimental measurements of $V$ – $I$ Lissajous plots at 25 kHz	36
3.7	Ozone chamber configuration	37
3.8	Ozone chamber used in this work	37
3.9	Circuit diagram of the variable inductor and zone chamber	40
3.10	Measurement setup for ozone chamber parameter determination	40
3.11	Gate drive circuit	41
3.12	Experimental setup for ozone chamber parameter determination	42
3.13	Image of the experimental setup for chamber parameter determination	43
3.14	Voltage and current waveforms of the ozone chamber at various resonant frequencies. At resonance frequencies of (a) 31.5 kHz, (b) 37.2 kHz	45
3.15	Variation in chamber's equivalent capacitance with frequency	46
3.16	Variation in ozone chamber's resistance with frequency	46
4.1	Series loaded resonant circuit topology	50

4.2	Frequency response of the SLR circuit. Family of curves for $Q_p = 3, 4, 5, 8, 10$	50
4.3	Parallel loaded resonant circuit topology	51
4.4	Frequency response of the PLR circuit. Family of curves for $Q_p = 3, 4, 5, 8, 10$	52
4.5	Series parallel loaded resonant circuit topology	53
4.6	Frequency response of the SPLR circuit. Family of curves for $Q_p = 3, 4, 5, 8, 10$	53
4.7	<i>LC</i> resonant circuit and equivalent circuit of ozone chamber	55
4.8	Voltage gain and phase versus frequency response of <i>LC</i> resonant circuit	57
4.9	Circuit diagram of power supply using <i>LC</i> resonant circuit	58
4.10	Switching pattern, output voltage and current waveforms of each element of the full-bridge inverter	61
4.11	Overall operating modes of full-bridge inverter	62
4.12	Full-bridge inverter, <i>LC</i> resonant circuit and ozone chamber simulation using Matlab/Simulink	62
4.13	Simulation results of full-bridge with <i>LC</i> resonant circuit. Ozone chamber voltage and current at input voltage of (a) 30 V (b) 35 V	64
4.14	Design for the resonant inductor	64
4.15	Experimental setup of full-bridge inverter with <i>LC</i> circuit	65
4.16	Voltage across the chamber versus the inverter input voltage	66
4.17	Experimental results of full-bridge with <i>LC</i> resonant circuit. Ozone chamber voltage and current at input voltages of (a) 30 V (b) 35 V	67
4.18	Switching signals of the MOSFETs and voltage across MOSFETs (a) Simulation (b) Experimental	68

4.19	Top: Switching signals for $M_1$ and $M_3$ , Middle: Switching signals for $M_2$ and $M_4$ , Bottom: Inverter current (a) Simulation (b) Experimental	69
4.20	Full-Bridge converter and $LC$ resonant circuit with internal resistances of elements	70
4.21	Input and output power of full-bridge converter and $LC$ resonant circuit	73
4.22	Efficiency of full-bridge converter and $LC$ resonant circuit	74
4.23	Ozone concentration versus chamber voltage using full-bridge converter with $LC$ resonant circuit	75
4.24	Ozone yield versus chamber voltage using full-bridge converter with $LC$ resonant circuit	75
5.1	$L_{s1}C_pL_{s2}$ resonant circuit and ozone chamber parameters	79
5.2	Voltage gain of $L_{s1}C_pL_{s2}$ resonant circuit versus frequency	80
5.3	Voltage gain of phase variation of chamber voltage and current waveforms of (a) Proposed $L_{s1}C_pL_{s2}$ resonant circuit (b) Normal $L_{s1}C_p$ resonant circuit	81
5.4	Ideal output voltage of the inverter applied to the $L_{s1}C_pL_{s2}$ resonant circuit	82
5.5	State-space model using Matlab/Simulink	83
5.6	Simulated input voltage ( $v_{in}$ ), input current ( $i_1$ ) and output voltage ( $v_g$ )	84
5.7	Voltage and current waveforms of ozone chamber at a frequency of 35.5 kHz	85
5.8	Voltage gain $A_{v2}$ , $A_{v1}$ , and $A_v$ of the $L_{s1}C_pL_{s2}$ circuit versus frequency	86
5.9	Effect of component variation of the $L_{s1}C_pL_{s2}$ circuit versus frequency	86
5.10	Full-bridge inverter, $L_{s1}C_pL_{s2}$ circuit and ozone chamber simulation using Matlab/Simulink	87
5.11	Simulated ozone chamber voltage and current	

	waveforms using Matlab/Simulink at inverter input voltages of (a) 7V (b) 12 V	88
5.12	Experimental setup of power supply using LCL circuit	90
5.13	Simulation and experimental results of chamber voltage as a function of inverter input voltage	91
5.14	Ozone chamber voltage and current waveforms at inverter input voltages of (a) 7V and (b) 12V. Note: high-voltage probe scale 1000:1	92
5.15	Full-bridge converter with $LCL$ circuit with internal resistance of elements	93
5.16	Input and output power of full-bridge converter and $LCL$ circuit	94
5.17	Efficiency of $LCL$ power converter versus chamber voltage	94
5.18	Ozone quantity versus inverter input voltage	95
5.19	Ozone efficiency versus input voltage of inverter	96
5.20	Efficiency comparisons of $L_{s1}C_pL_{s2}$ and transformer-based power supplies	97
6.1	Ozone concentration versus (a) flow rate [23] (b) power [106]	100
6.2	Equivalent circuit of $N$ ozone chambers connected in parallel	102
6.3	Voltage and current waveforms of chambers at 53.6 kHz	103
6.4	$L_{s1}C_pL_{s2}$ resonant circuit and an equivalent ozone chambers	105
6.5	Model of input voltage ( $v_{in}$ ), input current ( $i_{in}$ ) and chamber current ( $i_{gn}$ ) using Matlab/Simulink	107
6.6	Simulated input voltage ( $v_{in}$ ), input current ( $i_{in}$ ) and chamber current ( $i_{gn}$ )	107
6.7	Voltage gain of the $L_{s1}C_pL_{s2}$ resonant circuit with frequency	108
6.8	Voltage gain versus frequency for $L_{s1}C_pL_{s2}$ parameter	

	variation	109
6.9	Voltage gain versus frequency with different numbers of chambers	110
6.10	Proposed ozone generation system using parallel chambers	110
6.11	Full-bridge resonant inverter used as the ozone power supply	110
6.12	Electrical schematic diagram of the proposed control circuit	112
6.13	Proteus waveform of $i_{in}$ and $v_{in}$ to illustrate ZVS operation	113
6.14	Frequency response of system by adding/removing ozone chambers	114
6.15	Voltage gain versus frequency response for $LCL$ parameter variation of $\pm 5\%$ , $\pm 3\%$ and $\pm 2\%$	116
6.16	Full-bridge inverter, $LCL$ circuit and multiple ozone chambers simulation using Matlab/Simulink	116
6.17	Simulated ozone chamber voltage and current waveforms using Matlab/Simulink at inverter input voltages of (a) 13 V (b) 16 V	117
6.18	Voltage across the chambers versus the inverter input voltage	118
6.19	Voltage and current waveforms of ozone chambers at the inverter input voltages of (a) 13 V and (b) 16 V	120
6.20	Full-bridge converter and $LCL$ circuit with internal resistance of elements and ozone chambers	121
6.21	Output and input power of the full-bridge converter and $LCL$ circuit with three parallel ozone chambers	122
6.22	Efficiency of $LCL$ power converter versus chambers voltages	122
6.23	Ozone concentration versus flow rate	123
6.24	Ozone concentration versus flow rate	124
6.25	Ozone concentration versus chamber voltage for different flow rates	125

6.26	Ozone efficacy versus chamber voltage	125
------	---------------------------------------	-----

## LIST OF ABBREVIATIONS

AC	-	Alternating Current
AWG	-	American Wire Gauge
DBD	-	Dielectric Barrier Discharge
DC	-	Direct Current
ESR	-	Equivalent Series Resistance
IGBT	-	Insulated Gate Bipolar Transistor
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MPC	-	Magnetic Pulse Compressor
PLR	-	Parallel Loaded Resonant
PSD	-	Pulse Streamer Discharge
PT	-	Piezoelectric Transformer
PTFE	-	Polytetrafluoroethylene
PV	-	Photovoltaic
PWM	-	Pulse Width Modulation
RF	-	Radio Frequency
RMS	-	Root mean square
SLR	-	Series Loaded Resonant
SPLR	-	Series Parallel Loaded Resonant
VCO	-	Voltage Controlled Oscillator
V-Q	-	Voltage-Charge
V-I	-	Voltage-Current
ZVS	-	Zero Voltage Switching
ZCD	-	Zero crossing Detector
ZVZCS	-	Zero Voltage Zero Current Switching

## LIST OF SYMBOLS

$A_P$	-	Area Product
$A_V$	-	Voltage gain
$A_{Vm}$	-	Maximum voltage gain
$A_{V1}$	-	Voltage gain due to $L_1C_1$
$A_{V2}$	-	Voltage gain due to $L_2C_g$
$A_w(B)$	-	Bare wire area
$\beta_m$	-	Flux density
$C_a$	-	Capacitor due to discharge gap
$C_d$	-	Capacitor due to dielectric material
$C_g$	-	Chamber capacitance
$C_{gn}$	-	Equivalent capacitance of $N$ Parallel Chambers
$C_m$	-	Measurement Capacitor
$C_o$	-	Output capacitance of piezoelectric transformer
$C_p$	-	Parallel capacitor
$C_s$	-	Series capacitor
$C_t$	-	Fixed capacitor
$f$	-	Frequency
$f_{osc}$	-	Oscillator frequency
$f_s$	-	Switching frequency
$f_r$	-	Resonant frequency
$\Delta f$	-	Frequency variation
$I_{C_p}$	-	Maximum current flowing through $C_p$
$I_{pk}$	-	Peak Current
$I_D$	-	Drain to source current of the switches
$i_g$	-	Current flowing into chamber
$i_{gn}$	-	Current flowing into $N$ chambers

$i_{M1}, i_{M2},$ $i_{M3}, i_{M4}$	-	Current flowing through switches $M_1, M_2, M_3$ and $M_4$
$I_{C1}, i_{C2},$ $i_{C3}, i_{C4}$	-	Current flowing through capacitors $C_1, C_2, C_3$ and $C_4$
$i_{in}$	-	Input Current
$J$	-	Current Density
$K_u$	-	Window utilization factor
$^kP, ^kD$	-	Sub shell level of an atom
$L_D$	-	Leakage inductance
$L_M$	-	Magnetizing inductance
$L_S$	-	Series Inductor
$M$	-	Third collision partner
$M_1, M_2,$ $M_3, M_4$	-	Switching devices (MOSFETs)
$N$	-	Number of chambers
$O_2$	-	Oxygen molecule
$O_3$	-	Ozone molecule
$P_g$	-	Power consumed in the chamber
$P_{gn}$	-	Power consumed in the $N$ chambers
$P_{in}$	-	Accumulative input power
$P_{r_{L_S}}$	-	Power losses in inductor $L_S$
$P_{r_{L_{S1}}}$	-	Power losses in inductor $L_{S1}$
$P_{r_{L_{S2}}}$	-	Power losses in inductor $L_{S2}$
$P_{r_{C_P}}$	-	Power losses in inductor $C_P$
$P_{r_{DS}}$	-	Power losses in the switching device
$Q$	-	Quality factor
$Q_P$	-	Loaded quality factor
$R_g$	-	Chamber resistance
$R_{gn}$	-	Equivalent resistance of $N$ Parallel Chambers
$R_t$	-	Multi-turn Potentiometer
$S$	-	Chamber electrode area

$V$	-	Voltage
$V_{DS}$	-	Drain to source voltage of switching device
$v_g$	-	Voltage across chamber
$v_{gn}$	-	Voltage across $N$ chambers
$V_{in}$	-	Input voltage
$V_{out}$	-	Output voltage
$V_Z$	-	Chamber initiation voltage
$W$	-	Energy per cycle
$W_a$	-	Window area
$W_{a(eff)}$	-	Window effective area
$\omega_p$	-	Undamped natural frequency
$Z_{in}$	-	Input Impedance

## LIST OF APPENDICES

APPENDIX	TITLE		PAGE
A	Microcontroller code for the proposed feedback closed loop control system		143
B	List of Publications		146

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background**

The use of ozone gas ( $O_3$ ) has increased due to its excellent oxidizing properties. It exhibits strong anti-germicidal properties, a characteristic that is useful for air and water purification [1, 2]. Unlike other oxidizing chemicals such as chlorine, ozone leaves no harmful residue because its primary by-product is oxygen. It is used in many diverse fields such as the agricultural, pharmaceutical and solid waste treatment industries. In the semiconductor industry, dissolved ozone in water is used for the surface cleaning of device fabrication, as an alternative to sulphuric acid and ammonia-based mixtures [3]. It has been used in the food processing industry as a sanitizer. In hospitals, ozone is mainly used as a disinfectant for surgical equipment, clothes and linen. In agriculture, ozone is used for postharvest treatment to increase the shelf-life and freshness of fruits, flowers and vegetables [4, 5]. Moreover, ozone-enriched water is used for hydroponic applications and for the removal of pesticide residues from fruits. In waste treatment plants, solid waste is oxidized and the water is recycled for cooling tower requirements [6]. Although the application of ozone is widely recognised, its production is somewhat hindered due to the insufficient efficiency and high cost of equipment for ozone generation systems.

The best and most common economic method to generate ozone in normal atmospheric environments is by using the concept of electrical discharge.

Electrically, different types of discharge, such as corona, pulsed streamer and dielectric barrier discharge (DBD), have been applied for ozone generation [3, 7, 8]. The most viable method to generate ozone under atmospheric conditions and at ambient temperature is DBD [9, 10]. An important property of DBD is the creation of cold non-equilibrium plasma at atmospheric pressure. The DBD chamber typically consists of two electrodes; one is connected to a high voltage AC power supply, while the ground electrode is usually covered with dielectric [11]. Due to the presence of dielectric inside the chamber, this method is known as DBD or silent discharge. Air or oxygen is forced to flow between the electrodes, in a space known as the discharge gap. If the voltage applied to the electrodes creates a sufficiently high electric field, the oxygen molecules will be broken into oxygen atoms. The latter combines with other oxygen molecules to form ozone.

Commonly, glass or alumina ceramic are used as dielectrics for the DBD chambers. These materials are by nature fragile, and hence the chamber is constructed with a typical thickness between one to four millimetres. For one millimetre of thickness, the initiation voltage (the voltage required to initiate ozone formation) is approximately 10–20 kV [12, 13]. Consequently, with these materials a high voltage power supply is required. Recently, the use of mica as the dielectric has been demonstrated. Mica is flexible and non-fragile; by using this material a chamber can be readily constructed with a thickness of less than 0.5 mm. It has been shown that for the same discharge gap, mica exhibits a much lower initiation voltage – about one order of magnitude lower than glass or ceramic [14]. The lower voltage offers several advantages, namely lower power consumption and reduced stress on the dielectric. Subsequently the ozone power supply can be built at lower cost, of smaller volume and with none of the special safety precautions generally associated with high voltage equipment.

Traditionally, a low-frequency (50–60Hz) AC source, coupled with a high transformer turns ratio, is used as the power supply for the ozone generator [15-17]. This approach requires a high voltage to be present across the chamber, since it must operate close to the discharge potential. The high voltage limits ozone production in several ways. First it restricts the use of different dielectric materials due to the

inability of these materials to withstand high voltage stresses. Secondly, the high voltage limits the discharge gap size, which in turn limits the amount of ozone gas that can be produced in the ozone chamber. Thirdly, a low-frequency system is also associated with lower power conversion efficiency and larger power converter size [18].

To increase the ozone quantity, the chamber is fed by a high-frequency power supply. The high-frequency operation increases the power density applied to the electrode surface. This increases the ozone production for a given surface area, while decreasing the necessary peak voltage. Furthermore, at lower voltages it is possible to experiment with various types of dielectric materials with much lower voltage stress levels. Subsequently, the power supply can be built at lower cost, with smaller volume, low power consumption and no special safety precautions that are generally associated with high voltage equipment [19].

Although high-frequency resonant power converters are widely utilised for generating ozone, it has always been a challenge to increase ozone production. Typically, high-frequency resonant converters of various topologies are employed for ozone power supply. A step-up transformer is required to achieve high voltage across the chamber [20, 21]. Since these power supplies utilise high transformer turn ratios, the associated leakage inductance results in high voltage spikes across the switch during commutation. Hence, the switch utilisation factor is low and a protection circuit is necessary to avoid the destruction of the switch, which will increase the cost and complexity of the circuit. Another disadvantage of the transformer is electromagnetic interference and core saturation, particularly at high frequency operation. Moreover, the power supplies are fed by single or three-phase utility supplies. While a piezoelectric transformer (PT) is introduced to alleviate some of these problems, its bandwidth at resonance is extremely narrow; and as a result a closed loop control is mandatory [22]. Furthermore, a high step-up ratio PT with a reasonably high power rating is not readily available on the market.

In view of these drawbacks of resonant converters utilising transformers, this work introduces the transformerless power converter to improve the efficiency of

conventional ozone generation systems. The main idea is to remove the transformer from the converter and utilise a resonant circuit to achieve high voltage. The proposed approach offers several advantages: (1) with the absence of a transformer there will be no high voltage spikes in the power switches, resulting in increased efficiency, (2) the use of a protection circuit for switches is not necessary, (3) due to high-voltage gain, the power converter can be fed with a low-voltage source, and (4) the power converter cost and footprint are reduced and its efficiency is increased.

## **1.2 Objective, Scope and Importance of Research**

### **1.2.1 Objective of Research**

The objective of this research is to analyse, design and implement a power supply to drive multiple ozone chambers for high flow rates. The work focuses on the resonant converter design procedures, the effects of resonant circuit parameters variation and the control circuit to regulate the output voltage of the chambers. The expected outcome of this work is an efficient transformerless converter that is capable of driving multiple chambers, which can be fed by low voltage sources such as photovoltaic modules or batteries.

### **1.2.2 Scope of Research**

Based on the objectives, the research of this thesis works towards the following:

- (i) A strategic and critical and literature review of power supplies for

ozone generation is carried out. In this review, the basics principles of chambers and previous work on power supplies used for ozone generation are discussed. Their strengths and limitations are highlighted. Besides giving a comprehensive overview of existing power supplies, the objective of the review is to look for a gap in the literature, particularly on the issue of power supplies for ozone generation.

- (ii) In order to design an efficient high-voltage high-frequency power supply it is necessary to accurately comprehend the parameters of the chamber. Thus a simple and effective method to calculate the model parameters of a chamber is proposed. The correctness of the calculated chamber parameters are validated by designing resonant converters for ozone generation.
- (iii) The study on the selection of practicable resonant circuit topology to achieve a high voltage across the ozone chamber is conducted. Prototypes of two power converters with *LC* and *LCL* resonant circuits based on a full-bridge inverter are constructed. The efficiency analysis of both power converters is carried out by theoretical calculation, simulation and direct measurement. The ozone production is presented in terms of ozone concentration and ozone yield as a function of chamber voltage. An efficiency comparison of the transformerless power converter is made with previous transformer-based resonant power converters.
- (iv) An ozone generation system to maintain ozone concentrations at high flow rates is developed. This is achieved by connecting three chambers in parallel and is driven by single *LCL* resonant power converter. The chambers are fed at optimum flow rate to achieve high ozone concentration at higher flow rates. Moreover, a closed loop feedback controller is proposed to regulate the output voltage of the ozone chamber. This control system is able to accommodate changes in *LCL* component values and the adding/removal of ozone chambers.

### 1.2.3 Importance of Research

Due to the steadily increasing demand for ozone in various applications, its production at high flow rates is a challenging task. Since ozone is an unstable gas, it must be generated and consumed on site. In places where a utility supply is inaccessible, there is a demand for ozone generators powered by photovoltaic modules or batteries. Although, high frequency resonant power converters are widely employed in ozone generation systems. The drawback with the conventional power converters is its low efficiency due to the use of a step-up transformer.

The problem can be overcome by employing a transformerless resonant power converter for ozone generation. With the introduction of a resonant circuit to achieve high voltage-gain, the power converter can be fed by a low-voltage source such as a photovoltaic module or battery. Hence it can be used in places that lack electricity. Moreover, ozone production can be increased by driving multiple parallel ozone chambers.

## 1.3 Organisation of Thesis

This thesis is composed of seven chapters. Their contents are outlined as follows:

- (i) Chapter 2 briefly reviews ozone generation techniques and their corresponding power supplies. The fundamentals of ozone formation are introduced. The power supplies are categorised into various groups, namely DC, pulse, line frequency and high frequency resonant circuit. The merits and drawbacks of each power supply are highlighted. The benefits of transformerless resonant power supplies over transformer-based power supplies are stressed.

- (ii) Chapter 3 introduces a method to determine the ozone chamber parameters in considerable detail. The limitations of linear and non-linear models of chambers using the conventional Lissajous plot method are outlined. The proposed parameter determination approach is simple and accurate.
- (iii) Chapter 4 describes the operation of the  $LC$  resonant circuit power converter based on a full-bridge inverter. The overall operating modes are explained. The design procedure for  $LC$  circuit parameter values is outlined. A comparison of simulation and experimental results is carried out to validate the accuracy of the chamber model parameters.
- (iv) Chapter 5 covers the analysis, design and implementation of a transformerless  $LCL$  resonant circuit power converter. The benefits of the proposed  $LCL$  resonant circuit over normal  $LC$  circuits are elaborated. The experimental results of ozone production and efficiency of the power converter are provided.
- (v) Chapter 6 provides the analysis, design and implementation of multiple parallel ozone chambers for high flow rates. The closed loop feedback control circuit used to regulate the chamber's voltage is described. The laboratory prototype based on the  $LCL$  resonant circuit is capable of simultaneously driving three ozone chambers.
- (vi) Chapter 7 concludes the work and highlights the contribution of this research. Several ideas for future work are also proposed.

## REFERENCES

1. Selma, M. V., Allende, A., López-Gálvez, F., Conesa, M. A. and Gil, M. I. Disinfection potential of ozone, ultraviolet-C and their combination in wash water for the fresh-cut vegetable industry. *Food Microbiology*. 2008. 25(6): 809-814.
2. Gottschalk, C., Libra, J. and Saupe, A. *Ozonation of Water and Waste Water, A Practical Guide to Understand Ozone and its Applications*. 2 edn: ohn Wiley VCH Verlag GmbH & Co. KGaA. 2010.
3. Kogelschatz, U. Dielectric-Barrier Discharges: Their History, Discharge Physics, and Industrial Applications. *Plasma Chemistry and Plasma Processing*. 2003. 23(1): 1-46.
4. Kogelschatz, Ulrich and Eliasson, B. *Ozone generation and application, A Handbook of electrostatic processes*. New York :Marcel Dekker, 1995 1995. chapter 26: 581-606.
5. Guzel-Seydim, Z. B., Greene, A. K. and Seydim, A. C. Use of ozone in the food industry. *Lebensmittel-Wissenschaft und-Technologie*. 2004. 37(4): 453-460.
6. Smilanick, J. L. Use of Ozone in Storage and Packing Facilities. in *Washington Tree Fruit Postharvest Conference Wenatche, Washington*. 2003.
7. Chang, J. S., Lawless, P. A. and Yamamoto, T. Corona discharge processes. *IEEE Transactions on Plasma Science*. 1991. 19(6): 1152-1166.
8. Chang, Y. D., Tseng, S. Y., Wu, T. F. and Yang, H. R. Narrow pulsed electric field generator using forward / flyback hybrid converters for liquid food processing. *IEEE International Conference on Sustainable Energy Technologies*. November 24-27, 2008. 910-915.
9. Fridman, A., Chirokov, A. and Gutsol, A. Topical Review: Non-thermal atmospheric pressure discharges. *Journal Physics D. Application Physics*,. 2005. 38: R1-R24.

10. Fridman, A., Chirokov, A. and Gutsol, A. Non-thermal atmospheric pressure discharges. *Journal of Physics D: Applied Physics*. 2005. 38(2): R1.
11. Kogelschatz, U., Eliasson, B. and Egli, W. Dielectric-Barrier Discharges. Principle and Applications. *J. Phys. IV France*. 1997. 07(C4): C4-47-C4-66.
12. Koudriavtsev, O., Shengpei, W., Konishi, Y. and Nakaoka, M. A novel pulse-density-modulated high-frequency inverter for silent-discharge-type ozonizer. *Industry Applications, IEEE Transactions on*. 2002. 38(2): 369-378.
13. Zolkafle Buntat, Ivor R. Smith and Razali, N. A. M. Ozone Generation by Pulsed Streamer Discharge in Air. *Applied Physics Research*. 2009. 1(2 ): 1-9.
14. Facta, M., Salam, Z., Buntat, Z. and Yuniarto, A. Silent discharge ozonizer for colour removal of treated palm oil mill effluent using a simple high frequency resonant power converter. *IEEE International Conference on Power and Energy (PECon)*, November 29 2010. 39-44.
15. Buntat, Z., Smith, I. R. and Razali, N. A. M. Ozone generation using atmospheric pressure glow discharge in air. *Journal of Physics D: Applied Physics*. 2009. 42(23): 235202.
16. Jae-Duk, M. A wire-to-wire type nonthermal plasma reactor with ferroelectric pellet barrier. *Journal of Electrostatics*. 2006. 64(10): 699-705.
17. Manley, T. C. The Electric Characteristics of the Ozonator Discharge. *Transactions of The Electrochemical Society*. 1943. 84(1): 83-96.
18. Hae-Eun, J., Jae-Hun, Y., Chung, L., Seong-Hwa, K., Kyu-Boek, C. and Kee-Joe, L. Analysis of AC breakdown of composite-insulation depending on gas pressure and solid insulation thickness. *International Conference on Condition Monitoring and Diagnosis*. April 21-24 2008. 325-327.
19. Alonso, J. M., Garcia, J., Calleja, A. J., Ribas, J. and Cardesin, J. Analysis, design, and experimentation of a high-voltage power supply for ozone generation based on current-fed parallel-resonant push-pull inverter. *IEEE Transactions on Industry Applications*. 2005. 41(5): 1364-1372.
20. Nisoa, M., Srinoum, D., and Kerdthongmee, P. Development of High Voltage High Frequency Resonant Inverter Power Supply for Atmospheric Surface Glow Barrier Discharges. *Solid State Phenomena*. 2005. 107: 81-86.
21. Kinnares, V. and Hothongkham, P. Circuit Analysis and Modeling of a Phase-Shifted Pulsewidth modulation Full-Bridge-Inverter-Fed Ozone

- Generator With Constant Applied Electrode Voltage. *IEEE Transactions on Power Electronics*. 2010. 25(7): 1739-1752.
22. Alonso, J. M., Ordiz, C., Costa, M. A. D., Ribas, J. and Cardesin, J. High Voltage Power Supply for Ozone Generation Based on Piezoelectric Transformer. *IEEE Industry Applications Conference*. 2007. 1901-1908.
  23. Nisoa, M., and Srinum, T. Characteristics of Ozone Production by Using Atmospheric Surface Glow Barrier Discharge. *Walailak Journal of Science and Technology (WJST)*. 2009. 6(2): 284-292.
  24. JR., R. *Industrial Plasma Engineering: Applications to Non-thermal Plasma Processing*. vol. 2: Bristol and Philadelphia; 2001.
  25. Eliasson, B., Hirth, M. and Kogelschatz, U. Ozone synthesis from oxygen in dielectric barrier discharges. *Journal of Physics D: Applied Physics*. 1987. 20(11): 1421.
  26. Chalmers, I. D., Zanella, L. and MacGregor, S. J. Ozone synthesis in oxygen in a dielectric barrier free configuration. *Tenth IEEE International Pulsed Power Conference Digest of Technical Papers*. July 3-6, 1995. 1249-1254 vol.2.
  27. Langlais, B., Reckhow, D. and Brink, D. *Ozone in Water Treatment: Application and Engineering: Cooperative Research Report*. Chelsea, Michigan: Lewis Publishers. 1991.
  28. Masschelein, W. *Ozonization Manual for Water and Wastewater Treatment*. John Wiley and Sons. 1982.
  29. Whittaker, G., Mount, A. and Heal, M. *BIOS Instant Notes Physical Chemistry*. Taylor and Francis. 2000.
  30. Garamoon, A. A., Elakshar, F. F., Nossair, A. M. and Kotp, E. F. Experimental study of ozone synthesis. *Plasma Sources Science and Technology*. 2002. 11(3): 254.
  31. Fang, Z., Lei, X., Cai, L., Qiu, Y. and Kuffel, E. Study on the microsecond pulse homogeneous dielectric barrier discharges in atmospheric air and its influencing factors. *Plasma Science and Technology*. 2011. 13(6): 676-681.
  32. Samaranayake, W. J. M., Namihira, E., Katsuki, S., Miyahara, Y., Sakugawa, T., Hackam, R. and Akiyama, H. Pulsed power production of ozone using nonthermal gas discharges. *IEEE Electrical Insulation Magazine*. 2001. 17(4): 17-25.

33. Bogaerts, A., Erik, N., Renaat, G. and Mullen, J. Review: Gas Discharge Plasma and Their Application. *Spectrochimica Acta Part B*. 2002. 57.
34. Tendero, C., Tixier, C., Tristant, P., Desmaison, J. and Leprince, P. Atmospheric pressure plasmas: A review. *Spectrochimica Acta Part B: Atomic Spectroscopy*. 2006. 61(1): 2-30.
35. Salam, M., Husein, A., Morshedy, A. and Radwan, R. *High Voltage Engineering, Theory and Practice*. 1 edn. New York: Marcel Dekker; 2000.
36. G., H., JD., S., J., O., R., V. and NJ., M. Influence of the Outer Electrode Material on Ozone Generation in Corona Discharges. *Plasma Chem Plasma*. 2010. 30(1): 43-53.
37. Francke, K. P., Rudolph, R. and Miessner, H. Design and Operating Characteristics of a Simple and Reliable DBD Reactor for Use with Atmospheric Air. *Plasma Chemistry and Plasma Processing*. 2003. 23(1): 47-57.
38. Yanzhou, S. and Feng, Z. Investigation of influencing factors in ozone generation using dielectric barrier discharge. *IEEE 9th International Conference on the Properties and Applications of Dielectric Materials(ICPADM)*, 2009. 614-617.
39. Kitayama, J. and Kuzumoto, M. Analysis of ozone generation from air in silent discharge. *Journal of Physics D: Applied Physics*. 1999. 32(23): 3032.
40. Morgan, N., Metawa, A. and Garamoon, A. Planar atmospheric pressure dielectric barrier discharge for ozone production. *Indian Journal of Physics*. 2011. 85(11): 1631-1642.
41. Haverkamp, R. G., Miller, B. B. and Free, K. W. Ozone Production in a High Frequency Dielectric Barrier Discharge Generator. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 2002. 24(5): 321 - 328.
42. Naidu, M. and Kamaraju, V. *High Voltage Engineering*. 3 edn. New Delhi: Tata Mc Graw Hill Publishing Company Ltd; 2004.
43. Mesyats. GA. *Pulsed Power*. Kluwer Academic/Plenum Publisher; 2005.
44. Sakugawa, T., Yamaguchi, T., Yamamoto, K., Kiyan, T., Namihira, T., Katsuki, S. and Akiyama, H. All Solid State Pulsed Power System for Water Discharge. *IEEE Pulsed Power Conference*. June 13-17, 2005. 1057-1060.
45. Steigerwald, R. L. High-Frequency Resonant Transistor DC-DC Converters.

- IEEE Transactions on Industrial Electronics*. 1984. 31(2): 181-191.
46. Ben-Yaakov, S. and Peretz, M. M. A self-adjusting sinusoidal power source suitable for driving capacitive loads. *IEEE Transactions on Power Electronics*. 2006. 21(4): 890-898.
  47. Gulko, M. and Ben-Yaakov, S. Current-sourcing push-pull parallel-resonance inverter (CS-PPRI): theory and application as a discharge lamp driver. *IEEE Transactions on Industrial Electronics*. 1994. 41(3): 285-291.
  48. Peng, F. Z., Akagi, H., Nabae, A. and Sugawara, S. High-frequency current-source inverters using SI thyristors for induction heating applications. *IEEE Transactions on Industry Applications*. 1989. 25(1): 172-180.
  49. Hothongkham, P. and Kinnares, V. High-voltage high-frequency power supply using a phase-shifted PWM full bridge inverter fed ozone generator with constant applied electrode voltage. *International Power Electronics Conference (IPEC)*. 2010. 1560-1567.
  50. Hothongkham, P. and Kinnares, V. (Year). Measurement of an ozone generator using a phase-shifted PWM full bridge inverter. *International Power Electronics Conference (IPEC)*. 2010. 1552-1559.
  51. Hothongkham, P. and Kinnares, V. Analysis and modelling of an ozone generator using a phase-shift PWM full bridge inverter. *IEEE International Conference on Robotics and Biomimetics*. 2009. 1619-1624.
  52. Hothongkham, P. and Kinnares, V. Constant voltage control of high voltage high frequency power supply for ozone quantity adjustment. *IEEE International Symposium on Circuits and Systems*. 2009. 1977-1980.
  53. Shengpei, W., Konishi, Y., Ishitobi, M., Shirakawa, S. and Nakaoka, M. Current-source type parallel inductor-compensated load resonant inverter with PDM control scheme for efficient ozonizer. *VI IEEE International Power Electronics Congress*. 1998. 103-110.
  54. Alonso, J. M., Cardesin, J., Martin-Ramos, J. A., Garcia, J. and Rico-Secades, M. Using current-fed parallel-resonant inverters for electrodischarge applications: a case of study. *Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition ( APEC)*. 2004. 109-115.
  55. Alonso, J. M., Garcia, J., Calleja, A. J., Ribas, J. and Cardesin, J. Analysis, design and experimentation of a high voltage power supply for ozone generation based on the current-fed parallel-resonant push-pull inverter.

- Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE.* October 3-7, 2687-2693.
56. Alonso, J. M., Ordiz, C., Gacio, D., Ribas, J. and Calleja, A. J. Closed-loop regulated power supply for ozone generation based on buck converter and current-fed push-pull resonant inverter. *Power Electronics and Applications, 2009. EPE '09. 13th European Conference on*, 2009. 1-10.
  57. Ordiz, C., Alonso, J. M. J., Costa, M. A. D., Ribas, J. and Calleja, A. J. Development of a high-voltage closed-loop power supply for ozone generation. *Applied Power Electronics Conference and Exposition, 2008. APEC 2008. Twenty-Third Annual IEEE.* February 24-28, 2008. 1861-1867.
  58. Alonso, J. M., Calleja, A. J., Ribas, J., Rico-Secades, M., Corominas, E., Cardesin, J. and Garcia, J. Low-power high-voltage universal-input inverter for ozone generation. *Power Electronics Congress, Technical Proceedings. CIEP 2002. VIII IEEE International*, 2002. 153-159.
  59. Alonso, J. M., Calleja, A. J., Ribas, J., Valdes, M. and Losada, J. Analysis and design of a low-power high-voltage high-frequency power supply for ozone generation. *Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE*, 2001. 2525-2532.
  60. Alonso, J. M., Cardesin, J., Corominas, E. L., Rico-Secades, M. and Garcia, J. Low-power high-voltage high-frequency power supply for ozone generation. *IEEE Transactions on Industry Applications*. 2004. 40(2): 414-421.
  61. Facta, M., Salam, Z., Jusoh, A. and Bin Buntat, Z. Improvement in ozone generation with low voltage high frequency power converters. *IEEE Power and Energy Conference, 2008( PECon 2008)*. 2008. 1446-1450.
  62. Ponce-Silva, M., Aguilar-Ramirez, J., Beutelspacher, E., Calderon, J. M. and Cortes, C. Single-Switch Power Supply based on the Class E Shunt Amplifier for Ozone Generators. *IEEE Power Electronics Specialists Conference, 2007( PESC 2007)*. 2007. 1380-1385.
  63. Diaz, J., Nuno, F., Lopera, J. M. and Martin-Ramos, J. A. A new control strategy for an AC/DC converter based on a piezoelectric transformer. *IEEE Transactions on Industrial Electronics*. 2004. 51(4): 850-856.
  64. Ivensky, G., Shvartsas, M. and Ben-Yaakov, S. Analysis and modeling of a piezoelectric transformer in high output voltage applications. *IEEE Applied*

- Power Electronics Conference and Exposition, 2000(APEC 2000)*. 2000. 1081-1087.
65. Ivensky, G., Shvartsas, M. and Ben-Yaakov, S. Analysis and modeling of a voltage doubler rectifier fed by a piezoelectric transformer. *IEEE Transactions on Power Electronics*. 2004. 19(2): 542-549.
  66. Alonso, J. M., Ordiz, C. and Dalla Costa, M. A. A Novel Control Method for Piezoelectric-Transformer Based Power Supplies Assuring Zero-Voltage-Switching Operation. *IEEE Transactions on Industrial Electronics*. 2008. 55(3): 1085-1089.
  67. Alonso, J. M., Ordiz, C., Dalla Costa, M. A., Ribas, J. and Cardesin, J. High-Voltage Power Supply for Ozone Generation Based on Piezoelectric Transformer. *IEEE Transactions on Industry Applications*. 2009. 45(4): 1513-1523.
  68. Burany, N., Huber, L. and Pejovic, P. Corona Discharge Surface Treater Without High Voltage Transformer. *IEEE Transactions on Power Electronics*. 2008. 23(2): 993-1002.
  69. Jin, J. X., Dou, S. X., Liu, H. K. and Grantham, C. High voltage generation with a high  $T_c$  superconducting resonant circuit. *IEEE Transactions on Applied Superconductivity*. 1997. 7(2): 881-884.
  70. Ness, R. M., Pronko, S. G. E., Cooper, J. R. and Chu, E. Y. Resonance transformer power conditioners. *Power Modulator Symposium, 1990., IEEE Conference Record of the 1990 Nineteenth*. June 26-28, 1990. 38-43.
  71. Ness, R. M., Pronko, S. G. E., Cooper, J. R. and Chu, E. Y. Resonance transformer power conditioners. *IEEE Transactions on Electron Devices*. 1991. 38(4): 796-802.
  72. Teschke, M., Korzec, D., Finantu-Dinu, E. G., Engemann, J. and Kennel, R. Resonant, high voltage, high power supply for atmospheric pressure plasma sources. *IEEE 35th Annual Power Electronics Specialists Conference, 2004. (PESC 2004)*, 2004. 835-839.
  73. Bhat, A. K. S. Analysis and design of LCL-type series resonant converter. *IEEE Transactions on Industrial Electronics*. 1994. 41(1): 118-124.
  74. Borage, M., Tiwari, S. and Kotaiah, S. Analysis and design of an LCL-T resonant converter as a constant-current power supply. *IEEE Transactions on Industrial Electronics*. 2005. 52(6): 1547-1554.

75. Chwei-Sen, W., Covic, G. A. and Stielau, O. H. Investigating an LCL load resonant inverter for inductive power transfer applications. *IEEE Transactions on Power Electronics*. 2004. 19(4): 995-1002.
76. Dieckerhoff, S., Ruan, M. J. and De Doncker, R. W. Design of an IGBT-based LCL-resonant inverter for high-frequency induction heating. *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*. 1999. 2039-2045.
77. Hyoyol, Y., Eunyong, S., Jeabong, K., Gilyong, C., Changyo, L. and Byeongsu, B. 100kHz IGBT inverter use of LCL topology for high power induction heating. *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on*. 2011. 1572-1575.
78. Cai, Y.-x., Zhao, W.-d., Wang, J., Zhou, B. and Han. Study on Optimal Matching of DBD Load and Inverter Power of Series Resonant Type. *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*, March 28-31, 2010. 1-4.
79. Chen, Z. and Roth, J. R. Impedance matching for one atmosphere uniform glow discharge plasma (OAUGDP) reactors. *Pulsed Power Plasma Science, 2001. IEEE Conference Record - Abstracts*, 2001. 313-318.
80. Massines, F. and et al. Glow and Townsend dielectric barrier discharge in various atmosphere. *Plasma Physics and Controlled Fusion*. 2005. 47(12B): B577.
81. Ponce, M., Aguilar, J., Fernandez, J., Beutelspacher, E., Calderon, J. M. and Cortes, C. Linear and non linear models for ozone generators. *9th IEEE International Power Electronics Congress*. 2004. 251-256.
82. Alonso, J. M., Valdés, M., Calleja, A. J., Ribas, J. and Losada, J. High Frequency Testing and Modeling of Silent Discharge Ozone Generators. *Ozone: Science & Engineering: The Journal of the International Ozone Association*. 2003. 25(5): 363 - 376.
83. Olivares, V. H., Ponce-Silva, M., Osorio, R. and Juarez, M. DBD Modeling as a Function of Waveforms Slope. *IEEE Power Electronics Specialists Conference*. 2007. 1417-1422.
84. Kasap, S. O. Principle of Electronic Material and Devices. 3 ed. New York: Mc Graw Hill, 2006.
85. Park, S. L., Moon, J. D., Lee, S. H. and Shin, S. Y. Effective ozone

- generation utilizing a meshed-plate electrode in a dielectric-barrier discharge type ozone generator. *Journal of Electrostatics*. 2006. 64(5): 255-262.
86. Johnson, N., Johnson, J., Johnson, K., Abu-Naba'a, L., Al Shorman, H., Freeman, R. and Lynch, E. Patients' Attitudes to Dental Treatment Using Ozone vs. Conventional Treatment. In: *International Association of Dental Research (IADR) 2003*. Poster #6079.
  87. Cosby, M. C., Jr. and Nelms, R. M. A resonant inverter for electronic ballast applications. *IEEE Transactions on Industrial Electronics*. 1994. 41(4): 418-425.
  88. Wm, C. and Mclyman, T. *Transformer and Inductor Design Handbook*. Third Edition Maracel Dekkar, Inc New York.
  89. Sekiya, H., Sagawa, N. and Kazimierczuk, M. K. Analysis of Class-DE Amplifier With Linear and Nonlinear Shunt Capacitances at 25% Duty Ratio. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2010. 57(9): 2334-2342.
  90. Sekiya, H., Sagawa, N. and Kazimierczuk, M. K. Analysis of Class DE Amplifier With Nonlinear Shunt Capacitances at Any Grading Coefficient for High Q and 25% Duty Ratio. *IEEE Transactions on Power Electronics*. 2010. 25(4): 924-932.
  91. Sekiya, H., Watanabe, T., Suetsugu, T. and Kazimierczuk, M. K. Analysis and Design of Class DE Amplifier With Nonlinear Shunt Capacitances. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2009. 56(10): 2362-2371.
  92. Casanueva, R., Bra, x00F, as, C., Azcondo, F. J., Di, x and az, F. J. Teaching Resonant Converters: Properties and Applications for Variable Loads. *IEEE Transactions on Industrial Electronics*. 2010. 57(10): 3355-3363.
  93. Akpinar, E. and Yilmazlar, I. Transformerless Single Phase Inverter Design for LCD Television. *Consumer Electronics, IEEE Transactions on*. 2007. 53(2): 697-703.
  94. Hamill, D. C. Class DE inverters and rectifiers for DC-DC conversion. *IEEE Power Electronics Specialists Conference*. 1996. 854-860.
  95. Koizumi, H. and Kurokawa, K. Analysis of the Class DE Inverter With Thinned-Out Driving Patterns. *IEEE Transactions on Industrial Electronics*. 2007. 54(2): 1150-1160.

96. Koizumi, H., Suetsugu, T., Fujii, M., Shinoda, K., Mori, S. and Ikeda, K. Class DE high-efficiency tuned power amplifier. *Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on*. 1996. 43(1): 51-60.
97. Kessler, D. J. and Kazimierczuk, M. K. Power losses and efficiency of class-E power amplifier at any duty ratio. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2004. 51(9): 1675-1689.
98. Sullivan, C. R. and Muetze, A. Simulation Model of Common-Mode Chokes for High-Power Applications. *Industry Applications, IEEE Transactions on*. 2010. 46(2): 884-891.
99. Xu, T. and Sullivan, C. R. Optimization of stranded-wire windings and comparison with litz wire on the basis of cost and loss. *Power Electronics Specialists Conference, 2004*. June 20-25, 2004. 854-860.
100. Potivejkul, S., Kinnarees, V. and Rattanaichien, P. Design of ozone generator using solar energy. *IEEE Asia-Pacific Conference on Circuits and Systems*. 1998. 217-220.
101. Schonknecht, A. and De Doncker, R. W. A. A. Novel topology for parallel connection of soft-switching high-power high-frequency inverters. *IEEE Transactions on Industry Applications*. 2003. 39(2): 550-555.
102. Keeling, N. A., Covic, G. A. and Boys, J. T. A Unity-Power-Factor IPT Pickup for High-Power Applications. *IEEE Transactions on Industrial Electronics*. 2010. 57(2): 744-751.
103. Kissin, M., Chang-Yu, H., Covic, G. A. and Boys, J. T. Detection of the Tuned Point of a Fixed-Frequency LCL Resonant Power Supply. *IEEE Transactions on Power Electronics*. 2009. 24(4): 1140-1143.
104. Kowalski, W. J., Bahnfleth, W. P., Striebig, B. A. and Whittam, T. S. Demonstration of a Hermetic Airborne Ozone Disinfection System: Studies on E. coli. *AIHA Journal*. 2003. 64(2): 222-227.
105. Lei, X., Rui, Z., Peng, L., Li-Li, D. and Ru-Juan, Z. Sterilization of E. coli bacterium with an atmospheric pressure surface barrier discharge. *Chinese Physics*. 2004. 13(6): 913-917.
106. Drews, J., Kusano, Y., Leipold, F., Bardenshtein, A. and Krebs, N. Ozone Production in a Dielectric Barrier Discharge with Ultrasonic Irradiation. *Ozone: Science & Engineering*. 2011. 33(6): 483-488.

107. Itoh, H. and Teranishi, K. Recent Topics Related to Ozone Generation Technology in Japan. *Ozone: Science & Engineering*. 2011. 33(2): 93-97.
108. Yehia, A. and Mizuno, A. Silver discharge electrode for suppression of ozone generation in positive dc corona. *Industry Applications Conference Fourtieth IAS Annual Meeting*. October 2-6, 2005. 1828-1832.
109. R. G. Haverkamp, B. B. Miller and Free, K. W. Ozone Production in a High Frequency Dielectric Barrier Discharge Generator *Ozone: Science & Engineering*. 2002. 24: 321-328.
110. Retrieved on March 10, 2013 , from [http:// www.labcenter.com/products/](http://www.labcenter.com/products/)
111. Retrieved on March 2, 2013 , from <http://www.atmel.com/products/>
112. Teranishi, K., Shimomura, N., Suzuki, S. and Itoh, H. Development of dielectric barrier discharge-type ozone generator constructed with piezoelectric transformers: effect of dielectric electrode materials on ozone generation. *Plasma Sources Science and Technology*. 2009. 18(4): 1-10.
113. Wu, J. G, Luan, T. G., Lan, C. Y., Lo, W. H. and Chan, G. Y.S. Efficacy evaluation of low-concentration of ozonated water in removal of residual diazinon, parathion, methyl-parathion and cypermethrin on vegetable. *Journal of Food Engineering*. 2007. 79, 803-809.