**UNIVERSITI PUTRA MALAYSIA**

# DESIGN AND SIMULATION OF 10 kHz VOLTAGE-SOURCE THREE-PHASE RESONANT DC-LINK INVERTER FOR 10 kW OHMIC HEATING PROCESS

**ELSADIG MOHAMED ALI**

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By

**ELSADIG MOHAMED ALI**

**Thesis Submitted in Fulfilment of the Requirement for the**
**Degree of Master of Science in the Faculty of Engineering**
**Universiti Putra Malaysia**

**May 2001**

*This thesis is dedicated to*
*My parents.*
*My sincere wife Randa.*
*My daughters and son, Thwaiiba, Toga and Anas.*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in
fulfilment of the requirement for the degree of Master of Science

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**Chairman:** **Associate Professor Norman Bin Mariun, Ph. D.**

**Faculty:** **Engineering**

There has been much interest recently in heat processing and packing for rapid heating and non-thermal microbial inactivation of food. Ohmic heating is one of the new technologies used. It is an operation in which heat is internally generated within foods due to the passage of alternating electrical current. Much of the research carried out on ohmic heating to date has been done using frequency of 60 and 50 Hz. Low frequency has an electrolytic effect similar, though to a lesser extent to that of direct current. The major electrolytic effect is the dissolution of the metallic electrodes, which may contaminate the product.

One of the most effective methods utilised to overcome the electrolytic effect, and give high performance of ohmic heating is high frequency resonant converter. The literature review includes resonant DC-link inverter, three-phase sinusoidal PWM inverter, control of the inverter, filters design, ohmic heating, and power MOSFET.

Sinusoidal pulse width modulation was used to produce pure sinusoidal current at high frequency and low harmonics. Although it had drawbacks such as suffering high stress and losses during switching these effects were reduced by soft switching, where the MOSFET is switched on at zero voltage (ZVS). Power MOSFET was chosen for high switching device, low resistance and feature suitable for static power converter.

The study presented the design for 10 kHz of voltage-source resonant DC-link inverter involving the design of three-phase rectifier, filter, resonant circuit, sinusoidal PWM inverter and control circuit. The performance of three-phase resonant dc-link inverter was simulated based on the design parameters. Three-phase sinusoidal output current at 10 kHz was produced, which is suitable for driving AC resistive load (ohmic heating).

Abstrak tesis untuk dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan bagi ijazah Master Sains

# REKABENTUK DAN SIMULASI PENUKAR SUMBER VOLTAN RESONAN TIGA FASA HUBUNGAN DC UNTUK PROSES PEMANASAN OHMIK PADA 10 kW

Oleh

**ELSADIG MOHAMED ALI**

**Mei 2001**

**Pengerusi:** **Profesor Madya Norman Bin Mariun, Ph. D.**

**Fakulti:** **Kejuruteraan**

Terdapat begitu banyak minat sejak akhir-akhir ini dalam pemprosesan dan pembungkusan haba untuk pemanasan segera dan penyahaktif mikrobial bukan terma bagi makanan. Pemanasan ohmik adalah salah satu teknologi baru yang digunakan. Ia adalah satu operasi di mana haba dijana secara dalaman di dalam makanan disebabkan oleh pengaliran arus elektrik ulang alik. Banyak penyelidikan dijalankan terhadap pemanasan haba sehingga hari ini dengan menggunakan frekuensi pada 60 dan 50 Hz. Frekuensi rendah mengandungi kesan elektrolitik, walaupun berkurangan kesannya berbanding dengan penggunaan arus terus. Kesan elektrolitik utama ialah pencairan elektrod metalik, yang mungkin mencemari produk.

Satu daripada kaedah paling efektif yang digunakan untuk mengatasi kesan elektrolitik, dan memberikan prestasi pemanasan ohmik yang tinggi ialah dengan menggunakan penukar resonan berfrekuensi tinggi. Kajian penulisan merangkumi penukar resonan hubungan DC, penukar PWM bentuk sinus tiga fasa, kawalan bagi penukar, rekabentuk penapis, pemanasan ohmik, dan MOSFET kuasa.

Modulasi lebar denyut sinusoidal digunakan untuk menghasilkan arus bentuk sinus yang tulen pada frekuensi tinggi dan harmonik rendah. Walaupun ia mempunyai kelemahan seperti mengalami tekanan dan kehilangan kuasa yang tinggi sepanjang pensuisan, kesan-kesan ini dapat dikurangkan dengan pensuisan lembut, di mana MOSFET disuiskan pada voltan sifar. MOSFET kuasa telah dipilih kerana keupayaannya sebagai peranti bersuis tinggi, rintangannya yang rendah dan kesesuaian cirinya sebagai penukar kuasa statik.

Kajian ini menampilkan rekabentuk penukar sumber voltan titi penuh resonan hubungan DC pada 10 kHz yang mengandungi rekabentuk bagi penerus masukan tiga fasa, penapis, litar resonan, penukar PWM bentuk sinus dan litar kawalan. Kemampuan penukar resonan tiga fasa hubungan dc disimulasikan merujuk kepada parameter-parameter yang direkabentuk. Arus keluaran bentuk sinus tiga fasa pada 10 kHz dihasilkan, yang mana bersesuaian untuk memacu beban rintangan AC (pemanasan ohmik).

# ACKNOWLEDGEMENTS

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I certify that an Examination Committee met on 21th May 2001 to conduct the final examination of Elsadig Mohammed Ali on his Master of Science thesis entitled "Design and Simulation of 10 kHz Voltage-Source Three-Phase Resonant Inverter for 10 kW Ohmic Heating Process" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis is submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Masters of Science.

AINI IDERIS, Ph.D,
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Date: 14 JUN 2001

# DECLARATION.

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or currently submitted for any other degree at UPM or other institutions.

ELSADIG MOHAMED ALI ELSHIEKH,

Date: 31 · 5 · 2004

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| | |
|---|---|
| Ac | Alternating current |
| DC | Direct current |
| f | Frequency |
| L | Inductor |
| C | Capacitor |
| R | Resistance |
| N | Neutral |
| G | Gate |
| D | Drain |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| MGD | MOSFET Gate Drive |
| TTL | Transistor-Transistor Logic |
| PWM | Pulse Width Modulation |
| SOA | Safe Operation Area |
| T | Temperature |
| $\Theta$ | Thermal Resistance |
| $\delta$ | Pulse width |
| $\tau$ | Time constant |
| RMS | Root mean squares |
| IEEE | Institution of Electrical and Electronics Engineers |

| | |
|---|---|
| ML | MOSFET link switch |
| $V_{GML}$ | MOSFET link switch gate drive |
| $I_L$ | Resonant inductor current |

# CHAPTER I

# INTRODUCTION

There has been much recent interest in heat processing and aseptic packing for rapid heating and non-thermal microbial inactivation of food. Among the new technologies involved is ohmic heating.

## 1.1 Ohmic Heating

Ohmic heating is a process in which heat is generated within the food itself, from the passage of an electric current. As the current passes through the food, heat is generated from the resistance to its flow [1]. In most ohmic heating research, an alternating current of low frequency (50 to 60 Hz) is used. However, a low frequency current has an electrclytic effect similar to that of direct current, though to lesser extent. The major electrolytic effect is the dissolution the metallic electrodes, which may contaminate the product [2].

One of the most effective methods to minimize the electrolysis is to use a high frequency current from a resonant power inverter. The resonant inverter is a new technology for producing a high frequency current to minimise the harmonics, noise and switching loss in semiconductor devices.

For ohmic heating to be successful, the food must exhibit some electrical conductivity. It is normally a unique value to the food and increases with the temperature. However, in some food materials, it decreases instead [2].

## 2.1 Resonant DC-Link Inverter

Semiconductor power device consist of two different power losses, these are the conducting, and the switching losses. The conducting losses depend on the construction of the device and the switching losses depend on the voltage, current, and switching frequency of the device.

The soft-switching power converter has been one of the fastest growing areas in power electronics in the past several years. The resonant DC-link (RDCL) techniques reduced the switching losses of the power device in the inverter virtually to zero compared with hard-switching techniques. There are two types of RDCL soft switching these are zero-voltage-switching (ZVS) and zero-current-switching (ZCS). The voltage and current source RDCL can obtain nearly loss-less turn-ON and turn-OFF switching, thus increasing device switching frequencies of several order of magnitude higher than that achievable in hard-switching converters. The power device characterization and selection for the RDCL converters remain one of the important issues.

Metal oxide semiconductor field effect transistor (MOSFET) was chosen due for its high switching speed, low ON resistance and operating junction temperature to reduce conduction loss and yield a high efficiency. The advantage of three-phase sinusoidal pulse width modulation (PWM) is to produce pure sinusoidal output at high frequency, reduced filter requirements for harmonic reduction and the controllability of the amplitude of the fundamental frequency. The disadvantages include more complex control circuits for switches and increased losses due to more frequent switching, which are solved by topologies used.

## 1.3 Objectives of the Study

The study was conducted to design a three-phase voltage-source resonant DC-link inverter fed from a three-phase rectifier, and to simulate the performance of the resonant circuit.

The main objectives were to:

1. Design a 10 kHz three-phase voltage-source resonant DC-link inverter, fed from a three-phase rectifier for a 10 kW ohmic heating circuit.

2. Simulate a 10 kHz three-phase voltage-source resonant DC-link inverter fed from a three-phase rectifier for 10 kW ohmic heating circuit.

### 1.4 Thesis Layout

This thesis is organized in five chapters. Chapter I introduces the project, gives the problem statement and objectives of the research. Chapter II reviews the literature on the resonant DC-link inverter, voltage control, three-phase PWM inverter, power MOSFET and ohmic heating as a prelude to the research project. In Chapter III, the three-phase resonant DC-link inverter was designed and the performance of the circuit was simulated. Chapter IV presents the results and their discussion. Then, the work was concluded in Chapter V.

# CHAPTER II

# LITERATURE REVIEW

The literature review is divided into four sections for easy comprehension:

1. Resonant DC-link inverter.
2. Voltage control of the inverter.
3. Three-phase PWM inverter.
4. Power MOSFET.
5. Ohmic heating.

## 2.1 Resonant DC-Link Inverter

Semiconductor power device consist of two different power losses, which are the conducting, and the switching losses. The conducting losses depend on the construction of the device and the switching losses depend on the voltage, current, and switching frequency of the device [3].

The soft-switching power converter has been one of the fastest growing areas in power electronics in the past several years. The RDCL techniques reduced the switching losses of the power device in the inverter to virtually zero compared with hard-switching techniques. There are two type of RDCL soft switching inverter:

(a) RDCL voltage-source inverter, in which the voltage oscillates between zero and a peak value. The RDCL voltage-source achieved zero-voltage-switching (ZVS), and the connection of the power devices is in parallel with DC-link as shown in Figure 2.1.

(b) RDCL current-source inverter, where the DC-link current oscillates between zero and a peak value. The RDCL current-source inverter achieved zero-current-switching (ZCS), and the connection of the power device is in series with DC-link, Figure 2.2 [4].

The voltage and current source RDCL can obtain nearly loss-less turn-ON and turn-OFF switching, thus increasing device switching frequencies of several order of magnitude higher than that achievable in hard-switching converters [5]. The power device characterization and selection for the RDCL converters remain one of the important issues.

### 2.1.1 Main Advantages of the Voltage-Source Inverter

The main advantages of the voltage-source inverter are:

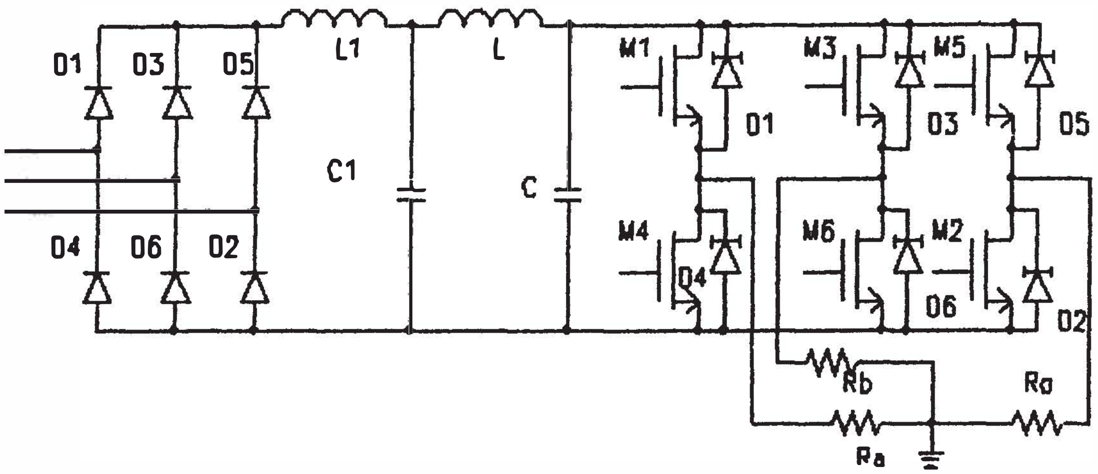

Figure 2.1: Voltage-source resonant DC-link inverter.

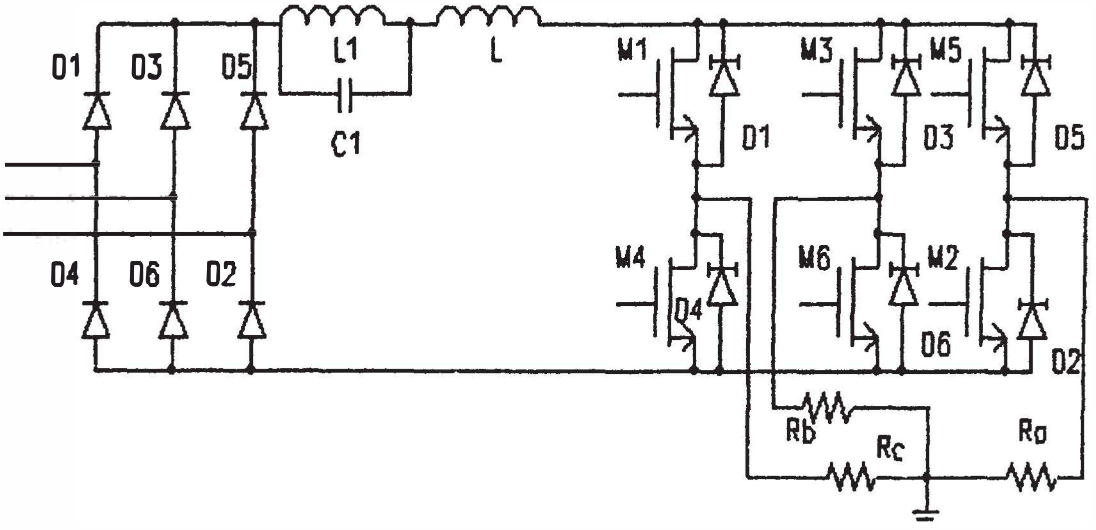

Figure 2.1: Current-source resonant DC-link inverter.

(a) The ZCS has considerably higher losses than the ZVS converter, because the device in ZCS circuit is required to carry the full load current while the device in ZVS circuit converter only need carry the resonant current [6].

(b) Safe operation with an open output circuit.

(c) Suitable for operation above the resonant frequency [7].

### 2.1.2 RDCL Voltage-Source Inverter

The basic topology for RDCL with zero-voltage-switching, is that the resonant circuit is connected between the DC input voltage and the PWM inverter so that the input voltage to the inverter oscillates between zero and slightly more than twice the DC input voltage as presented in Figure 2.3a [8-9]. Assuming that $I_o$ is the current drawn by the inverter, and that the circuit is loss-less (R = 0), the link voltage, $V_c$, is:

$$V_c = V_s (1 - \cos \omega_0 t) \qquad (2.1)$$

The inductor current, $I_L$, is

$$I_L = V_s \sqrt{C/L} \sin \omega_0 t + I_o \qquad (2.2)$$

Under loss-less conditions the oscillation will continue and due to the power loss in R and $I_L$, there is damped sinusoidal and $S_1$ is turned ON to bring the current to initial level. The value of R is small and the circuit is underdamped. Under this condition, $I_L$ and $V_c$ can be shown as: