Design of a Microcontroller-based, Power Control System for Microwave Drying

By

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ABSTRACT

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Design of a Microcontroller-based, Power Control System for Microwave Drying

Microwave drying is an energy-efficient drying method. The output power of most commercial microwave ovens is controlled in an intermittent fashion, where the amount of microwave energy is determined by the ratio of “ON cycles” to “OFF cycles.” To provide a more efficient and continuous power control for the magnetron, a microcontroller-based, feedback power control system was developed. The system was based on a phase-control principle to achieve smooth power variations depending on a feedback temperature signal of processed products. Two temperature sensors, a thermocouple and an infrared sensor, were used to measure the temperature. A fiber-optic thermometer was used for calibration and evaluation of the system performance during microwave drying. With the IR sensor, the mean standard deviation and maximum error in temperature measurement of controlled water samples were ?0.34?C and ?1.5°C, respectively. This result demonstrated the accuracy of the IR sensor in the system control. Under the IR sensor-controlled system, carrot cubes (*Daucus carota L.*) lost 85.37% of their water content and resulted in better color quality than the conventional microwave-hot air convective drying without a temperature feedback control.

RÉSUMÉ

Zhenfeng Li

M.Sc. Génie des bioressources

Conception d'un système muni d'un contrôleur de pépiphériques microprogrammé conçu pour régler le séchage par micro-ondes

Le séchage par micro-ondes est une méthode de séchage économe en énergie. La puissance de sortie de la plupart des fours à micro-ondes commerciaux est contrôlée de façon intermittente, la quantité d'énergie micro-onde étant determine par le rapport des cycles "en marche" à ceux "fermé". Afin de fournir un contrôle de puissance du magnétron à la fois plus éfficace et continu, un système de contrôle de puissance à retroaction, muni d'un contrôleur de pépiphériques microprogrammé, fut développé. Le système fut basé sur le principe de réglage de phase, afin d'obtenir un réglage continue lié à un produit signal processé de temperature à rétroaction. Deux capteurs de temperature, une sonde thermocouple et un capteur infrarouge fournirent pour mesurer la temperature. Un thermomètre à fibres optiques servit à la calibration et à l'évaluation du système lors du séchage par micro-ondes. Avec le capteur IR, l'écart type moyen et l'écart maximum de temperature furent de ?0.34?C et ?1.5?C, respectivement. Cela démontre la précision du capteur à infrarouge pour le contrôle du système. Avec un système contrôlé par capteur à infrarouge, des cubes de carotte (*Daucus carota* L.) perdirent 85.37% de leur contenu en eau et maintenirent une meuilleur couleur qu'après un séchage conventionel micro-ondes/air chaud par convexion sans contrôle par rétroaction.

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NOMENCLATURE

AC	Alternative Current
A/D	Analog-to-Digital converter
a_w	Water activity
a^*	Chromacity coordinate (redness or greenness)
b^*	Chromacity coordinate (yellowness or blueness)
BUFFALO	Bit User Fast Friendly Aid to Logical Operation
CPU	Central Processing Unit
E	Emissivity of a material
DC	Direct Current
EEPROM	Electrical Erasable Programmable Read-Only Memory
I/O	Input and/or output
IR	Infrared
L^*	Chromacity coefficiency (lightness)
LCD	Liquid Crystal Display
OPAMP	Operation Amplifier
PC	Personnel Computer
PN	Positive-Negative junction
PWM	Pulse Width Modulation
R	Reflectivity
RAM	Random Access memory
RMS	Root Mean Square
ROM	Read-Only Memory
RTD	Resistor Temperature Detector
SCI	Serial Communications Interface
SCR	Silicon Controlled Rectifier
SPI	Serial Peripheral Interface
T	Transmissivity
UPS	Uninterrupted Power System

I. INTRODUCTION

Humanity produced 1.84 billion tons of food in 2003 (FAO, 2004) to support 6.3 billion people, and this production is predicted to reach 2.4 billion tons in 2015 and 2.8 billion tons in 2030 (FAO, *World agriculture: towards 2050*, 2002). Although this quantity of food is available in one place or another on earth, a good portion of the produced food never benefits mankind and many people still remain hungry. An estimated 3-11% of annual world food production has deteriorated due to improper storage, drying, and other preservation methods, whereas in the last 5 years, the mean annual world food shortage (supply minus demand) has only represented 2% of world food production (FAO, 2000-2004). The need for new food preservation methods and improvement of existing methods is urgent.

Compared to canning, freezing, and aseptic processing, drying, which has been practiced since time immemorial, is an efficient, cost-effective way of food preservation. Considering energy use efficiency, environmental concerns, and increasing demands to feed the growing population, along with the goals of enhancing product quality and reducing spoilage, much research has been carried out to develop new techniques for food drying. Agricultural, industrial, and domestic applications of drying technologies over the preceding century have expanded our understanding and led to the development of many new drying techniques. Four main types of drying — hot air convective drying, vacuum drying, freeze-drying, and microwave drying — have demonstrated their respective superiorities in regard to specific products.

Over the past two decades, there has been an increasing interest in microwave drying, which can overcome certain limitations of conventional thermal food treatment methods. It has advantages in various aspects of performance, such as higher drying rate, shorter drying time, lower energy consumption, and better quality of the dried products (Sanga *et al.*, 2000) (Mullin, 1995). For ideal drying effects, microwave energy applied to the product needs to be controlled at suitable levels. Microwave power in most modern microwave ovens is controlled in an intermittent manner. To achieve the best drying quality of products, a number of studies seeking to optimize the quality of dried products have investigated the best ON: OFF cycle ratio within a predefined time interval. Changrue *et al.* (2004) recommended that, to achieve an efficient drying process, carrot cubes (1000 mm^3) should be dried under a fixed power density of 1 W/g with 70°C hot air. The power to the magnetron was manually controlled with an initial pattern of "55 sec ON: 5 sec OFF" followed by a pattern of "30 sec ON: 30 sec OFF" when the moisture content of the carrot cubes dropped below 30% (wet basis). Sunjka (2003) tested different pulse modes and power levels and combined microwave drying with mechanical and chemical pre-treatment to improve the cranberry drying process. He determined that high-quality, dried cranberries could be obtained under a microwave power level of 1.25 W/g with a pulse pattern of "30 sec ON: 45 sec OFF". Liang *et al.* (2004) concluded a "10 sec ON: 45 sec OFF" cycle was suitable for rose flower drying.

Due to their large variations of inherent properties, bio-products may react differently under microwave treatment. Each bio-product may need a specific intermittent power scheme. Furthermore, the best power control scheme also depends on the size, quantity, and moisture content of the material. Any changes in these factors would affect the efficiency and results of the drying process. More stable and convenient power control methods are needed to optimize the microwave drying process.

Among various modern power control methods, phase control is widely used in both industrial and domestic applications for its simplicity and high efficiency. Cheng (2004) developed a resistive-capacitor based phase control circuit using TRIAC for power control of a microwave oven and obtained different power levels by changing the value of the resistor. However, it was found difficult to obtain suitable resistive values manually to match different power level requirements for different objects, and more experiments are needed to find the optimal resistor values for different types of materials. Moreover, the most important factor for the drying processes — the temperature of the food — was still left uncontrollable and could only be estimated by experiments. For accurate and automatic adjustment of the power level and control of the temperature during the drying process, an intelligent tool is needed. A microcontroller with an accurate temperature measurement would serve as the most suitable candidate for this task.

This study focuses on developing a microcontroller-based, temperature-feedback control system for microwave drying.

II. OBJECTIVES

The primary objective of this study was to develop a microcontroller-based, temperature-feedback power control system for microwave ovens. Specific objectives included:

? Designing a zero-crossing detection circuit;

? Developing a TRIAC-based power control circuit;

? Designing a temperature-monitoring and signal-conditioning circuit;

? Testing the performance of the overall control system;

? Comparing drying results obtained with the modified microwave oven to that under microwave-assisted hot air conductive drying.

III. LITERATURE REVIEW

3.1 General introduction on drying

By far most of foods consumed by mankind are of biological origin, derived either from plant or animal materials. While such foods nourish human beings, they can also serve as suitable substrates for a number of micro-organisms involved in the deterioration of foods. The war between human beings and micro-organisms is always ongoing. Long before knowing of the existence of micro-organisms, people employed methods such as salting, smoking, heating, freezing, or canning to prevent or inhibit spoilage. Among these methods, an effective and broadly applied method is to reduce the food's water content through drying or dehydration, thus limiting the activity of micro-organisms.

Thermal drying, a very common and diversified process, converts solid, semi-solid, or liquid foodstuffs into a solid product through the heat-driven process of evaporating the liquid into a vapour phase. Mujumdar *et al.* (2000) stated that over 500 types of dryers had been reported in the literature, and that over 100 distinct types were commonly available. Currently, the most popular drying methods are solar drying, hot air convective drying, freeze-drying, vacuum drying, and microwave drying.

Both energy and mass transfers take place during the drying process. The former include conduction, convection, and radiation, while the latter represent the moisture removal.

Besides its application in the preservation of foodstuffs, drying is also necessary in producing easy-to-handle, free-flowing solids, reducing transportation costs, and achieving desired product quality.

3.1.1 Solar drying

Solar drying, among the oldest drying methods, has long been used to dry fish, meat, cloth, and grains and has proved to generate foodstuffs of high quality and low spoilage. With the worldwide tightening of energy policies in recent decades, people have realised the importance of solar energy and developed new scientifically-proven techniques to use it more efficiently. Some new solar drying systems, such as sun-hoods (Andrassy, 1978) and multi-rack dryers (Mathur *et al.*, 1989), were developed for the drying of cash crops, such as grapes (*Vitis vinifera* L.), saffron (*Crocus sativus* L.), and fruits (Mathur *et al.*, 1989).

While solar drying is a cheap, easy, and popular method, its application is restricted by the long drying time and the need for favourable weather. For example, Tulasidas (1994) showed that 6-9 weeks were required to dry grapes to a water content of 25-35%, and further steps were required to dry them completely.

3.1.2 Hot air convective drying

The principle of hot air convective drying is based on conventional heat transfer from heated air to the materials being dried. Hot air is forced through the materials and drives the moisture diffusion process that results in drying. This method has been widely used in industry. Different types of dryers (tunnel, belt-through, and pneumatic conveyor) have been developed and employed in commercial production (Jayaraman *et al.*, 1995).

A typical small-scale, experimental hot air drying unit is a cabinet dryer, which consists of an insulated cavity where the material is loaded on trays. Heated air is blown through the material by cross flow or by fan-generated flow.

In hot air drying, the inlet air temperature, air velocity, physical properties of the foodstuff, and design characteristics of the drying equipment can influence the drying rate and results.

Compared to solar drying, hot air convective drying can greatly shorten the drying time from several weeks to several days. However, some studies have reported that the taste, colour, and overall quality of dried berries could be improved by using alternative methods, such as microwave drying (Tulasidas, 1994).

3.1.3 Freeze-drying

Not all products can be exposed to high temperature during the drying processes. For example, some pharmaceuticals are heat-sensitive. Similarly, some fruits and vegetables lose their aroma and flavour if they remain at high temperatures for a significant period of time. For such cases, freeze-drying is an alternative.

Defined as a drying process in which the solvent and the medium of suspension are crystallized at low temperature and thereafter sublimated from the solid state directly into the vapour phase (Oetjen, 1999), freeze-drying was introduced on a large scale in World War II, when it was used in the production of dried plasma and blood products (Barbosa-Canovas *et al.*, 1996). The primary object of freeze-drying is to preserve biological materials without injuring them by freezing the water they contain and then removing the ice by sublimation. Freeze-drying requires several successive steps, including pre-freezing, primary drying, secondary drying conditioning, and rehydration. While freeze-drying is critical for blood plasma and certain foodstuffs because it stops the growth of micro-organisms, inhibits deleterious chemical reactions, and maintains a product's integrity along with an excellent rehydration capacity, its greater expense and technical sophistication render it difficult to apply to all commercial drying needs.

3.1.4 Vacuum drying

Unlike under freeze-drying where water sublimates from the frozen state, under vacuum drying, water evaporates from its liquid state and the material is subjected to a low-pressure environment, such that the boiling point of water inside the material is reduced. During such a drying process, the main heat transfer modes are conduction and/or radiation. Improved product quality is associated with low temperatures and reduced oxidation.

There are four essential elements in a vacuum drying system: a vacuum chamber to support the material, a device to maintain a vacuum during the drying process, a system for collecting the water vapour evolved during drying, and means for supplying the heat needed to vaporize the water (Brown *et al.*, 1964).

For reasons similar to freeze-drying, vacuum drying is also an expensive drying method. It is only used for costly products like citrus juices, apple flakes, and heat-sensitive products.

3.1.5 Microwave drying

The potential of microwave energy for thermal processing of agricultural commodities was recognised in the 1950's. Due to economic and technical barriers, only in recent decades has low cost, mass-produced domestic and industrial microwave equipment found applications in the drying of food and biological commodities.

Compared to traditional drying methods, microwave drying is a new and distinctly different drying method. Convection drying depends on the relatively slow processes of convective heat transfer from the medium to the surface, followed by conductive transfer to the interior of the materials. By contrast, heating with microwave energy is a volumetric process in which the electro-magnetic field interacts with the material and causes a high instantaneous heating of foodstuffs.

Microwave heating and drying present the following advantages over conventional thermal heating/drying methods (Mullin, 1995; Sanga *et al.*, 2000).

1) Heating is instantaneous due to radiative energy transfer, hence the surface-to-centre conduction stage is largely eliminated. Moreover, rapid, efficient and accurate control of heating rates can be achieved by controlling the output power of the generator.
2) During conventional drying, moisture is initially evaporated from the surface while the internal water diffuses to the surface slowly. Under microwave drying, internal heat generation leads to an increase in internal temperature and vapour pressure, both of which promote liquid flow towards the surface, thus increasing the drying rate.
3) More of the applied energy is converted to heat within the target material, because transfer of energy to the air, oven walls, conveyor, and other parts is minimal given their low dielectric constants. This can result in significant energy savings.
4) Drying time can be shortened by 50% or more, depending on the products and the drying conditions.
5) Microwave drying equipment occupies less space and reduces handling time.
6) Microwave drying improves product quality and, in some cases, eliminates case hardening, internal stresses, and other problems of quality such as cracking. The

exposure to high temperatures is shorter, resulting in less degradation of heat-sensitive components such as vitamins and proteins.

7) Microwaves can be conveniently combined with other methods of drying, such as hot air drying, freeze-drying, and the application of a vacuum.

Microwave drying of grapes is not only faster but also requires less energy consumption than conventional drying (Tulasidas, 1994). In the drying of osmotically pre-treated strawberries (*Fragaria chiloensis* Duchesne, var, *ananassa* Bailey) or blueberries (*Vaccinium angustifolium* Ait.), Venkatachalapathy (1998) showed that microwave drying required shorter drying time than freeze drying, while maintaining the same final product quality. Sanga *et al.* (2000) also reported that the use of microwaves in freeze-drying could substantially increase drying rate and, consequently, decrease drying time.

Beaudry (2001) compared hot air drying, freeze-drying, vacuum drying and a combination of hot air and microwave drying of cranberries (*Vaccinium macrocarpon* Ait.). It was concluded that microwave-assisted hot air drying resulted in the shortest drying time and acceptable colour, taste and texture. Sunjka (2003) compared microwave-assisted vacuum drying to microwave-assisted hot air drying and concluded that the microwave-assisted vacuum drying offered a slight advantage in product quality and process efficiency.

Liang *et al.* (2003) dried flowers with microwaves in conjunction with a colour-protecting treatment, which offered a number of advantages over conventional methods, including faster heating, more uniform drying, and little variation in colour values.

However, microwave-drying systems are not without disadvantages (Sanga *et al.*, 2000). These disadvantages can be summarized as follows:

1) High initial cost for purchase and installation;
2) Possible aroma loss in microwave-dried juice-powder and colour change due to charring or scorching;
3) Possible physical damages caused by localized areas of continuously rising temperatures;

4) Specific sample sizes and shapes of products are usually required because of microwave's limits on penetration.

3.2 Microwave and Microwave oven

Given the low-cost, well-established and stable technology of commercial microwave ovens, most microwave drying experiments have used such units as they are, in modified forms, or in user-constructed units (Beaudry, 2001; Liang, *et al.*, 2003). Within the microwave oven, microwaves are generated by a magnetron and conducted to an applicator through a waveguide tube. The power of the microwave can be controlled by a high voltage transformer.

3.2.1 Microwave technology

Microwave technology was developed during World War II, when vacuum tubes termed magnetrons were invented and perfected. These magnetrons were capable of generating many kilowatts of electromagnetic power at previously unattainable frequencies (Buffler, 1993). By the middle of the twentieth century, microwave ovens had been made avai1able for commercial and consumer uses. Sales rose from 100,000-125,000 units *per annum* in 1971 (Zante, 1973) to over one million units *per annum* in 1975 (Buffler, 1993). By 1985, over 50% of U.S. households owned microwave ovens, and food companies had begun to develop microwaveable products (Buffler, 1993). Today, the microwave oven is in daily use in almost every household.

Figure 3.1 shows the block diagram of a microwave oven. The line power (110V) is converted to 4kV by a high voltage transformer and supplied to a magnetron, which generates the microwave. The microwave is guided to an applicator through a waveguide for heating or drying.

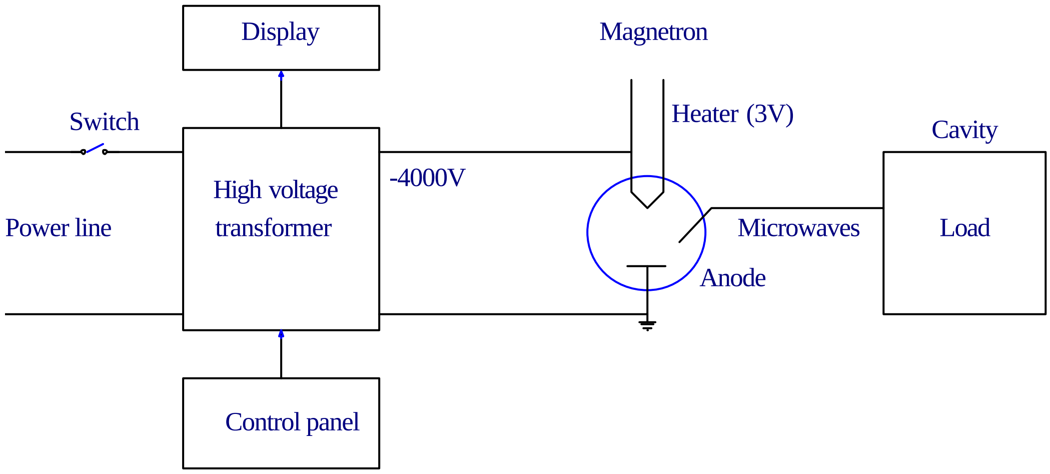


Figure 3.1 Block diagram of microwave oven (Buffler, 1993)

Conventional modes of foods heating include conduction, convection, and radiation. Microwaves are not heating themselves. Microwave-generated electric fields are a form of energy, converted to heat through their interaction with charged particles and polar molecules (Buffler, 1993).

Microwave ovens heat by radiation, using a monochromatic form of electromagnetic waves. The waves are of a single wavelength, longer than those used in conventional radiation, but shorter than those of common radio waves (Zante, 1973). The present range of frequencies defined as microwaves is from 0.3-300 GHz, with corresponding wavelengths of 1.0 mm to 1.0 m. Under microwave heating, heat is transferred to the food by *ionic* and *dipolar* interactions.

Ionic interaction

Water-bearing foodstuffs usually contain dissolved salts, such as the chlorides of sodium, potassium, and calcium. When dissolved in water, molecules of these salts are separated into two inversely (+ and -) charged particles or ions. Any charged particle in a microwave-generated electric field experiences an alternating force that alternates 2.45×10^9 times per second. The charged particle is first accelerated in one direction by the force and then drawn back in the opposite direction. Particles opposite in charge are accelerated in opposite directions. The accelerated charged particles collide with adjacent particles and impart an increasing agitated motion to them, resulting in a higher temperature. In addition, particles in motion interact with neighboring particles and transfer their motion to heat. Eventually, all neighboring particles have their temperatures increased. Thus, energy from the oscillating microwave electric field in the microwave oven cavity transfers to the materials inside the cavity, resulting in an increase in their temperature (Buffler, 1993).

Dipolar Interaction

Dipolar interactions occur mainly with water itself. In all foods and materials, water molecules are made up of two hydrogen atoms and one oxygen atom. These two hydrogen atoms each bear a positive charge, while the oxygen atom bears two negative charges. The charges are physically separated and, in this form, they are called a dipole (two poles). When exposed to a fixed or static electric field, the water molecules will rotate to orient themselves according to the direction of the field. Prior to applying the microwave electric field, all the water molecules in the food sample are thermally agitated in a random fashion, according to the initial temperature of the sample. When the electric field is applied, the molecules all attempt to orient themselves in the initial field direction. When the field reverses, the molecules attempt to reverse direction, collide with their neighbors and generate heat. Thus, energy is transferred from the oscillating electric field and generates higher temperatures. The dipolar interaction is the predominant microwave interaction in food heating and drying (Buffler, 1993).

3.2.2 The Magnetron

As the heart of the microwave oven, the magnetron is a device that efficiently produces continuous electromagnetic waves that serve as the source of energy within the microwave cavity. The magnetron is a specialized vacuum tube surrounded by a support frame and cooling fins. An antenna, generally mounted atop the tube, radiates the microwaves generated to a cavity or applicator. Within the magnetron is a cylindrical copper tube, capped at both ends with copper plates to maintain a vacuum. The tube is equipped internally with 12 coppers plates or vanes, which do not extend completely to the center, but leave an empty cavity where a spiral wire filament is located (Buffler, 1993; Figure 3.2).

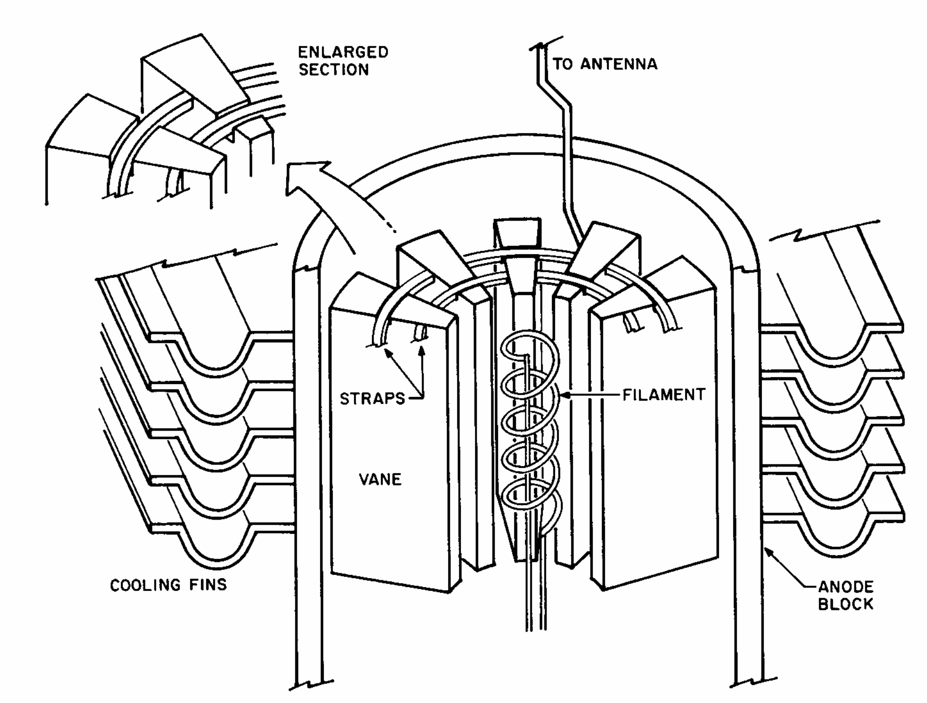


Figure 3.2 Principle of the magnetron (Buffler, 1993)

When the filament is heated, it emits electrons, forming an electron cloud in the centre of the vacuum tube. When 4 kV are applied between the vanes and the filament, an electric field is produced that rapidly accelerates the electrons away from their cloud toward the vanes. The magnetic field generated around the vanes causes the electrons to move in a curved path rather than a straight line as they jump from the cloud to the vanes. If the strength of the applied magnetic field is adjusted properly, the electrons will just skim by the tip of the vanes without striking them.

The twelve vanes form two electric circuits, with adjacent vanes being in different circuits, and every other vane being connected by electrical connections termed strapping. As an electron approaches a vane, it induces an equal but positive charge in this vane group, while the other vane group develops an equal and opposite (negative) charge. Consequently, adjacent vanes have alternating positive and negative charges. Because unlike charges attract and like charges repel, electrons adjacent to positively charged vanes would be accelerated, while those adjacent to negative vanes would be retarded. The retarded electrons fall behind and are met by the accelerated group forming clusters of electrons. As these electron clusters remain within the circular enclosure of the vanes, the positively charged vane group would begin to alternate between positive and negative charges, while the initially negatively charged vane group will alternate in a matching but oppositely charging sequence. If the velocity of these electrons is adjusted according to the space between vanes, it is possible to generate a vane group charge that alternates 2.45×10^9 times per second. Using the antenna, this alternating charge produces a radiating 2.45GHz microwave signal (Buffler, 1993). These waves are transmitted through a wave-guide to a feed box from whence they are distributed into the oven cavity.

3.2.3 Power supply and control of the microwave oven

As a magnetron of a commercial microwave oven requires 4kV for its operation, a high voltage supply is required. For most household microwave ovens, this voltage is provided by a half-wave doubler's power supply circuit. In this type of circuit, half of the voltage, 2kV, is supplied by the transformer, and then is doubled to 4kV by a capacitor-diode combination (Buffler, 1993). A transformer within the power supply portion of the system raises the voltage from the power line (110V) to that required by the supply circuit. The microwave output power from a magnetron can be varied by a number of techniques (Buffler, 1993):

1) Variable voltage supply. If the line voltage supplied to the transformer can be varied, so can the magnetron output power. Variable transformers and electronic circuits are available for this purpose, but are seldom used because of their high cost. The sensitivity of output power to line voltage is also a concern to microwaveable-food developers, as well as the consumer.
2) Resistive control. A resistance, serially connected to the diode in the capacitor-diode combination (the capacitor-diode combination used to raise the 2kV to 4kV) can limit the charge, hence reducing the voltage to below 4 kV. Power can then be controlled by switching between resistors. This technique is inefficient because the resistor must dissipate unused power, thus wasting heat and energy.

Furthermore, the heated resister must be cooled by some means. As a result, this concept has been used sparingly.

3) Capacitive control. By switching capacitors, the voltage supplied to the magnetron can also be changed. This technique is difficult to implement because the switching must take place at high voltages. It has thus seen only limited applications.
4) Duty cycle control. Almost all microwave ovens use duty cycle control to vary the oven power. The power is simply turned on and off periodically. The ratio between the time the oven is turned on and the time it is turned off determines the mean power delivered to the load.
5) Phase control. This is similar to duty cycle control, but the on-off time occurs within one cycle of the line power.

Most commercial microwave ovens apply "on-off" power control of the voltage supply (110V) to change the power output of the magnetron in an "on-off" mode (Duty cycle control). Different power levels can be achieved by different intervals of the "on" and "off" time. This method has also been extended to research experiments on the drying of bio-products. Many researchers are seeking for the best "on-off" intervals to achieve the best drying result for their specific products (Changrue *et al.*, 2004; Liang *et al.*, 2004). Even some specially designed feedback systems also use the "on-off" control of the power supplied to the magnetron to achieve temperature control in the drying process (Ramaswamy *et al.*, 1991; Ramaswamy *et al.*, 1998). Other power control methods have seldom been used until now.

3.3 Temperature measurement

As the organoleptic qualities of a dried foodstuff strongly depend on the temperature during the drying process, monitoring of temperature is necessary through all microwave-drying experiments. However, in a microwave environment, temperature sensors are restricted to those types that are not influenced or damaged by electromagnetic waves.

Temperature measurement techniques can be classified into two categories: contact and non-contact. Thermocouples, RTDs (Resistance Temperature Detector), and thermistors are the most prevalent and low cost contact sensors, whereas fiber optic probes are accurate, but expensive temperature measuring units. The response speed of contact-type temperature sensors is low. An infrared thermometer, which is a non-contact sensor, measures infrared energy emitted by the materials being measured. It is usually faster than the contact sensors.

3.3.1 Thermocouple

If two different metals, A and B, are joined together, a contact potential voltage is formed. The value of the potential depends on the types of the metals and the temperature of the junction (OMEGA, 2000).

A thermocouple is a temperature measurement device with two junctions. During temperature measurement, the two junctions are placed under different temperatures. If one junction is in contact with the target material and the other is left at 0°C, the temperature of the object can be measured directly.

The thermocouple signal is very small, typically a few mV, and often requires amplification for successive uses.

Only shielded, well-grounded thermocouples can be used in microwave ovens. Ramaswamy *et al.* (1998) evaluated several shielded thermocouples for temperature measurement inside a microwave cavity and reported that the shielded thermocouples could be used for temperature measurement in microwave ovens if they were well grounded to the cavity wall. Errors in temperature measurement were reported within 2°C. A feedback temperature control system based on a shielded thermocouple was designed for microwave ovens at an earlier time (Ramaswamy *et al.*, 1991). This system was successfully used to test thermal and microwave inactivation of soybean lipoxygenase (Kermasha *et al.*, 1993).

3.3.2 Fibre optic probe

A fiber optic sensor includes a small amount of temperature-sensitive phosphor, typically manganese-activated magnesium fluorogermanate, mounted at its tip. When excited with blue-violet light, the phosphor exhibits deep red fluorescence. After the excitation pulse is over, the intensity of fluorescence radiation decays. This decay time is measured and then correlated to the phosphor temperature by comparing the measured decay time with a digital look-up table. The temperature data is then converted to an analog or digital signal and/or displayed on an LCD.

The fiber probe is designed primarily for bulk measurement use, where the sensing tip is immersed in the medium whose temperature is to be measured. An unavoidable offset (-5ºC to -7ºC at 100ºC) would occur if it is used to measure the surface temperature.

The upper operational temperature limit of the probe is dictated by the plastics used in the jacket and cladding, and is usually 200ºC. The plastic melts at 320ºC. While drying temperature of foodstuffs in a microwave oven is always under 100°C. The 200°C limitation is more than enough for the fibre optic sensor to be used for temperature measurement in microwave drying.

The fiber optic probe is made of dielectric material and can thus safely be used in the microwave environment without further modification. Ramaswamy *et al.* (1991) compared the performance of a shielded thermocouple, a fiber optic sensor, and a thermistor under a microwave environment, respectively, and concluded that these three sensors performed very identical in temperature measurements. The overall range of standard deviations of the temperatures between 40 and 90°C for the three tested temperature sensors were 0.6-0.8°C, 0.5-0.6°C, and 0.4-0.6°C, respectively, which also indicated that the accuracy of fiber optic sensor was acceptable in microwave drying process. Today, the fiber optic sensors are widely used as a standard temperature measurement tool in the microwave environment at the research level. But its high price restricts its use in commercial market.

3.3.3 IR sensor

Infrared thermometers allow users to measure temperatures in applications where conventional sensors cannot be employed, for example, with moving objects (rollers, moving machines, and conveyer belts), or in contaminated and hazardous areas. They are also used for measuring temperatures that are too high for thermocouples or other contact sensors.

Field of view, emissivity, spectral response, and response time are the parameters considered in selection of given applications for an infrared sensor. The field of view is the angle of vision at which the instrument operates. The target must completely fill the field of view for accurate measurement. The temperature read by an IR device is the area-weighted mean temperature within the field of view.

Emissivity is the ratio of the energy radiated by an object at a given temperature to the energy emitted by a perfect radiator, or blackbody, at the same temperature. The emissivity of a blackbody is 1.0. All values of emissivity thus fall between 0.0 and 1.0. Emissivity is an uncontrollable factor in IR temperature measurement (OMEGA, 2000).

For any kind of materials, the sum of their emissivity (E), reflectivity (R), and transmissivity (T) for energy is equal to 1:

$$E + T + R = 1 \qquad (3.1)$$

Most commercial instruments have the ability to compensate for different emissivity values.

The spectral response is the width of the infrared spectrum covered by an instrument. Most general-purpose IR units use a wideband filter in the 0.7-14 µm range and would thus not be influenced by the 1.0-1000 mm microwaves. This spectral range also allows measurement to be taken without atmospheric interference.

The mean response time for IR thermometers is within 300 ms for most commercial products.

In an IR thermometer's electronic package, the nonlinear and small output (100-1000µV) from the sensor is amplified with a gain of approximately 1000, regulated, and linearized. The final output signal is at the mV or mA (4-20 mA) level, linear to the temperature. Some IR thermometers also provide digital signals through an RS 232 port.

Due to its non-contact characteristic and relatively low cost, the IR sensor can be successfully used for temperature measurement in the microwave environment. Its reaction time is much shorter than any other contact temperature sensors. Its time-stable property is also a great advantage over other sensors.

IV. TECHNICAL BACKGROUND

4.1 Motorola 68HC11 microcontroller

4.1.1 Microcontroller

Microcontroller devices, essentially tiny microcomputers with additional control features, are widely used by today's electrical engineers. They replace many analog and digital components and have far more advanced functions than those available decades ago. Microcontrollers can handle complex algorithms and cope with more input and output signals that are necessary for medium-complexity control systems. Different functions can be implemented by altering the programs that drive the microcontrollers, and the capability of performing variable functions makes a microcontroller a nearly universal device in many industrial and domestic applications.

Since the first microprocessor unit, Intel's 4004, was introduced in 1970, microprocessors have become a fundamental device for engineering design (Fox, 2000). Recent advances in semiconductor technology have resulted in more powerful, integrated microcontroller circuits. The Intel 8085, or Zilog Z80 microprocessors, which dominated the market during the 1980s, have now become essentially obsolete and have been replaced by far more capable and flexible microprocessors, such as the 68HC11. The 68HC11 is generally regarded as the best and most powerful 8-bit microprocessor for general use. For example, millions of 68HC11 have been used in electronic control modules of automobiles. In most mass-produced items that contain a microprocessor, the superior computational capability of a 16-bit microprocessor is often unnecessary. Thus, 8-bit microprocessors, such as the 68HC11, have continued to outsell the 16-bit microcontrollers (Miller, 1993).

4.1.2 Functions of the 68HC11

The 68HC11 is one of Motorola's newest and most powerful 8-bit microprocessors. Not only does it have a more advanced Central Processing Unit (CPU), and features such as two index registers that greatly simplify programming, it also is a true microcontroller owing to the following main functional components (Figure 4.1):

1) An On-Chip RAM, mainly reserved for interrupt vectors and for some monitor variables. User programs are usually not written in this area because of its small size and importance for system operation.
2) An On-Chip EEPROM. The user can write small programs to this area. The programs are maintained when the power is off. This allows the 68HC11 to run its program without a PC.
3) An On-Chip ROM, which is an accommodation for fixed programs that support the operating system.
4) An asynchronous Serial Communications Interface (SCI). This allows the 68HC11 to transmit and receive serial data in an asynchronous format. In this format, every character is represented by a 9-bit number.
5) A synchronous Serial Peripheral Interface (SPI). These parallel channels allow a 68HC11 to communicate with other microcontrollers or outside devices such as a keypad.
6) An 8-Channel, 8-Bit Analog-to-Digital (A/D) Converter. The converter accepts an analog input within a certain range of voltage and converts it into 8-bits digital numbers. Measured values of temperature and mass can thus be digitized and used in calculations undertaken within the microcontroller.
7) An 8-Bit Pulse Accumulator, which can count pulses by capturing the falling or rising edge of a pulse signal.
8) A Real-Time Interrupt Circuit. It allows the 68HC11 to be interrupted by outside devices such as a keyboard or another microcontroller, to execute another part of the program.
9) A 16 bit Timer with 3/4 Capture and 4/5 Compare. The capture function serves to capture an input signal. The compare function can be used to signal the 68HC11 that an event has occurred (Greenfield, 1992).
10) Power Saving STOP and WAIT Modes. The STOP instruction puts the 68HC11 in sleep mode by disabling the clock and dramatically reduces power consumption. The WAIT instruction stacks all registers and allows the 68HC11 to rapidly respond to an interruption (Greenfield, 1992).

11) Three I/O Ports (Expanded Mode)

a) Port A - 3 in, 3 out, 2 I/O (Timers). This is the port for real-time interrupts, input capture, output comparison, pulses accumulation and pulse width measurement. The versatility of port A functions makes the Motorola 68HC11 the most powerful 8-bit microcontroller currently available.

b) Port D - 5 I/O (Serial, keypad). This port is used as a serial communication interface (SCI) if the SCI function is enabled. Otherwise it serves as a general I/O port for digital signals.

c) Port E - 8 in (A/D, keypad). It is an 8-channel A/D converter, or a parallel communication interface used for a keypad.

Two Additional I/O Ports (Single Chip Mode)

d) Port B - 8 out in the single-chip mode. In the expanded mode, it acts as the upper 8 bits of the address bus.

e) Port C - 8 I/O in the single-chip mode. It acts as the lower 8 bits of the address bus and also functions as the data bus.

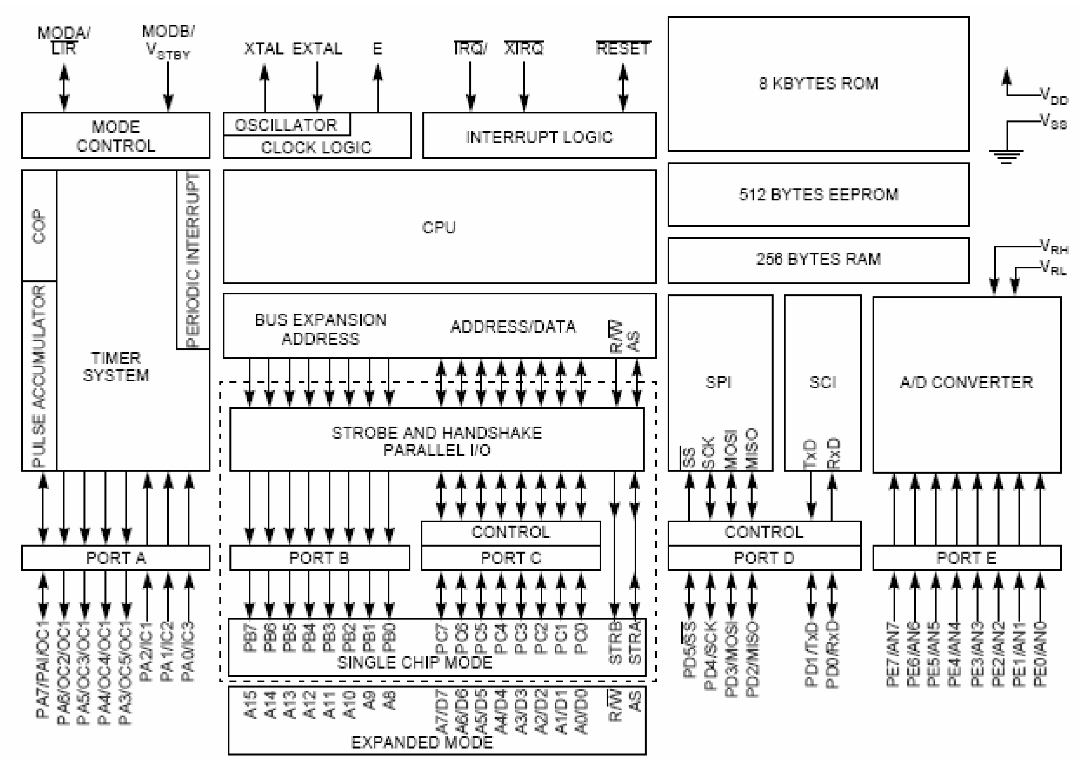


Figure 4.1 Block diagram of a Motorola 68HC11 microcontroller

(Motorola reference manual)

Based on the Motorola 68HC11, a number of development boards have become available. The CME11E9-EVBU development board includes the following components and some extra functions (Figure 4.2):

1) A Motorola 68HC11E9 Microcontroller;
2) Three configurable, 28-pin memory sockets, with two of them mounted with a RAM and an EEPROM separately;
3) A 32K RAM chip;
4) An 8K EEPROM chip;
5) Keyboard / SPI interface;
6) An LCD interface (memory mapped);
7) A Bus Expansion Port with seven chip selects;
8) A 3" x 1.5" solder-less prototype area. Users can build a small circuit in this area and connect it to the main development board easily.

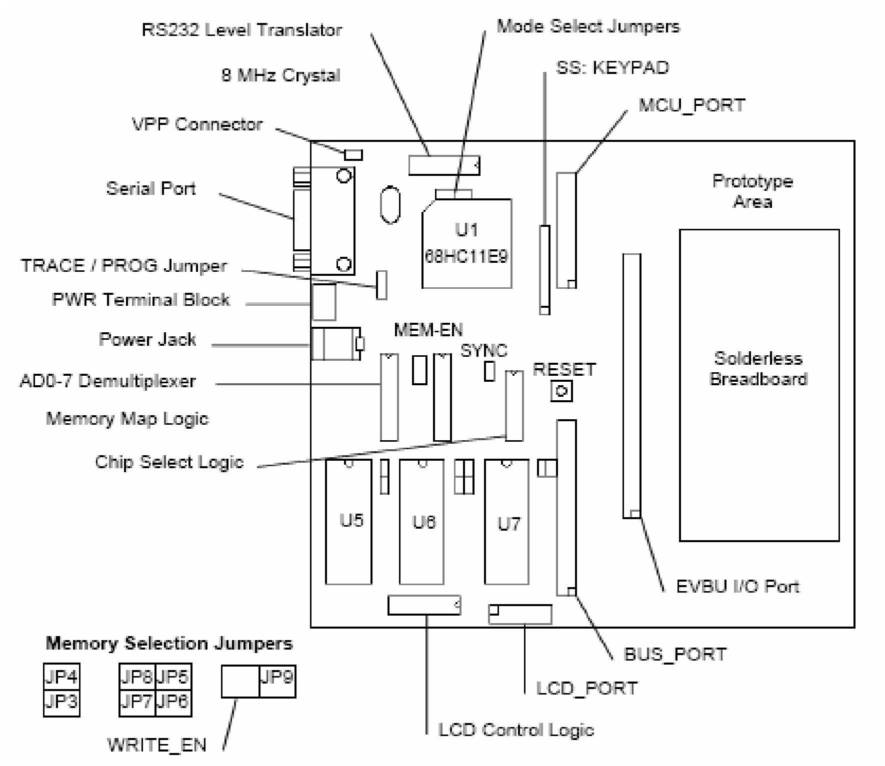


Figure 4.2 Block diagram of CME11E9-EVBU (Axiom manufacture, 1999)

4.1.3 Microcontroller programming

The CPU in the microcontroller can only recognize certain groups of bits as valid instructions in machine language. It is difficult to program directly in this binary machine language even for the simplest microcontrollers. Instead, several languages have been developed to "talk" with the microcontroller, e.g., the assembly language.

Assembly language is very close to machine language. It allows users to write programs using easily remembered mnemonics for the instructions, and symbolic names for memory locations and variables. It can produce the most efficient codes and allows users to set flags and registers that are inaccessible in high-level languages (Horowitz *et al.*, 1998).

Every microcontroller has its own special assembly language, and no standard for assembly language exists (Horowitz *et al.*, 1998). Usually the program, or source code, is written in Microsoft Notepad or Word, and then translated by an assembler program to produce the output as an object code that the microcontroller can execute. The microcontroller cannot execute assembly language instructions directly; instead, it can recognize object code that has been converted into machine language.

Besides assembly language, C, BASIC and FORTRAN, etc. can also be used to program a microcontroller. These languages need specific compilers to translate the source code into machine language, the only code that a microcontroller can accept. The problem with higher-level languages is that it is cumbersome, some time even impossible, to implement some convenient functions such as bit operations, and that the translation from the source code to machine language is complex and time consuming. Furthermore, compilers for these programs are always far more expensive than a simple assembler. Consequently, for some medium-size programs, it may be more suitable to program in assembly language.

All microcontrollers include built-in ROMs and RAMs, and most still have EEPROM available. After the program is assembled or compiled, it is usually recorded in the EEPROM and the microcontroller can run by itself after a reset or powering on, even without an auxiliary PC. This makes a microcontroller a convenient and useful device for a number of applications in household appliances and automobiles.

4.2 Power control techniques

4.2.1 Power control devices

While it is difficult to vary the output of the 4 kV power supply to the magnetron in a microwave oven, it is possible to control the power supplied to the primary coil of the main transformer.

Two main kinds of power switches are available: mechanic switches and electrical devices. Mechanic switches fulfill the switching duty in most commercial microwave ovens. However, they are relatively slow and not suitable for phase control. Electrical switches such as SCRs and TRIACs can be good alternatives to serve this purpose.

4.2.1.1 SCRs

The introduction of the silicon-controlled rectifier (SCR) in 1957 marked the beginning of a new era in the control of high-power devices by electronic devices. In equipment that requires power controls, SCRs replaced relays, thyratrons, magnetic amplifiers, and larger, auxiliary equipment such as mercury arc rectifiers (Fisher, 1991).

The SCR is actually a three-terminal, four-layer, PNPN junction semiconductor device. The three terminals form the anode, the cathode, and the gate, respectively. It provides a relatively small voltage drop in forward operation and only conducts a very small current when subjected to a reverse voltage, with a rapid transition from conducting to blocking states that takes only a few microseconds to tens of nanoseconds. The structure of a SCR is given in Figure 4.3, and its electrical symbol is shown in Figure 4.4.

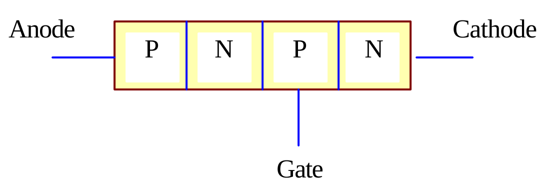


Figure 4.3 SCR structure

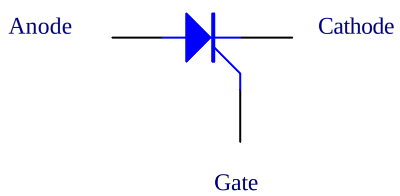


Figure 4.4 SCR electrical symbol

Due to its fast switching action, small size, high current and voltage ratings, the SCR is adaptable to many applications.

4.2.1.2 TRIAC

As an improvement on SCR, the TRIAC is a bi-directional device with three terminals that can be turned on in either direction by a gate current either in or out of the gate terminal, for either direction of the main terminal current (Fisher, 1991). It is a two-directional electronic switch that can conduct current in both directions when it is triggered (turned on). The TRIAC can be triggered by either a positive or a negative gate voltage. This makes the TRIAC a convenient switch for AC circuits. Applying a trigger pulse at a controllable point in an AC cycle allows one to control the percentage of current that flows through the TRIAC.

The TRIAC is actually built with two SCRs connected in anti-parallel, as shown in Figure 4.5. The five layers, N_1, P_1, N_2, P_2, and N_3, are combined to form a new device. When terminal T_1 is positive relative to T_2 by a voltage greater than the break-over voltage and the trigger signal is available, the device would break over by normal SCR action P_2, N_2, P_1, and N_1. For reverse current, layers P_1, N_2, P_2, N_3 would break over so that the other PNPN structure is presented to the external system. Figure 4.6 shows the electrical symbol of a TRIAC.

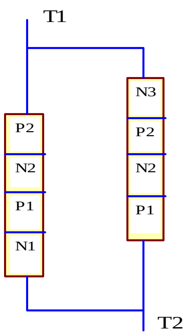


Figure 4.5 TRIAC structure

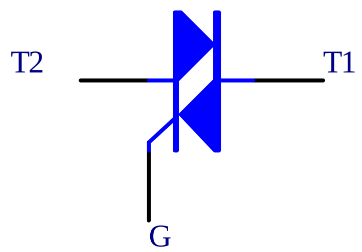


Figure 4.6 TRIAC electrical symbol

The TRIAC is commonly used in phase-control applications with a 60-Hz source voltage. Phase control requires repetitively triggering of the TRIAC at some fixed point after the zero crossings of the source voltage for both positive and negative half-cycles of operation. This means that the triggering circuit must be synchronized to the 60-Hz source voltage so that timing can begin from the zero crossings of the source voltage.

The gate current needed for TRIAC to be turned on is specified on a device's datasheet. This value depends on temperature, voltage between main terminals, gate-current duration for pulse operation, and the quadrant being used. Values also vary among individual TRIAC devices. To minimize turn-on losses, the TRIAC should be turned on as rapidly as possible by means of a gate current that is several times the minimum required value. This generally means a gate-current pulse of large amplitude but short duration. This pulse can be conveniently provided in several ways, but three common ways are (1) to rapidly discharge a capacitor into the gate terminal and (2) to use a pulse transformer to couple such pulses into the gate terminal, (3) to use an amplified signal from a digital device.

4.2.2 Power control methods

Electronic power control is not a new discipline; it began with the invention of SCRs more than forty years ago. This technology is now used in a wide range of areas, from industrial motor control and power supply to household use in audio amplifiers, heat controls, light dimmers, and hand power tools. For most applications, the 60-Hz fixed voltage power must be conditioned. Trzynadlowski (1998) estimated that, at the end of the 20th century, close to 60% of electrical power generated in the United States flowed through electronic power converters, and that this percentage would approach 100% in the following few decades.

Power conditioning involves AC to DC conversion or vice versa, and control of the magnitude and/or frequency of voltages and currents. Four general power conversion types represent the majority of power electronics applications (Datta, 1985):

AC-to-DC converters: Serve to obtain variable DC voltages from a constant AC voltage. One application is to use the DC source to drive a DC motor in variable speed modes.

DC-to-AC inverters: Serve to switch a DC source to an AC voltage with a fixed or variable frequency. In some cases an AC input voltage is rectified to DC, then inverted back to an output voltage with a fixed or variable frequency. Such inverters are used for variable speed motors, uninterrupted power systems (UPS), induction heating, and standby power supply.

DC-to-DC converter: Serve to convert a fixed DC to a different DC voltage level. One of its applications is to convert the output of solar cells on a spacecraft to other voltages to support various spacecraft systems.

AC-to-AC: Serves to periodically switch an AC input on and off, or to produce a phase-controlled alternating output of the same frequency. Phase control is included in this mode.

4.2.2.1 Phase control

As a widespread device for power conversion and power control, phase-control rectifier has been used for several decades. Before new techniques such as pulse width modulation (PWM) were developed, phase control had been the dominant mode of power control.

Phase-controlled rectifiers are applied in a number of different ways: half-wave resistive, full-wave resistive, half-wave inductive, and full-wave inductive. Under these applications, the AC voltage is rectified, and the beginning of conduction is delayed in each half-cycle to achieve a variable output voltage. Fisher (1991) stated that, given their ability to control large currents with relatively small pulsed-gate currents, SCR and TRIAC were uniquely adapted for power control.

Figure 4.7 illustrates a TRIAC-controlled, bi-directional power control circuit with a resistive load

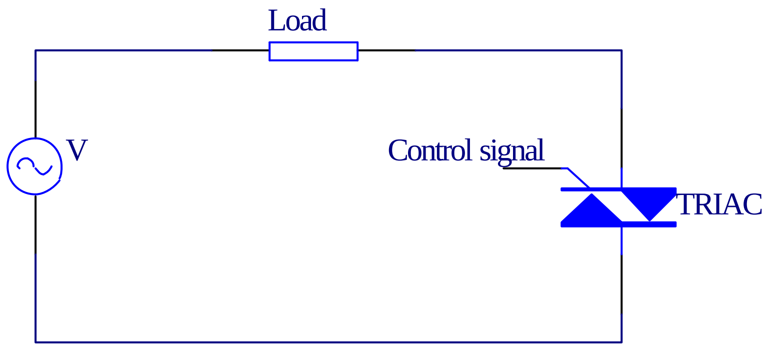


Figure 4.7 Principle of TRIAC control

During the first positive half-cycle of the sinusoidal supply, the anode is positive with respect to the cathode. Until the gate is triggered by a proper positive signal from the trigger terminal, the TRIAC blocks the flow of the load current in the forward direction. At some arbitrary delay angle, a positive trigger signal is applied between the gate and the cathode that initiates TRIAC conduction. Immediately, the full supply voltage, minus an approximately 1.5 V drops across the TRIAC, is applied to the load. For an inductive load, the current would continue but in the reverse direction for a finite time (Figure 4.8), after the supply voltage reverses for another half-cycle. The TRIAC continues to conduct while the stored inductive load energy is fed back to the supply (Datta, 1985).

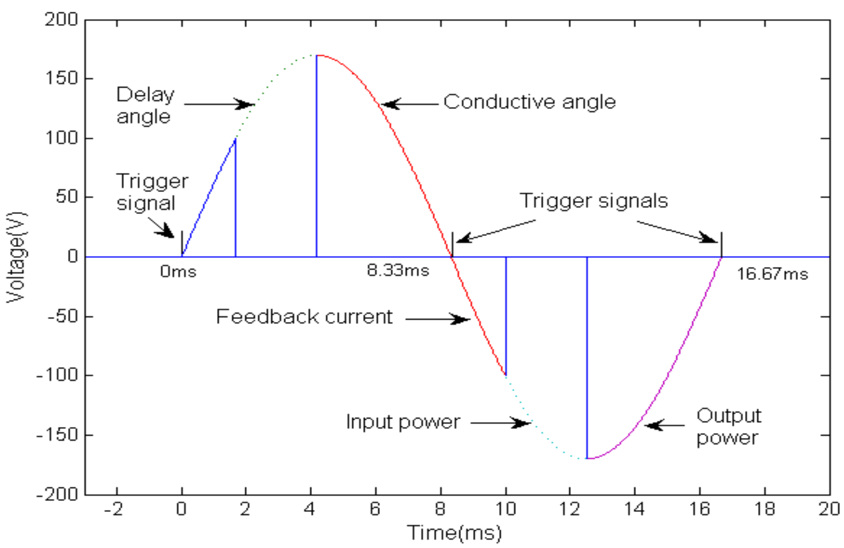


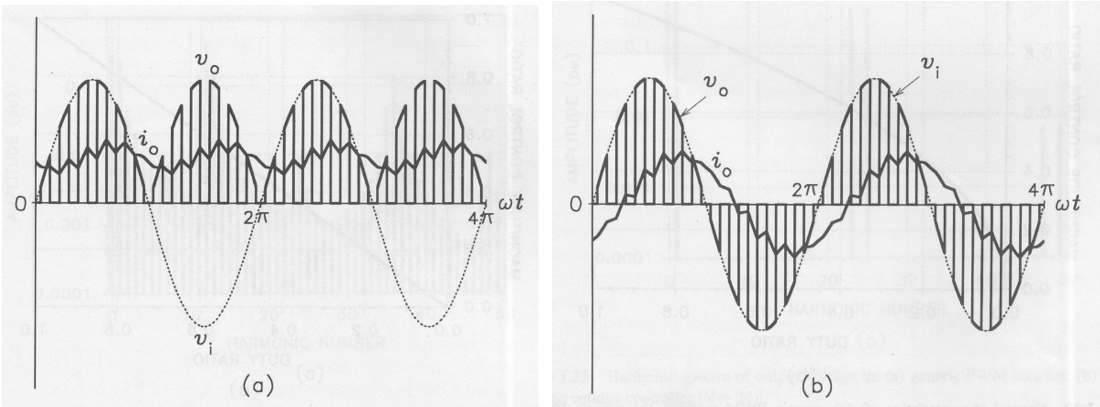
Figure 4.8 Inductive load in phase control

By controlling the delay angle with respect to the supply voltage, the phase relationship between the initiation of current flow to the supply voltage may be varied and the load current can be controlled from its maximum value down to zero.

4.2.2.2 Pulse width modulation

An alternate method of power control is *pulse width modulation* (PWM). It can offer better output power spectral characteristics than phase control and is increasingly being adopted in modern electronic power converters (Trzynadlowski, 1998).

The principle of pulse width modulation is to control the source voltage by using converter switches in such a manner that the output voltage consists of a train of *pulses* interspersed with *notches*. It can be used both as a constant voltage source or an alternating voltage source, and can even convert a DC source to a variable AC source by adjusting the ratio of the pulses. By increasing the frequency of the control pulses, current changes between the corresponding "jumps" of the output voltage can be largely prevented and high quality output can be obtained. Figure 3.11 shows the principle of pulse width modulation. V_i is the source voltage, V_o is the output voltage, and i_o is the output current. Figure 4.9 (a) and Figure 4.9 (b) show the rectified and the original source signals, respectively. However, the allowable switching frequency in practical electronic power converters is limited by two factors: (i) transition time of the semi-conductor from the on state to the off state and (ii) speed of the control system, or the so-called *switching losses* in a practical switch. According to Trzynadlowski (1998), a PWM converter's switching frequency balances the output quality and operation efficiency of the converter.



(a) Generic PWM rectifier (b) Generic PWM ac voltage controller

Figure 4.9 Output voltage and current waveforms in PWM control

(Trzynadlowski, 1998)

4.2.2.3 Adjustable resistor control

Prior to the advent of SCR and PWM technologies, adjustable resistors had been widely used for controlling the magnitude of load voltages. Even today, resistive control remains in use in relay-based starters for electric motors and near-obsolete, adjustable-speed drive systems, and some are employed in the power control of microwave ovens (Beaudry, 2001).

In some low-power electrical and electronic circuits, in which the issue of power efficiency is not of major importance, the use of small rheostats and potentiometers is still possible. However, in high-power circuits, one must consider the power losses associated with the resistors, which are unacceptable in many practical power control systems. Apart from economic considerations, large power losses in the resistor would require an extensive cooling system, because most of the lost electric energy would be converted to heat. Figure 4.10 shows why resistive controls should not be used in high-power applications (Trzynadlowski, 1998).

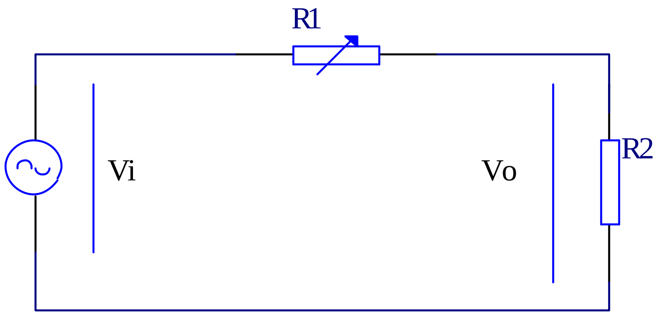


Figure 4.10 Resistive control schemes

For simplicity, it is assumed that the source is an AC voltage. Then V_o denotes the value of the adjustable component of the output voltage, V_i is the maximum available voltage, R_1 is the adjustable controlling resistor, and R_2 is the load. As the efficiency of the circuit is always far less than 1, R_1 would be heated.

4.2.3 Zero-crossing detection

A zero-crossing circuit is an electrical circuit that detects points at which the voltages of a signal are close to zero. The purpose of such a circuit is to control TRIAC conduction. In many applications, a power source is shut off for a specific time period and is turned on for another time period to achieve a desired load power. The applied power then can be adjusted by the on-off time of the TRIAC within a half cycle of the AC power or based on the time proportion. For example, if the time base is ten seconds and the desired power is 50%, the power would be applied for 5 sec and shut off for 5 sec. If the desired power is 25%, then the power would be applied for 2.5 sec and shut off for the remaining 7.5 sec. The load can be both resistive and conductive.

4.2.3.1 TTL zero-crossing detector

The circuit illustrated in Figure 4.11 generates a square wave output of 0-5V. The resistor R_1, in conjunction with diodes D_1 and D_2, acts as a voltage limiter that limits the voltage within the range of -0.6V to +5.6V. Resistors R_2 and R_3 then divide the –0.6V input to –0.3V for the LM393 comparator, while resistors R_5 and R_6 provide hysteresis and resistor R_4 sets the trigger points symmetrically about the ground. Consequently, the input to LM393 can go all the way to ground, which makes a single 0-5V supply operationally possible (Horowitz *et al.*, 1998).

The problem with this circuit is that it has no effective means of protection. If any of these diodes or LM393 is burned by an unexpected high voltage, the following TTL devices, or even the microcontroller, can be destroyed.

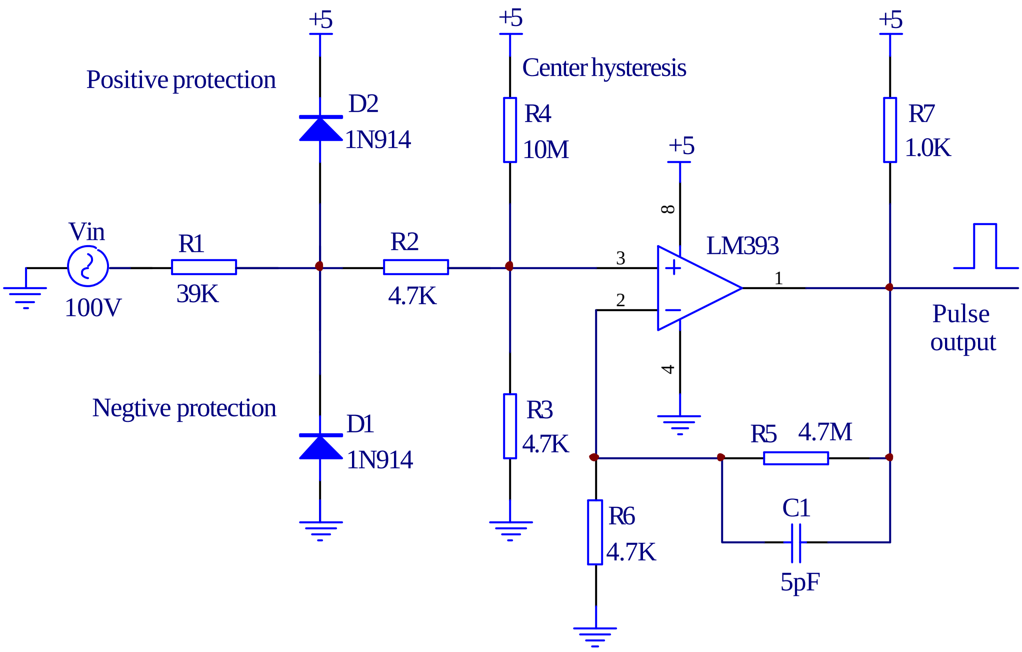


Figure 4.11 Zero-crossing level detectors with input protection (Horowitz and Hill, 1998)

4.2.3.2 Opto-coupler zero-crossing circuit

The Opto-coupler is an electrical component that is often used to isolate AC line power to digital/logic devices by optical means. It can also keep AC line noise and transients out of sensitive digital circuits. The principle of the opto-coupler is illustrated in Figure 4.12.

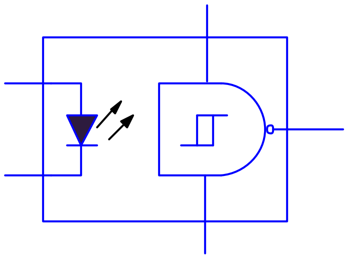


Figure 4.12 The principle of the opto-coupler

The most important feature of this component is that it can protect the successive devices by interrupting high voltage from optical transfer. Furthermore, as opto-couplers are fast, accurate, and safe, they have found applications in many circuits.

V. MATERIAL AND METHODS

In this research a feedback, temperature control system was designed for microwave drying. The power supply of a commercial microwave oven was redesigned so that the power to the magnetron can be adjusted according to the difference between the actual temperature measured from an object and a user-preset drying temperature. The actual temperatures were measured by temperature sensors. The temperature difference was calculated by a microcontroller and was used as a feedback signal. The smaller the difference, the lower the power sent to the magnetron. If the actual temperature reached or exceeded the user-preset temperature, the power sent to the magnetron was completely turned off.

The system was tested with water, carrot, and strawberry samples. The results were compared with a similar process of "microwave hot air convective drying" (Changrue *et al.*, 2004). Drying rate, colour change, and water activity were analysed after the drying process.

5.1 Hardware Design

The feedback, power control system designed for a microwave oven consisted of:

? a commercial household microwave oven,

? a zero-crossing detection circuit,

? temperature sensors,

? a microcontroller,

? a keypad and an LCD display,

? a TRIAC and associated circuit, and

? two personnel computers.

A block diagram and a figure of the feedback, power control system are shown in Figures 5.1 and 5.2, respectively.

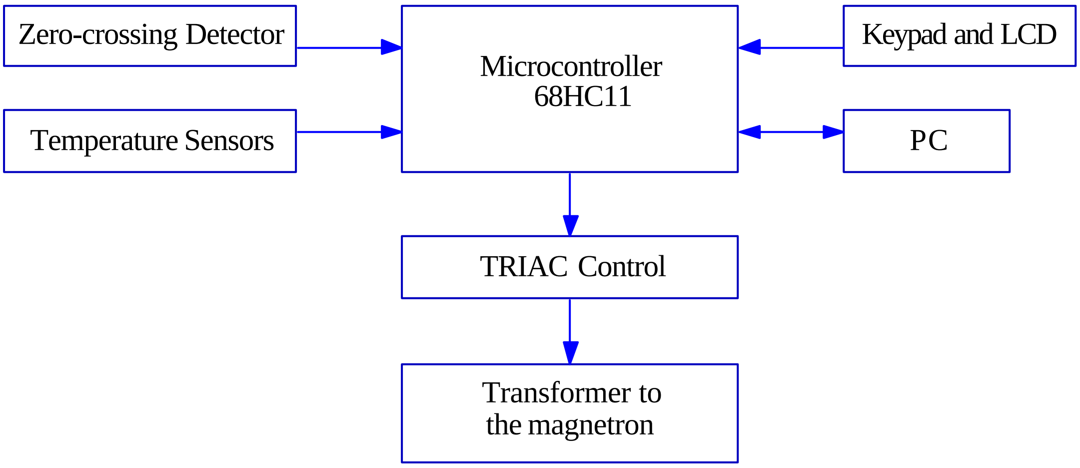


Figure 5.1 Block diagram of the feedback, power control system

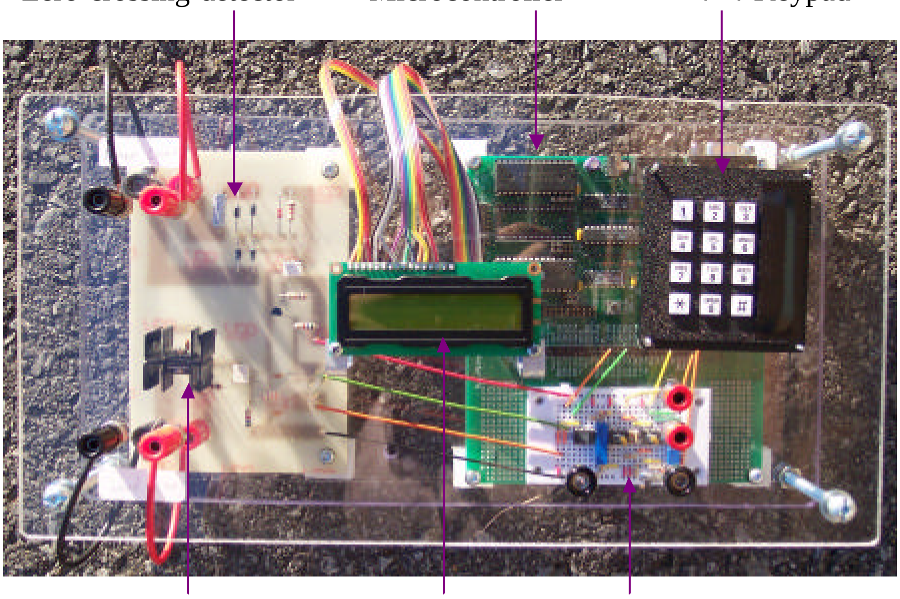


Figure 5.2 The feedback, power control system

5.1.1 Microwave oven

A commercial microwave oven (Danby, SMC Microwave products Co., Ltd., China) with a nominal power of 950W at a frequency of 2450 MHz was used as the test platform. To quickly exhaust moisture during the dry process, an air fan (5.88W, 12V) was mounted outside the cavity and close to a multi-hole outlet. Two small holes (4mm diam.) and a large hole (24mm diam.) were drilled through the ceiling of the cavity to allow the insertion of temperature sensors. The large hole accommodated an infrared sensor, while the two small holes accommodated a thermocouple and fibre-optic probes. The holes were sufficiently small to prevent microwave leakage from the cavity.

The infrared sensor head was mounted between the two layers of the ceiling cover to prevent possible arcing between the IR senor head and the microwave oven cavity. The thermocouple sensor was well grounded to the metal cavity of the microwave oven to avoid arcing. The fibre probe was fed through a plastic pipe to avoid scratching by the metal of the hole. To achieve uniform temperature distribution, a turntable was used.

The timer of the original microwave oven was disabled so that long-term drying process could be conducted. A power switch, which allowed the magnetron to be turned ON or OFF, was connected to a lamp in the cavity to indicate the power status. The fan and the turntable were turned ON or OFF with the main power in order to exhaust the moisture and to measure the temperature continuously while the magnetron power was OFF. The continuous turning of the turntable was necessary when the magnetron power was OFF, because the power for the magnetron must be turned on again when the actual temperature was lower than the user-preset temperature. Figure 5.3 shows a diagram of the modified microwave oven.

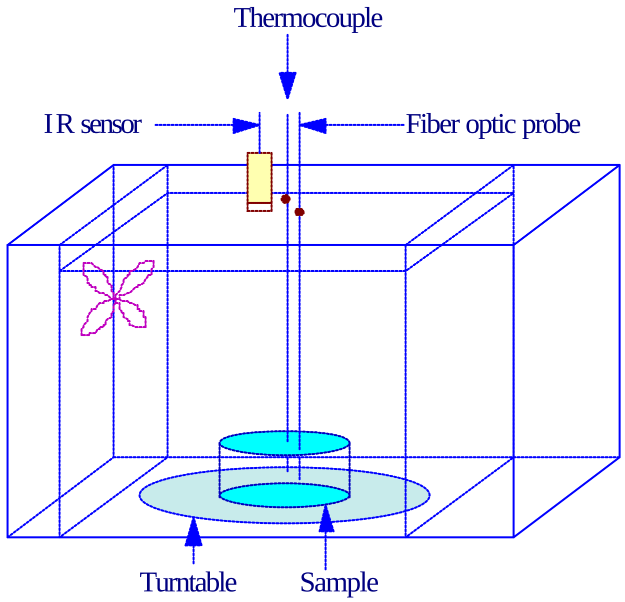


Figure 5.3 Diagram of the modified microwave oven

Originally, the output energy of the magnetron was controlled in an intermittent pattern. The energy level was determined by a ratio between the number of ON-cycles and the number of OFF-cycles within a predefined time period (Figure 5.4). In this study, the power control circuit of the microwave oven was modified so that a feedback power control system could be applied.

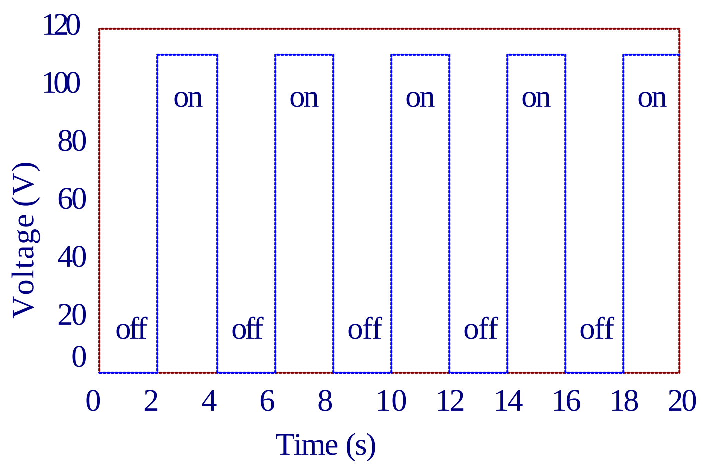


Figure 5.4 Illustration of the intermittent control

5.1.2 Zero-crossing detection circuits

A zero-crossing detection circuit was developed to provide trigger signals — a pulse train to the microcontroller for a phase-control of the magnetron (Figure 5.5). The zero-crossing detection circuit consisted of:

? A current limiter (R1), which absorbs extra voltage to protect the diodes and H11L1 (an opto-coupler). The 10kO resistor is much larger than the total internal resistance of the full-wave rectifier diodes, zener, and H11L1; the 3W power rating is matched with the maximum current.

? A full-wave rectifier. In every cycle of the sinusoidal wave, there are two zero-crossing points: one occurred when signal changes from negative to positive, the other from positive to negative. The full wave rectifier reverses the negative halves of the sine wave to positive. These straight positive signals allow the diode inside the H11L1 to conduct and trigger a Schmitt Trigger. This operation also made it possible to use one zener diode in the circuit to shift the zero point thresholds to +11V.

? A zener diode. The zener diode shifts rectified signal up to 11V. Compared with the 170V source peak voltage, this value is considerable small and near zero. The function of the zener is to avoid possible fluctuation that might occur around actual zero crossing points.

? An opto-coupled Schmitt Trigger (H11L1). The opto-coupler transmits signal by light, which isolates the following components from high voltages, and thus protecting them. The speed of transmission is sufficiently high to follow the 60Hz sine wave.

? Transistor. The output signal of H11L1 is insufficient to drive the analog input of the microcontroller. A transistor amplifies the current of the signal in order to drive the 68HC11 microcontroller.

The output signals of the zero-crossing circuit are 680?s wide pulses at a frequency of 120Hz, representing 120 zero-crossing points of the sine wave each second. The source voltage has to be the same as that of the main transformer; otherwise phase shift may occur to influence the control accuracy.

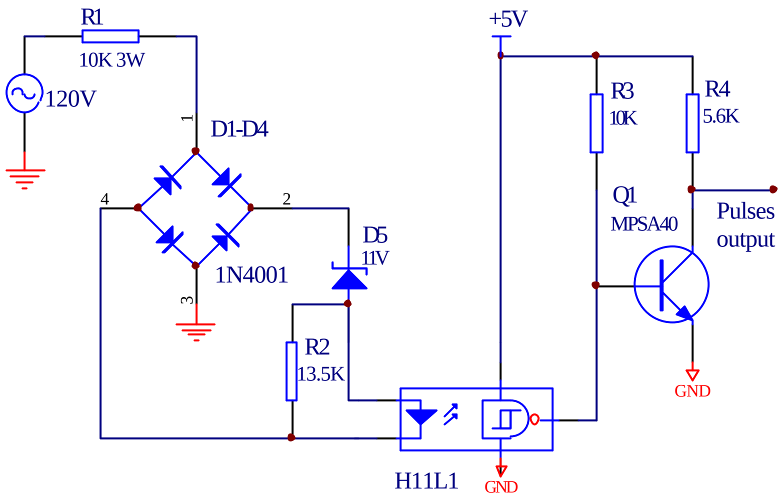


Figure 5.5 Zero-crossing circuit

5.1.3 Temperature sensors

Three temperature sensors, including a thermocouple, an IR temperature sensor, and a fibre-optic thermometer, were used to measure the temperature of the tested products.

1. Thermocouple

   A T-type thermocouple probe with a grounded sheath (HTQss-116, Omega, CT, USA) was used to measure the temperature of water during microwave heating. The thermocouple was inserted into the water sample through a hole with 4mm diameter on the top of the cavity. The sheath was soldered to the metal cover of the oven to avoid arcing between the thermocouple and the cavity walls. A signal conditioning circuit (Figure 5.6), including cold-junction compensation, signal amplification, and noise reduction, was designed to regulate the measured signal to a range of 0V-3.93V for a temperature range of 0ºC-99ºC, before it was read by the microcontroller.

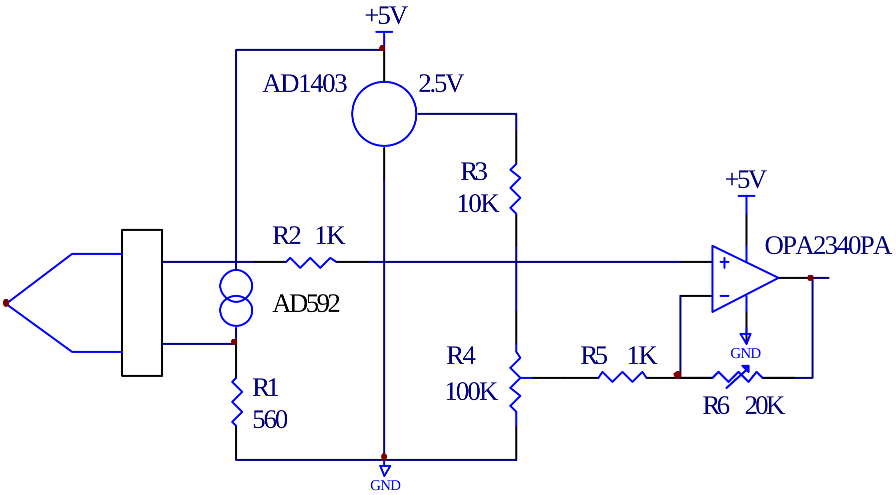


Figure 5.6 Conditioning circuit for thermocouple

2. IR sensor

A low-cost infrared temperature sensor (OS100, Omega, CT, USA) was used to measure the temperature of the test samples. The IR sensor was mounted between the two layers of the top of the cavity. The distance between the sensor and the measured samples was 160 mm. The field of view was 26 mm in diameter. The relationship between the field of view and the distance of a sample to IR is showed in Figure 5.7.

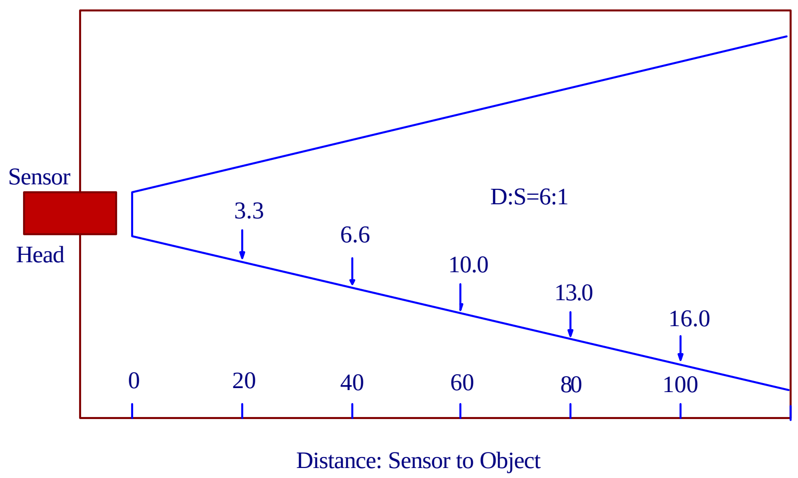


Figure 5.7 Field of view of the Infrared sensor (OS100, OMEGA, User's Guide)

The output voltage range of the sensor was 0.16V-1.05V for the temperature range of 0?C - 99?C. A signal conditioning circuit was designed to amplify the signal to 0V-3.93V to achieve a higher resolution for the A/D conversion (Figure 5.8). Four operation amplifiers (Op-amp) were used in this circuit:

? Op-amp 1 was set up as a "follower" circuit. This allowed the input signal to be duplicated at the same scale to the output and the input and output signals to be isolated with each other to reduce interference.

? Op-amp 2 shifted the zero point to 0.16V, since the output of the IR circuit at 0?C was 0.16V, not 0V.

? Op-amp 3 served as a subtractive circuit. The signal, after passing through Op-amp 3 had the 0.16V zero offset removed.

? Op-amp 4 implemented the amplifying function.

In this conditioning circuit, the zero-point shifting and amplification functions were independent of each other. When the zero-point shifting (the intercept of the amplification line) was changed, the gain (the slope of the amplification line) was not influenced. On the other hand, changing the gain would not affect the zero-point shifting either. This was very important, because these two variables may vary according to different factors, such as emissivities of different materials. This circuit provided an adjustable bridge between the sensors and the microcontroller. The zero point (the intercept) can be changed with R2 and the gain (the slope) can be changed by R10 separately.

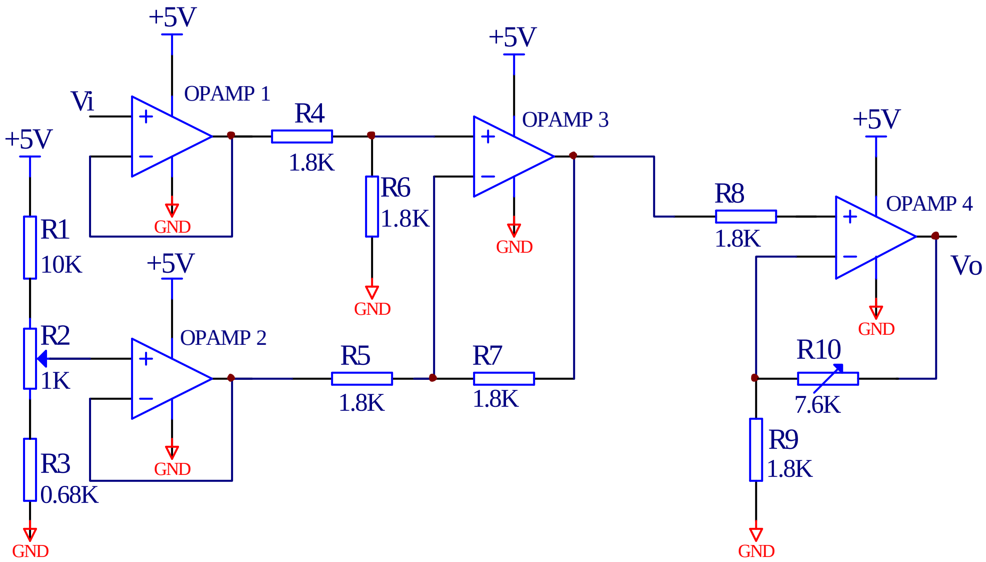


Figure 5.8 Conditioning circuit for IR sensor

For this circuit, the relationship between the input and output signals is:

$$V_o ? 4.42 ? ?V_i ? 0.16? \qquad (5.1)$$

3. Fiber-optic thermometer

A fluorescence fiber-optical thermometer (755 Fluoropitic?, Luxtron Corp., CA, USA) was used to provide temperature calibration. This thermometer has an absolute accuracy of ?0.5?C. Two fiber-optic probes, each sheathed in a protective plastic tubing, lest the probe be scratched, were inserted through two small holes in the ceiling of the cavity and were placed on or in the sample of interest. Temperature readings were recorded on-line by a computer with the "Hyper Terminal" program through an RS-232 port. To measure the temperature difference between the center and the surface of a processed product, two fiber probes were used, one for surface temperature and the other for center temperature. The surface temperature readings were used to calibrate and monitor the IR sensor.

The properties of the three types of temperature sensors are compared in Table 5.1, with the IR being the fastest and fiber-optic being the most accurate.

Table 5.1 Comparison of three temperature sensors

	Thermocouple	Infrared sensor	Fibre optic
Accuracy	±1°C	±2.2°C	±0.5°C
Response speed	1s	0.15ms	2s
Signal output (0°C -99°C)	-0.9-3mV	0.16V-1.05V	1-5V
Influenced by microwave?	Yes	No	No
Price	Low	Medium	High

5.1.4 Microcontroller

A single-board development system for Motorola 68HC11 microcontroller (CME11E9-EVBU, Axiom Manufacturing, TX, USA) was used as a core controller for the feedback, power control system. The main functions included:

? Collecting the temperature data from a temperature sensor and displaying the readings on the LCD;

? Reading a user-preset temperature from a keypad and displaying it on the LCD;

? Collecting a trigger signal from the zero-crossing circuit;

? Calculating the conduction angle based on the measured temperature and preset temperature;

? Outputting a square wave to control the conduction time of the power TRIAC so as to control the power reaching the high-voltage transformer, and

? Communicating with a PC for programming, debugging, and data uploading.

In 68HC11, an analog input channel (PE7) was used to collect temperature data from the temperature sensors (thermocouple or IR temperature sensor). Four digital I/O channels of Port D were used to collect the keypad readings for the user-preset temperature. A digital I/O channel, PA0, was used to read the falling edges of the trigger pulses from the zero-crossing detection circuit. PA6 was used to output a square-wave to control the conduction of the power TRIAC. Four special memory locations, $B5F0 through $B5F3, were used for LCD display. The duty cycle of the square wave was determined by the calculated conduction angle. This square wave was sent to an opto-isolator (MOC3012), which then turned on the TRIAC when the signal was "HIGH".

5.1.5 Keypad and LCD display

A 4×4 matrix keypad (ZEON 2 94VO, Grayhill Inc., LaGrange, IL, USA)(Figure 5.9) was used to preset the designated temperature. The keypad was connected to the 68HC11 through a ten-pin connector on the CME11E9-EVBU Development Board that employed 4 bits of Port D and 4 bits of Port E as a simple keypad interface. This interface provided an implementation for software key scan for the passive keypad.

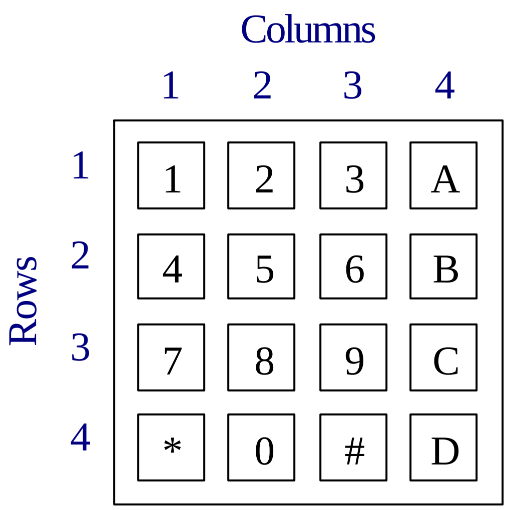


Figure 5.9 4×4 matrix keypad

An LCD (TM161ABA6, TIAMA Microelectronics, China; Figure 5.10) was used as the temperature display. It was connected to the 68HC11 through the LCD_PORT on the CME11E9-EVBU Development Board. The LCD interface was connected to the data bus in a memory mapped to locations $B5F0 through $B5F3. Address $B5F0 and $B5F1 are the Command and Data registers, respectfully.

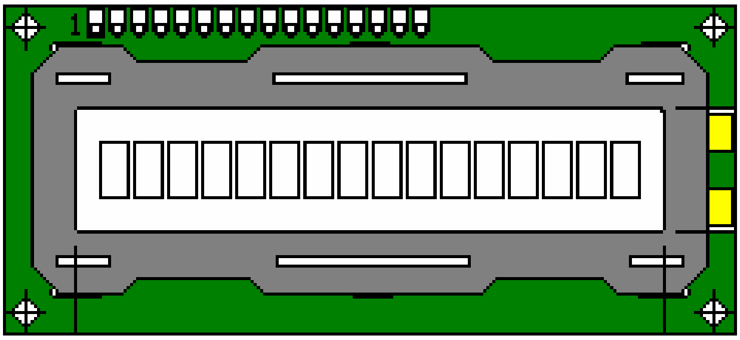


Figure 5.10 16×1 LCD

The LCD interface also includes power, ground and Vee pins. Table 5.2 shows commands of the LCD.

Table 5.2 LCD Commands

Commands	Instruction	Execution time
$01	Clear display & return cursor to home	1.53ms
$0F	Display on, cursor visible, blinking cursor	39µs
$3C	Set LCD as 8 bits data	39µs

5.1.6 TRIAC control circuit

A power TRIAC (Q4025L6-ND, Teccor Electronics Inc., Des Plaines, IL, U.S.A) was used to control the AC source (120V, 60Hz) to a high-voltage transformer of the microwave oven, which powered up the magnetron based on a phase-control principle. The TRIAC was wired to the low-voltage side (the primary coil) of the high-voltage transformer. To conduct the reverse current that may occur in the TRIAC during the power-off period, an RC circuit was installed in parallel with the anode-cathode of the TRIAC (Figure 5.11). A MOC3012 opto-coupler was used as a high voltage isolator to protect the microcontroller. R1 was used to load majority of the +5V of the signal to protect the MOC3012; R2 was used to dissipate the reverse current to speed up the reaction time of the MOC3012. R2 must be much larger than R1 to ensure that most of the input voltage V_i is directed to the MOC3012. With H11L1 and MOC3012, potential high voltage inputs and outputs were isolated from the 68HC11, thus protecting the microcontroller and other digital devices.

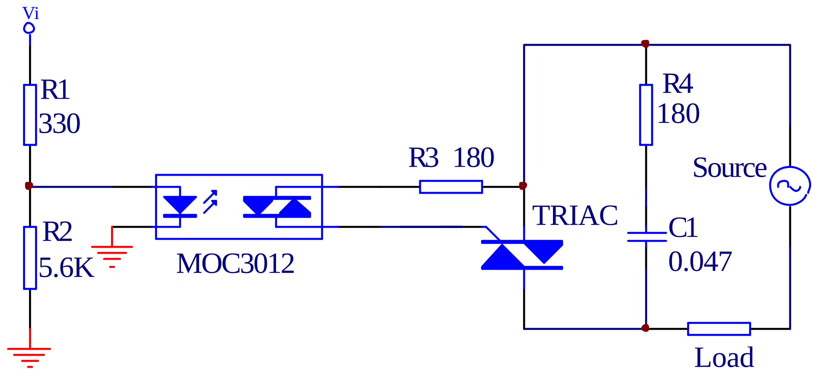


Figure 5.11 TRIAC circuit

In phase control, after each zero-crossing point, the power was cut away at a "delay" angle (in time) and then conducted for a "conduction" angle (in time) (Figure 5.12). The ratio of these two angles determined the power supplied to the transformer and the magnetron.

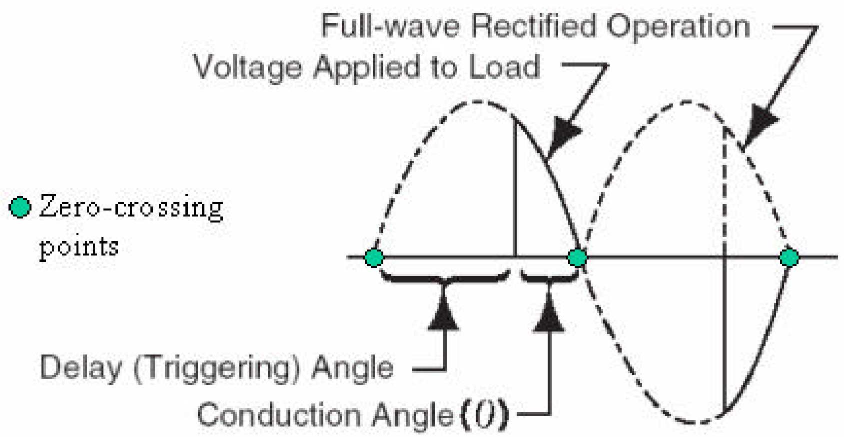


Figure 5.12 Concept of phase control (Courtesy: Teccor Electronics Inc.)

5.1.7 Personnel computers

A PC was connected to the 68HC11 through RS-232 and was used to program in assembly language, to download programs to 68HC11, to debug the program, and to read and record data from the 68HC11. An interface (BUFFALO: Bit User Fast Friendly Aid to Logical Operation, Axiom Manufacturing, TX, USA) between the microcontroller and the PC was installed to accomplish these functions. Once the program was downloaded to the EEPROM of the development board, the microcontroller could operate without the PC. Thus, a PC was not an essential part of the system.

Another PC was employed to record the temperature from the fibre-optic thermometer. An RS232 cable was used to connect the PC and the fibre-optic thermometer. The temperature was recorded every two seconds through the "Hyper Terminal" interface.

5.2 Software Design

The system software included a program for user interface, a program for data acquisition and pre-processing, a program for LCD and data recording, a program to calculate the triggering angle, and a program to generate a control waveform for the power TRIAC. All programs were written in assembly language of the Motorola 68HC11 (Greenfield, 1992), compiled and debugged by the Buffalo Development Tools (Axiom Manufacturing, TX, USA), and run on the 68HC11 microcontroller.

5.2.1 User interface

The program first scanned the keypad in rows. If a key was pressed, its row and column positions were recorded and saved in a memory space. After the first digit of the preset, desirable temperature was pressed, the program waited for 66ms. This avoided the same key to be read twice, since 66ms exceeded the time a person's finger generally stays on a key, but was sufficiently long that the program could correctly read the next key input. After this 66ms waiting period, the second digit should be entered and its row and column positions were saved in another memory place. These two key inputs were converted to a decimal number, which was then shown on the LCD display. After the desired temperature was entered by the user through the keypad, it was converted to a hexadecimal number for convenient comparison with the actual temperature, and the system then shifted to the main program.

As the food drying temperatures were usually between 0?C to 99?C, the preset desirable temperature was defined within a range of 00-99. As the keypad was a 4×4 matrix, the right column (A, B, C, D) were considered dead keys and the keys of the fourth row (*, 0, #) were all recognized as "0" by the program. Figure 5.13 shows a flowchart of the keypad reading and processing procedure.

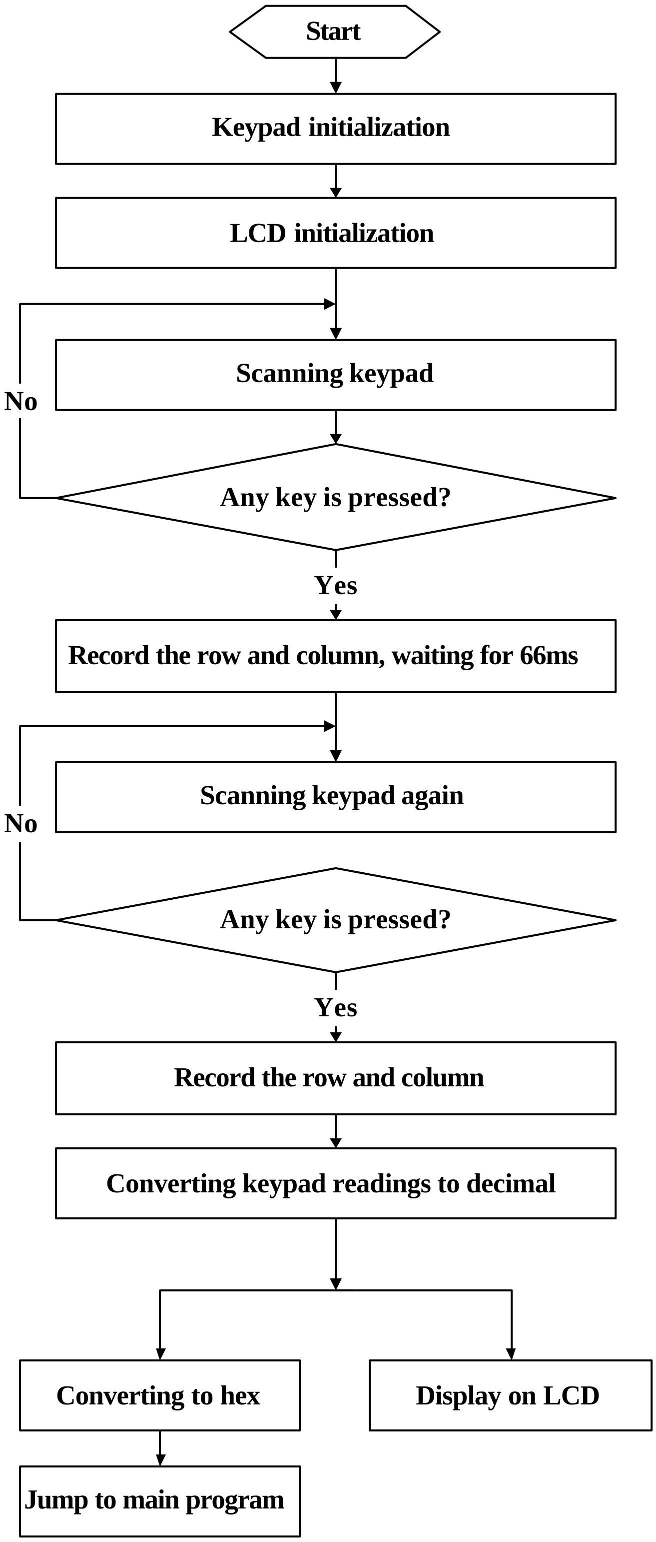


Figure 5.13 Keypad reading and processing

5.2.2 Data acquisition and pre-processing

At every zero-crossing point of the AC power source signal, a falling edge generated by the zero-crossing detection circuit was detected by the 68HC11. The program was designed to wait until this falling edge was captured.

This falling edge was followed by a data collection from the temperature sensor (thermocouple or IR sensor) immediately. Because the AC power source signal had a frequency of 60Hz and thus 120 zero-crossing points, 120 falling edges were generated by the zero-crossing circuit each second. Thus, 120 temperature readings were collected within a second.

The maximum value among the 120 readings was selected to calculate the delay angle for TRIAC control. This delay angle was updated every second. The purpose of this operation was to identify the maximum temperature of the food while the turntable was turning. The maximum value was used to avoid over-heating.

The user-preset temperature value was in decimal format and the actual temperature read by the 68HC11 was in hexadecimal. Hence, a program was designed to convert the user-preset temperature readings from decimals to hexadecimals to calculate the delay angle and to convert the result from hexadecimals to decimals for LCD display.

The A/D converter of the 68HC11 converted 0-5V (0-5.08V in this CME11E9-EVBU evaluation board) signal to 00-FF, or 0-256 in decimal. The user-preset temperature was defined as 00-99 in decimal, which became 00-198 if multiplied by 2. This 00-198 range corresponded to 0-3.93V within the full range of 0-5.08V (00-256). The temperature conditioning circuits thus converted the original signal of the temperature sensors to 0-3.93V to make calculation in the program easier.

5.2.3 LCD and data recording

The user-preset temperature (00-99) was displayed on the LCD, followed by a "-". The second to second maximum measured temperature was converted from hexadecimal to decimal and was displayed after the "-". The display was updated every second.

A 20kB memory space, which was sufficient to record 5.68 hours of data, was reserved for data recording. The second to second maximum measured temperature was converted into decimal values and saved in the memory of the development board. The Buffalo interface allowed these data to be transferred to Microsoft Word files on the PC.

5.2.4 Calculation of the conduction angle for TRIAC control

The conduction or triggering angle of the TRIAC was based on the rated power of the microwave oven, the user-preset temperature (t_0) and the actual temperature (t_1).

If $t_0 > t_1$, the triggering angle was calculated by Equation 5.2, where k and c are constants based on the capacity of the oven and are derived experimentally from the relationship between the power output of the magnetron and the power supplied to the microwave oven (Buffler, 1993). The value of k should be large enough to ensure a temperature change between two temperature readings, yet not too large to exceed the half cycle of the sine wave (8.33ms). In the latter case, an extreme circumstance would occur: the preset temperature is 99?C and the actual temperature is 0?C. The value of c is used as a complement of k.

$$\text{Triggering Angle(sec)} ? k ? (temp_0 ? temp_1) ? c \qquad (5.2)$$

If t_0 ? t_1, the power was turned off.

5.2.5 Generation of a control waveform for the power TRIAC

Based on the calculated delay angle, the 68HC11 generated a square wave to control the conduction of the TRIAC. The period of the square wave was a half of the period of the AC source (8.33ms). The calculated triggering angle determined, within a given period, the duration of “LOW” (**0**, i.e. TRIAC does not conduct) or “HIGH” (**1**, i.e. TRIAC conducts). Figure 5.14 illustrates the TRIAC conduction control using the square wave.

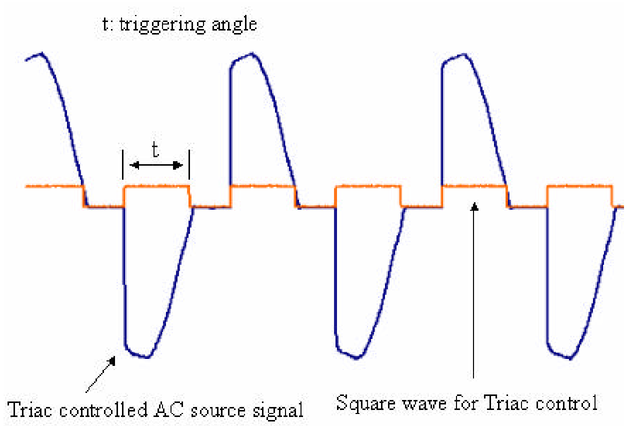


Figure 5.14 TRIAC conduction control using a square wave

In the program, only the ‘LOW” time in a period of square wave was calculated. The rest of period was assigned “HIGH” until next zero point came. The duration of “LOW” was determined by a “Delay” subroutine, which decremented a hex value determined by k and c until the value reached zero.

The “real time” function of the 68HC11 was not used in the software design because it required the use of port A in the timing system, which would disturb the function of PA0 and PA6 that were essential in zero-crossing data acquisition and square wave output (Greenfield, 1992).

This square wave was generated by PA6 of 68HC11, and was outputted to a power opto-coupler (MOC3012 in Figure 5.11), which isolated and protected the microcontroller by way of an optical switch. Table 5.3 lists the I/O ports of the 68HC11 microcontroller.

Table 5.3 I/O port configuration of the 68HC11

I/O port	Function
PA0	Zero-crossing reading
PA6	Square wave output
PD2, 3,4,5	Keypad reading
PE7	A/D converter for temperature reading

A flowchart of the software is presented in Figure 5.15.

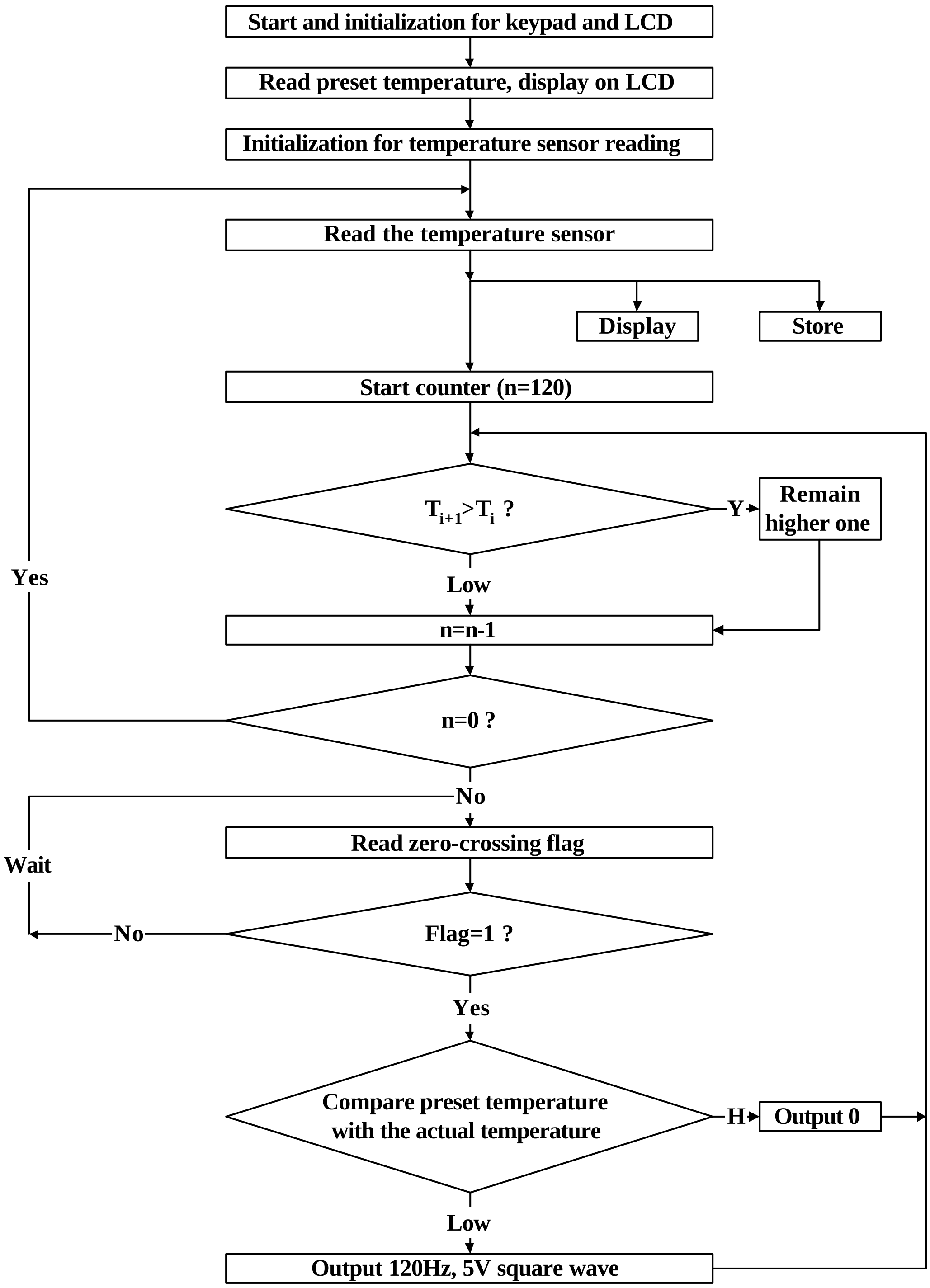


Figure 5.15 Flowchart of the program

The program for the control system is given in Appendix A.

5.3 System Tests

Individual parts of the system, including the zero-crossing detection circuit, temperature sensors, conditioning circuit, microcontroller square-wave output, and TRIAC circuit, were tested first. Individual parts of the program were also checked separately.

Before applying to a drying process, the system was first calibrated with a fibre-optic thermometer and a water sample. A conditioning circuit was used to adjust the slope and intercept of the amplification line. A water sample was used for calibration because it provided a more uniform temperature distribution across the depth. The non-contact IR sensor only measured the surface temperature whereas the fibre-optic sensor required penetration into the sample. If a solid sample was used for calibration, the difference between the surface temperature measured by the IR sensor and the internal temperature measured by the fibre-optic sensor would have caused significant calibration errors.

After calibration, the system was tested with carrot samples. Same drying tests was also conducted using microwave hot air convective drying. The drying rate, product colour, and water activity were analysed and compared with those of the on-off microwave power control system without feedback temperature control.

5.3.1 Hardware Tests

5.3.1.1 Zero-crossing detection circuit test

The zero-crossing detection circuit was designed to output 0-5V pulses every time the sine wave passed a zero point. These pulses must have high output current to be accepted by the 68HC11.

The pulse output of the zero-crossing circuit was first tested with an oscilloscope (Agilent 54621D. Agilent, Palo Alto, CA, USA). The waveform was recorded and converted to an Excel graph. The magnitude, width, and frequency of the pulses were also measured by the oscilloscope. A capacitor was connected in parallel to the load to reduce the noise.

5.3.1.2 Temperature sensors tests

The thermocouple and IR sensor were tested from 0ºC-99ºC. Their output signals were recorded and linear relationships between the readings and the temperature were established. The fibre-optic thermometer was used for calibration. Tap water and frozen-ice were mixed as the test sample at 0ºC. The microwave oven was used to heat the water.

The signal-conditioning circuit for the IR temperature sensor was adjusted and tested from 0ºC to 99ºC. Two potentiometers, R2 and R10 (Figure 5.8) were adjusted for intercept and slope of the amplification line, respectively. The conditioning circuit for the thermocouple was not used due to safety concerns for the thermocouple under the microwave environment.

The logic power supply of the CME11E9 Development Board was measured, and was used as the reference voltage for A/D conversion. The output of this circuit was within the range of 0-3.93V, corresponding to 00-198 in decimal or 00-C6 in hexadecimal.

5.3.1.3 Control tests

The output in PA6 of the 68HC11 was checked by an oscilloscope before it was used to drive the TRIAC. Various duty cycles, from 0% to 100% of the half sine wave, were tested. Various temperature inputs to PA0 were imitated by a Proto-Board (Proto-Board PB 503, Global Specialties, Cheshire, CT, USA), which generated potentials of 0-3.93V. A digital multimeter (FLUKE 73III, John Fluke Mfg. Co., Inc., Everett, WA, USA) was used to measure the voltage output. The influence of electric noise on PA6 output was also considered and a capacitor was used to reduce the noise.

The TRIAC circuit was also checked with an oscilloscope. Two kinds of load, resistive and inductive, were used as testing loads. The waveform is analysed and discussed.

5.3.2 Software tests

The keypad scanning and LCD-display program was tested first. The delay time of the LCD command and the interval between two preset temperature digits were checked and selected.

The data-recording program was inserted into the main program. Contents of the memory were extracted by the “READ” function of the Buffalo to test the ability of the system in recording the results.

The square wave generation and calculation programs were tested separately before they were combined.

The Buffalo Monitor system was used to monitor the execution of the program. Breakpoints were set in the program. Finally, the complete program was tested for system operation.

5.3.3 Drying tests

Tap water in an open, round plastic container (110mm diam., 55mm depth) was used to calibrate the temperature control by the feedback control system. Two different temperature sensors (a thermocouple and an IR sensor) were calibrated and their functions in the feedback control system were compared.

Carrots of an unknown cultivar were used to evaluate the drying process under the feedback control system. Carrots were cut into $1000mm^3$ cubes, and 200±5g of cubes were placed on a plastic colander, forming a single layer. During the drying process the bulk weight of each carrot sample was measured every 15 minutes for the first two hours and every 30 minutes afterwards.

Three sets of tests were conducted to evaluate the performance of the feedback power control system. The objectives of these tests were:

1. Test 1: calibrating the system to control the temperature of a water sample during microwave heating using a thermocouple.
2. Test 2: calibrating the system to control the temperature of a water sample during microwave heating using an IR temperature sensor.

3. Test 3: evaluating system performance in controlling the temperature of a carrot sample during microwave drying.

In Test 1, the thermocouple probe was used to measure temperature of the water sample inside the cavity of the microwave oven. A fibre-optic temperature probe was used to calibrate and verify the temperature control. The tips of both probes were placed 10mm apart. Various target temperatures, ranging from 35 ºC to 85 ºC in 10ºC intervals, were preset using the keypad. Temperature readings from the fibre-optic sensors were used to calibrate the conditioning circuit and to verify the control performance.

Test 2 followed the same procedures as Test 1, but used the IR sensor to measure the water temperature. Target temperatures ranged from 30 ºC to 80 ºC in 10ºC intervals. Temperatures controls using the thermocouple and the IR sensor were compared.

Test 3 served to evaluate the microwave drying process under the control system. The IR sensor was used to measure the surface temperature of a carrot sample placed underneath the sensor. A turntable was used to rotate the sample in order to achieve a uniform temperature distribution. The carrot sample was taken out and weighed on an electronic scale (TR-4102D, Denver Instrument Co. Ltd., CO, U.S.A) at the time intervals described above. Drying curves were obtained in the form of moisture ratio versus time. The moisture ratio (*MR*) was calculated as:

$$MR ? \frac{M ? M_e}{M_0 ? M_e} \qquad (5.3)$$

Where M is the moisture content (wet basis), M_0 is initial moisture content, and M_e is the equilibrium moisture content, which equals 4.6% (wet basis), according to Prabhanjan (1994).

Surface colours of the carrots were measured using a chromameter (CR-300, Minolta Camera Co. Ltd., Japan). Colours of both fresh and dried carrots were measured for comparison. The 3-dimensional L*, a* and b* scale is used in Minolta Chromameter. The L* is lightness coefficient, ranging from 0 (black) to 100 (white) on a vertical axis. The a* ranges from red (positive value) to green (negative value) on a horizontal axis.

The second horizontal axis is b*, which represents yellow (positive value) or blue (negative value) colours (McGuire, 1992).

The water activity, a_w, was measured by an Aqua Lab (Model series 3 TE, Decagon Devices Inc., Pullman, WA, U.S.A). The carrots were cut into small pieces (approximate $2mm^3$ cubes) and put in the device for water activity measurement.

The drying results (drying rate, product colour, and water activity) were compared with those obtained in a prior experiment with combined microwave and hot air convective drying (Changrue *et al*., 2004).

Finally, to evaluate the drying process, two fibre-optic temperature probes were used to monitor the temperatures in the centre and on the surface of a product. Whole strawberries were used as the test samples. The IR sensor, which measured the surface temperature of the test sample, was used to provide the feedback temperature signal. The surface and centre temperatures were compared.

Figure 5.16 shows the test setup using the IR sensor to provide the feedback temperature signal and the fibre-optic thermometer to provide a calibration temperature to examine the control performance. A block diagram is given in Appendix B.

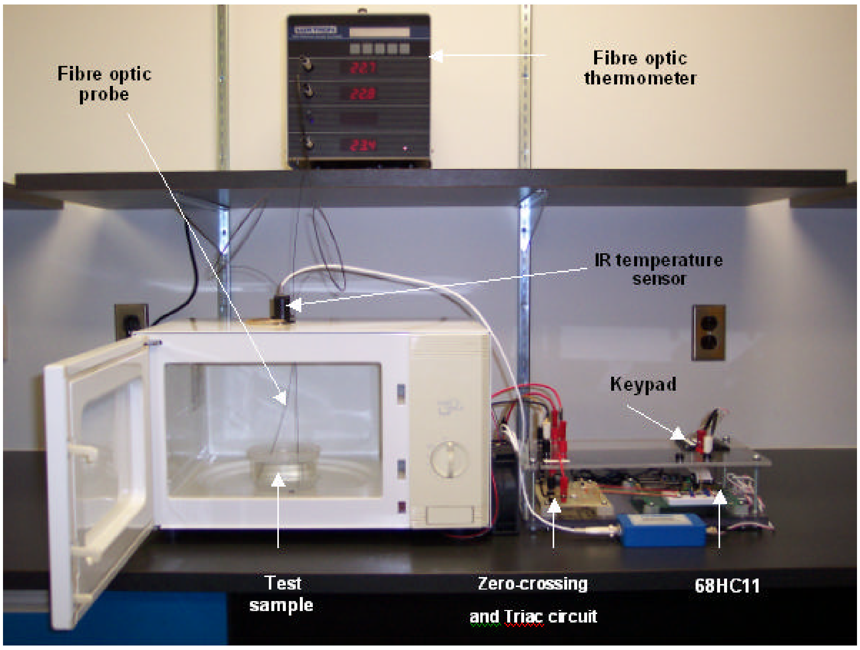


Figure 5.16 Test setup for the feedback power control system

VI. RESULTS AND DISCUSSION

Results of the hardware testes, software tests, and drying tests are reported in this Chapter.

6.1 Hardware tests

6.1.1 Zero-crossing detection circuit test

The output of the zero-crossing detection circuit is shown in Figure 6.1.

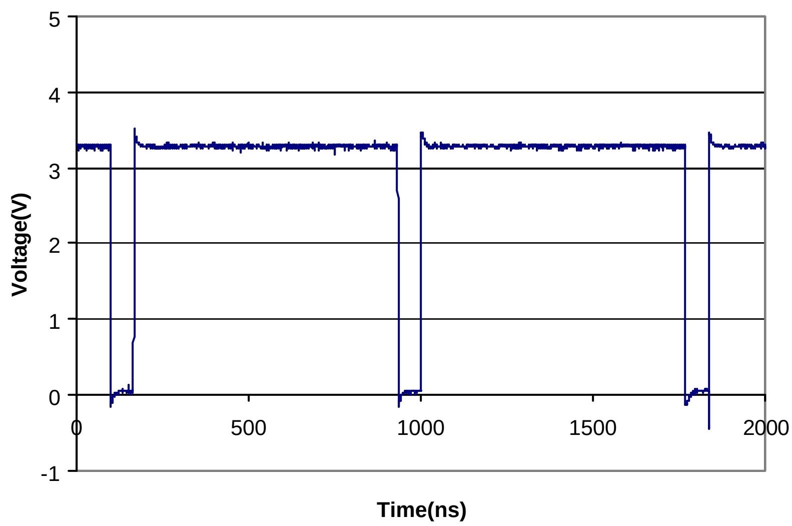


Figure 6.1 Pulses generated at zero-crossing points of the power signal

The magnitude, width, and frequency of the pulses were set to 3.22V, 680?s and 120Hz, respectively. The magnitude of the output is amplified by the transistor Q1 (Figure 5.5) to drive the microcontroller, 68HC11. The width of the pulses was determined by the H11L1 (Figure 5.5). The 120Hz pulses corresponded to 120 zero-crossing points of the 60Hz line power. The noise was minimized by a 470? F capacitor.

6.1.2 Tests for temperature sensors

During the tests, the signal conditioning circuits for the thermocouple and the IR sensors were fine-tuned. Parameters of the electronic components in the conditioning circuits were adjusted to achieve the best linearity for temperature measurements.

Figure 6.2 shows that the relationship between the temperature and the voltage output of the thermocouple is nearly linear. The output voltage was from –0.9mV to +3mV for the temperature from 0?C to 95?C.

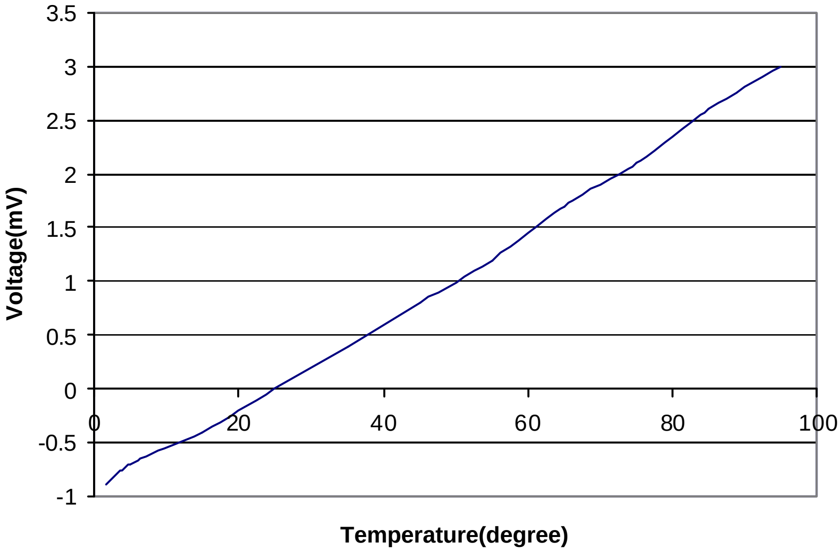


Figure 6.2 Calibration results for the thermocouple

Figure 6.3 shows the relationship between the temperature and the voltage output of the IR sensor. It also has a nearly linear relationship. The output voltage was 0.16V to 1.01V for temperatures ranging from 0?C to 95?C.

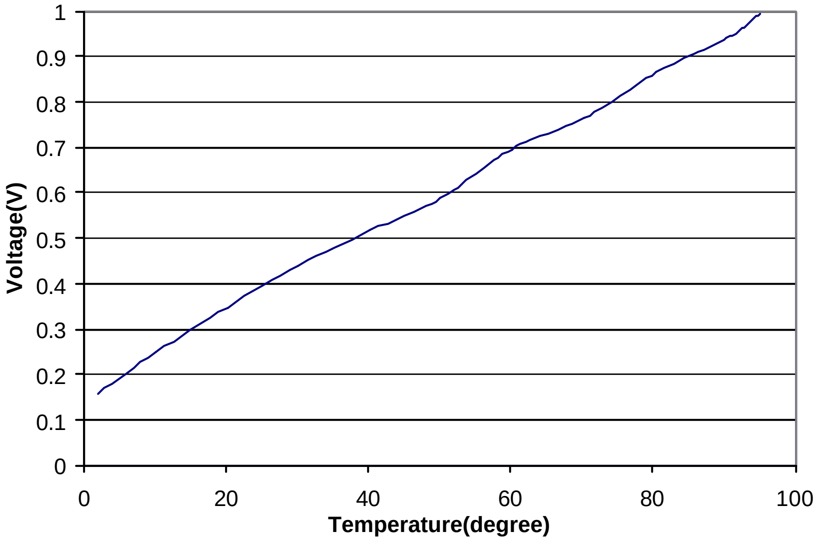


Figure 6.3 Calibration results for the IR sensor

Figure 6.4 shows that the output of the conditioning circuit for the IR sensor was from 0V to 3.90V for temperatures from 0?C to 95?C. The signal is not exactly at zero when the temperature is 0?C. A resistor (R2 in Figure 5.8) in the circuit was used to adjust the intercept for different emissivities of the measured objects.

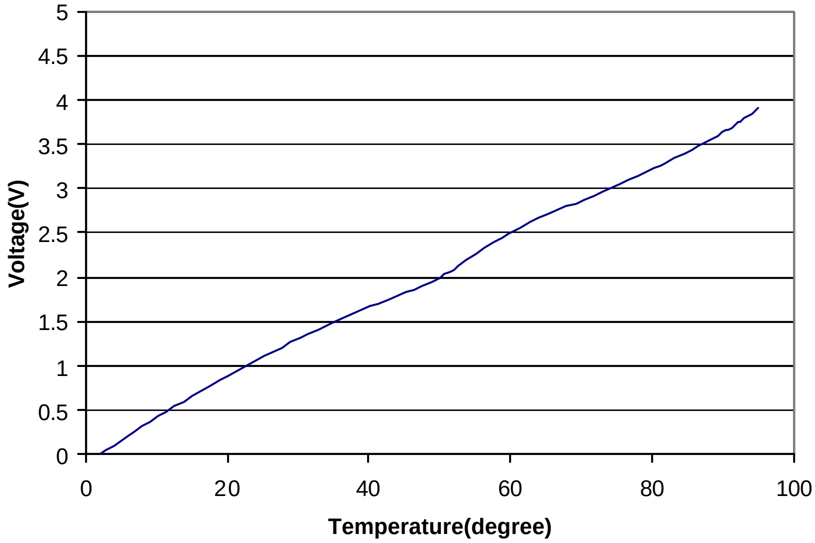


Figure 6.4 Calibration results for the IR sensor circuits

6.1.3 Tests for TRIAC control

One of the major tasks for 68HC11 was to read a signal from the zero-crossing circuit and output a square wave with a specific frequency to trigger the TRIAC control circuit. Figure 6.5 shows an example of the square wave output from a digital I/O channel, PA6, of 68HC11.

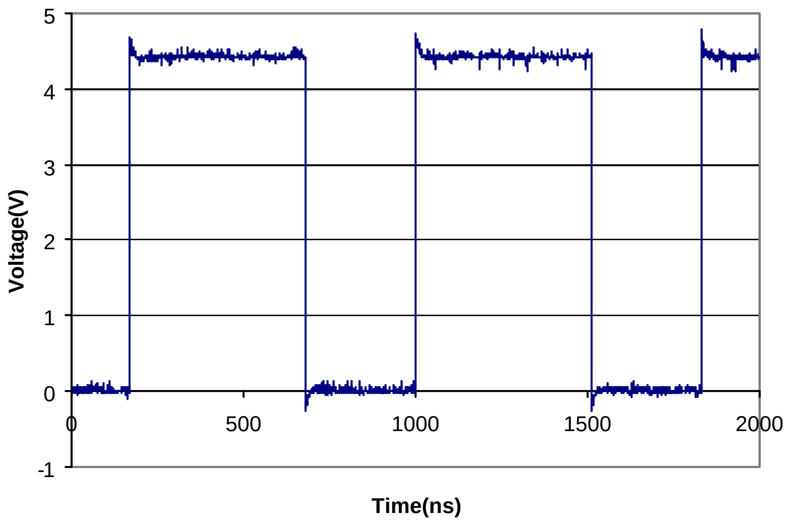


Figure 6.5 Square wave output of 68HC11

The pulse width of the square wave could be adjusted according to the temperature difference between the user-preset value and the sensor-measured value. The magnitude of the square wave was 4.41V, which was high enough to drive the TRIAC. The frequency of the square was 120Hz for the line power.

TRIAC control circuit was firstly tested with a resistive load (a 40W desk-lamp). The results are shown in Figure 6.6.

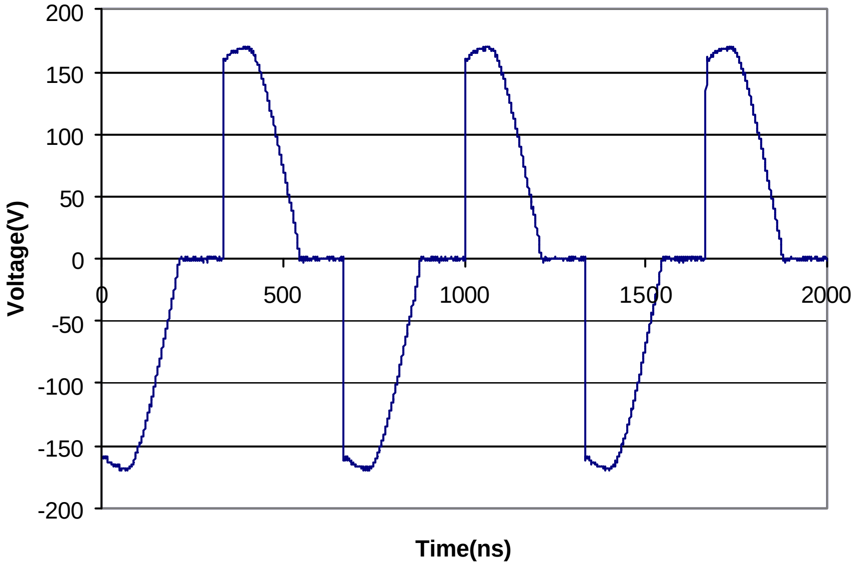


Figure 6.6 TRIAC control output for a resistive load

The signal frequency was 60Hz. The RMS was 105.8V, which was lower than the 120V power line voltage. The peak-to-peak voltage was 342V. Figure 6.6 shows that the TRIAC conduction time can be controlled based on the user's requirement.

The major goal of the designed TRIAC circuit was to control an inductive load, e.g. a transformer. Figure 6.7 shows the test results of the TRIAC control circuit with an inductive load — the high voltage transformer of the microwave oven.

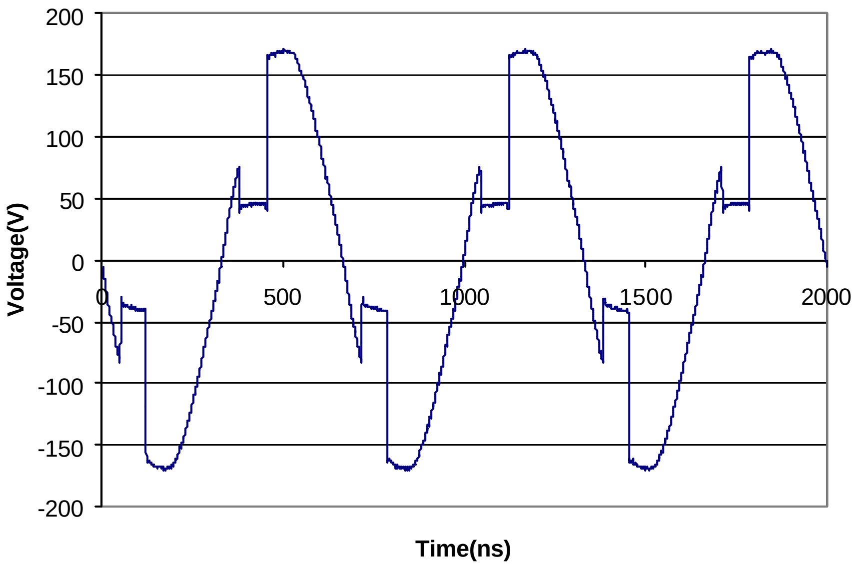


Figure 6.7 TRIAC output for an inductive load

The signal frequency was still 60Hz. The RMS was 107.5V, which was a little higher than that of the circuit with resistive load. The delay angle was not as clear as that in Figure 66 for the resistive load. This was because for an inductive load, a feedback current due to remaining voltage in the transformer coil flowed back through the load in a reverse direction. This difference did not affect the temperature control of the system.

6.2 Software tests

Due to the fast speed of 68HC11, the keypad could be scanned within a much shorter time than the time needed for a human to press a key. Hence, keypad scanning could always complete before the operator's finger left the keypad The fast scanning speed may also cause problems in reading two consecutive keypad inputs, as in the case of entering two numbers for a user-preset temperature. A 66ms interval was therefore implemented between consecutive keypad readings to avoid confusion.

The LCD-display needs 1.53ms for its "Clear Display" and "Return Home" commands. A delay with 1.6ms was used in the program. The data display also needed a 39?s delay or waiting for the flag of data transfer completion.

The data record process was tested by the "READ" function of the Buffalo after a drying process. The temperature measured by the IR and recorded by the 68HC11 was stored in the memory 3000-7FFF of the RAM.

The square wave generation and the calculation of the delay angle for triac control are related to the hardware and can be checked from Figure 6.5 - Figure 6.7.

6.3 Drying test

6.3.1 Test 1 – Temperature control in a water sample with the thermocouple probe

Figure 6.8 shows the temperature control results for a water sample using the thermocouple probe to provide the feedback temperature. The preset temperature for each test was marked in the figure. All the preset temperatures were reached within 6 minutes. The average standard deviation of the temperature control during the steady state (400 sec – 1600 sec after the test was started) was ?0.95?C, which was obtained by the following formula:

$$\text{Average standard deviation} = \frac{\sum_{j=1}^{m} \sqrt{\frac{\sum_{i=1}^{n} (temp_i - temp_0)^2}{n}}}{m} \qquad (6.1)$$

where

n is the total number of samples, $n = 600$;

m is the total number of control tests for different temperatures, $m = 6$;

$temp_0$ was the user-preset temperature; and

$temp_1$ was the measured temperature.

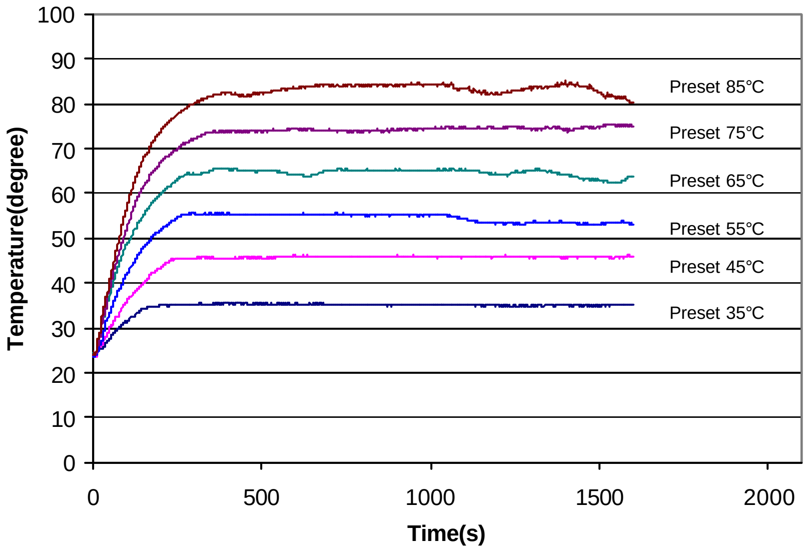


Figure 6.8 Temperature control using thermocouple

The maximum error was ±6ºC. This error was introduced by the conditioning circuit. The AD592 drifted with the temperature. The non-separable intercept and slope adjustments (R4 in Figure 5.6) also made it difficult to accurately amplify the thermocouple signal.

Large oscillations were also observed in the controlled temperature with a preset temperature of 85?C. At this temperature, many bubbles were generated, resulting in non-uniformity of temperature distribution within the water sample.

6.3.2 Test 2 - The temperature control in a water sample using the IR sensor

Figure 6.9 shows the temperature control in a water sample using the IR sensor to provide the feedback temperature signal. The water temperature was also measured by the fibre-optic thermometer to verify the IR temperature readings. The preset temperatures were also reached within 6 minutes. The average standard deviation of the temperature control was ±0.34°. The maximum control error was ?1.5?C.

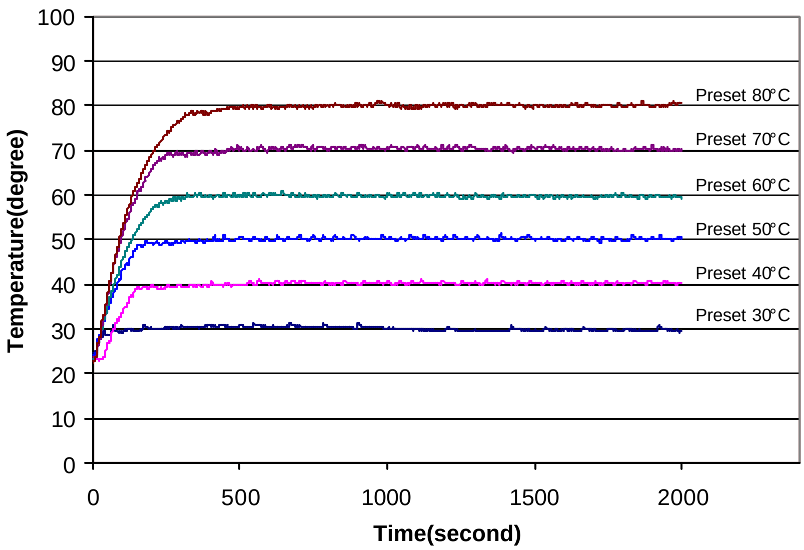


Figure 6.9 Temperature control using the IR sensor

The control accuracy of the IR sensor was much better than that of the thermocouple. The following figure (Figure 6.10) shows the temperature recorded by the 68HC11.

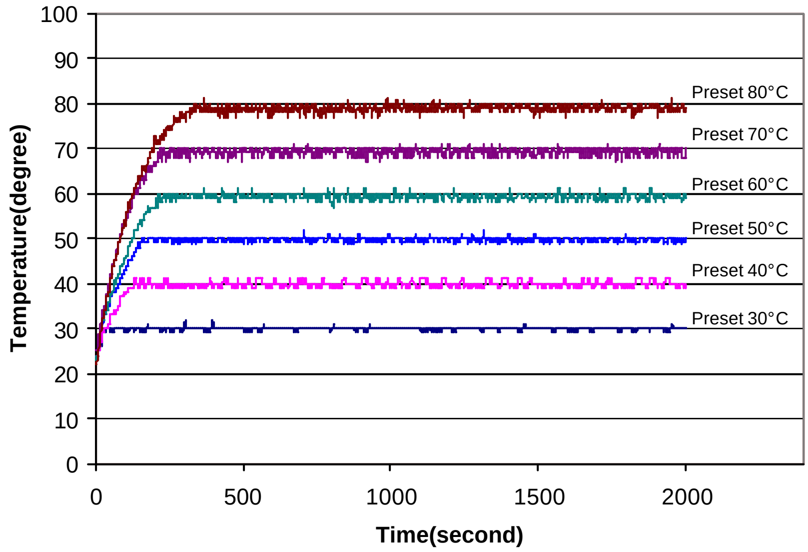


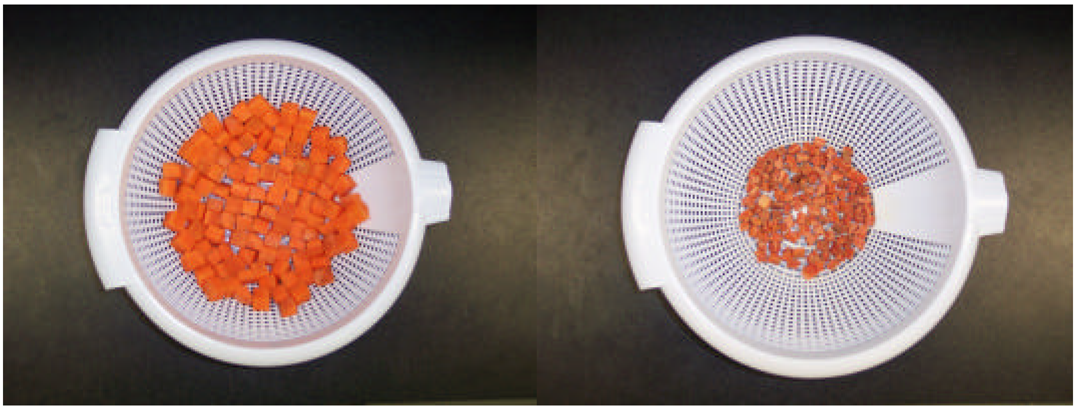
Figure 6.10 Temperature control using the IR sensor (Recorded by 68HC11)

The IR sensor measures the average temperature of the surface within the field of view. Therefore, it was able to filter out the temperature variations to provide a stable feedback control signal. The temperature drift was also overcome by the IR sensor. The intercept and slope adjustments within the conditioning circuit were separated, making accuracy adjustment of the amplifier possible.

The results from Tests 1 and 2 showed that the feedback control system using both the thermocouple probe and the IR sensor was able to control the water temperature to a preset value. The control system with the IR sensor gave higher accuracy and smoother control. The conditioning circuits had a strong effect on the control accuracy. The conditioning circuit for the IR sensor greatly improved the control accuracy.

6.3.3 Test 3 – Performance of the feedback power control system on carrot drying

A carrot sample was used for drying test. Figure 6.11 shows the carrot samples before and after being dried for 180 minutes. Based on the data provided by Techasena et al. (1992), the preset drying temperature was set at 70?C.



(a) (b)

Figure 6.11 Carrot sample (a) Before (b) After being dried for 180 minutes

Drying curve

The drying curve (moisture ratio versus time) is showed in Figure 6.12. Within 180 minutes, the carrot sample was dried to 14.63% moisture content (wet basis). The drying speed was slower than the 1W/g, 70°C microwave-hot air combined drying mode of on-off power control, which achieved 12% moisture ratio within 90 minutes (Changrue *et al*., 2004). Apparently, the hot air had a significant effect on the drying speed.

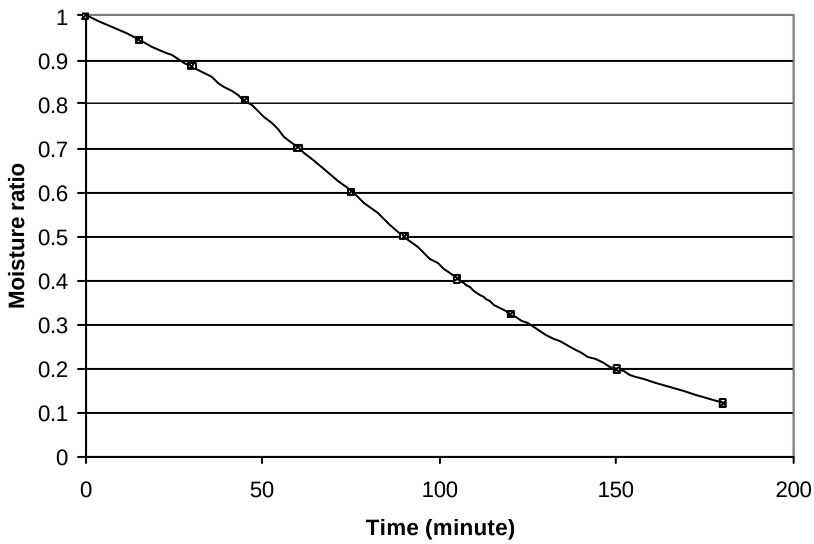


Figure 6.12 Drying curve of the carrot sample

Surface colour

Surface colour was measured before and after drying. The results are shown in Table 6.1. The colour of dried carrots using this control system was obviously lighter than that using the on-off power control system [Changrue *et al.*, 2004; Table 6.2; L* represents lightness coefficient, ranging from 0(black) to 100(white)]. Therefore, it can be concluded that the control system designed in this study resulted in better colour of the dried products.

Table 6.1 Colour values for dried carrots

Treatment	L*	a*	b*
Before drying	53.40	16.21	35.09
After drying	46.03	10.88	13.68

Table 6.2 Colour values for dried carrots obtained by Microwave-hot air drying (Changrue *et al.*, 2004)

Treatment	L*	a*	b*
Power 1W/g - air	6.55^{b}	67.39^{a}	16.12^{ab}
Power 1W/g - hot air	7.55^{ab}	65.79^{a}	16.47^{ab}
Power 1.5W/g – air	7.27^{ab}	65.35^{a}	15.43^{ab}
Power 1.5W/g – hot air	8.01^{ab}	65.12^{a}	16.63^{ab}
Power 2W/g - air	7.47^{ab}	65.17^{a}	16.54^{ab}
Power 2W/g – hot air	10.27^{a}	64.90^{a}	19.09^{a}

Water activity

Table 6.3 shows the water activity result. The value of the a_w was lower than 0.7, which indicates microbiological stability of the end product (Beaudry, 2001).

Table 6.3 Water activities of carrots

Initial	0.990
Final	0.605

The temperature difference between the surface and the center of a product during microwave heating was also tested. Two fiber-optic probes were used in the test. A whole strawberry was used without turntable. The minimum difference for a strawberry, which had high water content, was 10?C (Figure 6.13).

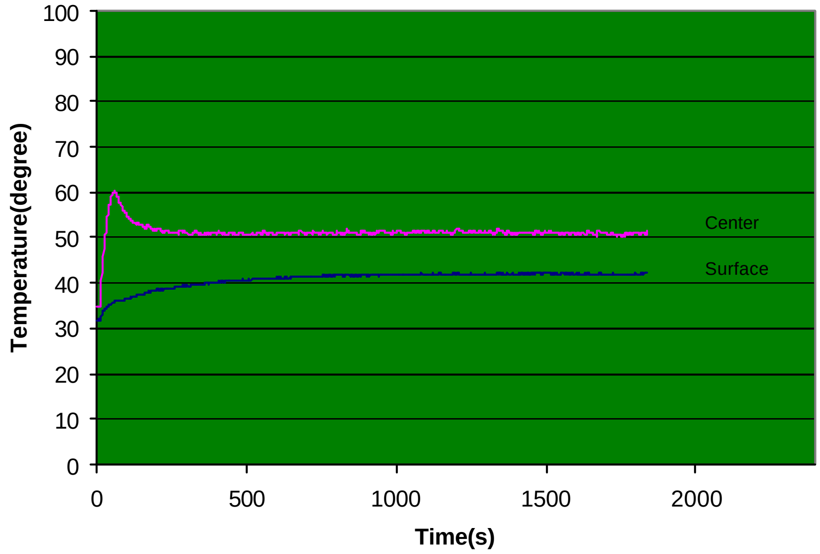


Figure 6.13 Temperature difference between the surface and the center of a strawberry

To achieve the optimum drying effect, a uniform temperature distribution inside the cavity of the microwave oven needs to be maintained. A turntable can help improve the uniformity. However, it is difficult to use contact sensors to measure the temperature when the sample is moving. Under this circumstance, an infrared sensor becomes a good candidate owing to its non-contact nature. A disadvantage of the infrared sensor is its weak penetration capability. In fact, an infrared sensor can only measure surface temperatures. Further study is needed to model heat distributions within the products, from the center to the surface. The feedback control system would then be based on the models to determine optimal control strategies for every product to achieve the best drying effect.

In this study, three temperature sensors were used: a thermocouple probe with grounded sheath, a fiber-optic thermometer, and an infrared sensor. Each sensor has its pros and cons. The thermocouple probe is inexpensive, capable of measuring the internal temperatures, but easy to cause sparks in the microwave oven. The fiber-optic thermometer is accurate, stable, but much expensive. Both the thermocouple probe and the fiber-optic probe are contact-type sensors. They are difficult to use when a turntable is needed in the microwave oven. The major advantage of the infrared sensor is its non-contact nature. Although an IR sensor only measures the surface temperature, it still can be used for feedback temperature control in the microwave environment by combining modeling techniques and software corrections.

VII. CONCLUSIONS

1. Overall performance of the power control system for microwave oven was within the design criteria.
2. The zero-crossing detection circuit detected the zero points of sine waves successfully and the digital output signals of this circuit could be accepted by the 68HC11 microcontroller.
3. Three temperature sensors, a thermocouple probe, an IR sensor, and a fiber-optic thermometer, were tested and compared. The IR sensor demonstrated its advantage as a non-contact measurement device.
4. The TRIAC could be controlled by a digital output signal of the microcontroller, which was used as its gate trigger signal and could successfully turn on and off the line power for the microwave oven according to the output waveform of the 68HC11.
5. The system software completely fulfilled the design objectives. The program for user interface could identify the two-digit number from a keypad and display it on the LCD; the program for data acquisition and pre-processing could capture the zero-crossing signals, read the actual temperature value from the temperature sensors and process them according to design requirements; the data recording program could store long-term data in a memory space and be extracted by the BUFFALO, converted to Microsoft Word; the program for calculating the triggering angle and the program to generate a control waveform could output square waveforms and drive the TRIAC as designing.
6. Employing the thermocouple probe and the IR sensor to provide feedback control signal, the system was tested on a water sample. With feedback control, the mean standard deviations for temperature were ? 0.95?C for the thermocouple probe and ? 0.34?C for the IR sensor.
7. Using the control system, carrot samples lost 85.37% of their water content in 180 minutes with no sign of damage due to burning. The color of the end products was better than that of the microwave-assisted hot air drying and water activity was within the range of microbiological stability.

8. A difference of 10°C was found between the surface and center temperature in a whole strawberry during microwave drying process, which indicated the special heating characteristics of the microwave energy.

VIII. RECOMMNDATIONS FOR FURTHER STUDY

Large differences between surface and internal temperatures of strawberries were observed during the drying process. Further study is recommended to develop models that describe internal temperature variations in bio-products during microwave drying. To achieve optimal temperature control with such models, control strategies based on surface temperature measurement alone could be developed.

Continuous mass weighing is also recommended during drying, since mass is another essential parameter for food drying. As the mass of the object decreases the temperature should be lowered to avoid burning the object.

To achieve better drying result and faster drying rate, the system can be combined with hot air or vacuum drying. Some reflectors can be installed inside the cavity to obtain equal microwave distribution. This can serve as a replacement of the turntable.

The life of the microwave oven under the new power control mode should be tested. The effect of frequent phase control to the magnetron should be considered.

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APPENDIX A

System program

The Function of the Program

The program first checked the keypad input. If the two-digit preset temperature was entered by a user, it would be displayed on the LCD. The program also stored this number in a memory space and then jumped to the main program.

The main program first read the temperature from the sensor, and then started a counter (120). After a zero-crossing point was detected, the temperature from the sensor was read again and compared with the previous one. These cycles were repeated 120 times. The maximum temperature within the 120 readings was selected and used as the feedback control signal. This number was compared with the preset temperature. If it was lower than the preset value, a pulse was output to drive the TRIAC for power generation. The larger the difference was, the longer the power was generated, and hence the more power was supplied to the magnetron. When the actual temperature reached the preset value, the power was fully cut away.

The maximum temperature value within one second (120 readings) measured by the sensor was also displayed on the LCD and updated every second. Therefore, the user can easily read the preset temperature and actual maximum temperature on the LCD.

```
                NAM     LZF
* Define ports, bits, and reserve memory space for calculation
PORTA           EQU     $1000
PORTD           EQU     $1008
DDRD            EQU     $1009
PORTE           EQU     $100A
TCTL2           EQU     $1021
TFLG1           EQU     $23
ADCTL           EQU     $1030
ADR4            EQU     $1034
OPTION          EQU     $1039
LCD_CMD         EQU     $B5F0           *LCD command address
LCD_DATA        EQU     $B5F1           *LCD DATA address
BIT0            EQU     %00000001
BIT6            EQU     %01000000
BUF0            RMB     1
BUF1            RMB     1
BUF2            RMB     1
BUF3            RMB     1
BUF4            RMB     1
BUF5            RMB     1
BUF6            RMB     1
BUF7            RMB     1
BUF8            RMB     1
BUF9            RMB     1
BUFA            RMB     1
BUFB            RMB     1
BUFC            RMB     1
BUFD            RMB     1
BUFE            RMB     1
BUFF            RMB     1
COUNT1          RMB     1
COUNT2          FDB
SUM             FDB
**********************************************************************
* Program begins from preset temperature. Press two numbers on the keypad (00-99)
                ORG     $E000           *program in EEPROM
START
                LDS     #$23FF          *stack position
                LDAA    #$3C
                STAA    DDRD            *set port D 2 3 4 5 as rows control
                STAA    LCD_CMD         *setup LCD for 8 bit interface
                JSR     DELAY
                LDAA    #$0E            *display on, blinking cursor
                STAA    LCD_CMD
                JSR     DELAY
                LDAA    #$01            *clear display, return home
```

```
                STAA   LCD_CMD
                SR     DELAY
SCAN1
                LDAB   #$04         *begin from first row
SCANLP1
                STAB   PORTD
                STAB   BUF2         *save the row of first number
                XGDY                *wait sometime
                XGDY
                LDAA   PORTE        *pressed any key?
                ANDA   #$0F         *mask for key rows
                STAA   BUF1         *save the column of first number)
                CMPA   #$00
                BNE    SC2          *waiting for another
                LSLB                *if not, check next row
                CMPB   #$40         *if 4 rows have all been checked,
                BEQ    SCAN1        *go back and start again
                BRA    SCANLP1      *if not, go for next row
SC2
                BSR    DL           *delay for 66ms
SCAN2
                LDAB   #$04
SCANLP2
                STAB   PORTD
                STAB   BUF4         *save the row of second number
                XGDY
                XGDY
                LDAA   PORTE
                ANDA   #$0F
                STAA   BUF3         *save (column of second number)
                CMPA   #$00
                BNE    PREPARE      *after second number, go to prepare
                LSLB
                CMPB   #$40
                BEQ    SCAN2
                BRA    SCANLP2
DL
                LDY    #$0002
DL1             LDX    #$FFFF
DL2             DEX
                BNE    DL2
                DEY
                BNE    DL1
                RTS
* Deal with pressed number
PREPARE
* First number
```

```
        LDAA   BUF2          *process number
        CMPA   #$20
        BEQ    ZERO11
        LSR    BUF1
        LSR    BUF2
        LSR    BUF2
        LSR    BUF2
        LDAA   BUF2
        LDAB   #$03
        MUL
        ADDD   #$0001
        ADDB   BUF1
ZERO1
        STAB   BUF5
        STAB   BUFC          *display first number on LCD
        JSR    LOOPC
        JSR    DELAY2
* Second number
        LDAA   BUF4
        CMPA   #$20
        BEQ    ZERO22
        LSR    BUF3
        LSR    BUF4
        LSR    BUF4
        LSR    BUF4
        LDAA   BUF4
        LDAB   #$03
        MUL
        ADDD   #$0001
        ADDB   BUF3
ZERO2
        STAB   BUF6
        STAB   BUFD          *display second number on LCD
        JSR    LOOPD
        JSR    DELAY2
        LDAB   #$2D          *display a "-"
        STAB   LCD_DATA
        JSR    DELAY2
* First number multiplies A, then add with second number (BCD to HEX)
        LDAA   BUF5
        LDAB   #$0A
        MUL
        ADDB   BUF6
        STAB   BUF7
        LDAA   BUF7
        LDAB   #$02
        MUL
```

```
                    STAB    BUF8
                    BRA     STARTER
ZERO11
                    LDAB    #$00
                    BRA     ZERO1

ZERO22
                    LDAB    #$00
                    BRA     ZERO2
****************************************************************************
STARTER
                    LDAA    #$80            *main program
                    STAA    OPTION
                    LDAA    #$34
                    STAA    ADCTL
                    LDAA    #$02
                    STAA    TCTL2
* Main program input by PAO PE7
                    LDAA    ADR4            *read temperature
                    STAA    BUFA
                    LDY     #$3000          ******for data record
                    STY     COUNT2
LOOP1
                    LDAB    BUFA
                    STAB    BUF0
                    LDAA    #$00            ***for LCD display
                    LDX     #$0002          ***
                    IDIV                    ***
                    XGDX                    ***
                    LDAA    #$00            ***
                    LDX     #$000A          ***
                    IDIV                    ***
                    STAB    BUFD            ***
                    STAB    BUFF            ******for record
                    XGDX                    ***
                    STAB    BUFC            ***
                    STAB    BUFE            ******for record
                    JSR     LOOPC           ***
                    JSR     DELAY2          ***
                    JSR     LOOPD           ***
                    JSR     DELAY2          ***
                    LDAA    #$10            ***
                    STAA    LCD_CMD         ***
                    JSR     DELAY           ***
                    LDAA    #$10            ***
                    STAA    LCD_CMD         ***
                    JSR     DELAY           ***
```

```
                    JSR      RECORD            ******for record
                    CLR      BUFA
                    LDAA     #$78              *120 times per second
                    STAA     COUNT1
LOOP
                    LDAA     ADR4
                    STAA     BUFB
                    CMPA     BUFA
                    BHI      SUB1              *maximum of 120 temperatures
LOOP3
                    DEC      COUNT1
                    BEQ      LOOP1
                    LDX      #$1000
                    LDAA     #$01
                    STAA     TFLG1,X
LOOP2               BRCLR    TFLG1,X  BIT0 LOOP2     *zero point detection
                    LDAA     BUF8
                    CMPA     BUF0
                    BHI      PUL1              *jump to triggering angle loop
                    BCLR     PORTA, BIT6
                    BRA      LOOP
* Output pulses by PA6
PUL1
                    BCLR     PORTA, BIT6
                    JSR      DELAY1
                    BSET     PORTA, BIT6
                    BRA      LOOP
DELAY1              LDAA     BUF8              *angle calculation
                    SUBA     BUF0
                    STAA     BUF9
                    LDAA     #$C6
                    SUBA     BUF9
                    LDAB     #$05
                    MUL
                    ADDD     #$0080
                    STD      SUM
                    LDY      SUM
DELAY11
                    DEY
                    BNE      DELAY11
                    RTS
*
SUB1
                    LDAA     BUFB
                    STAA     BUFA
                    BRA      LOOP3
DELAY
```

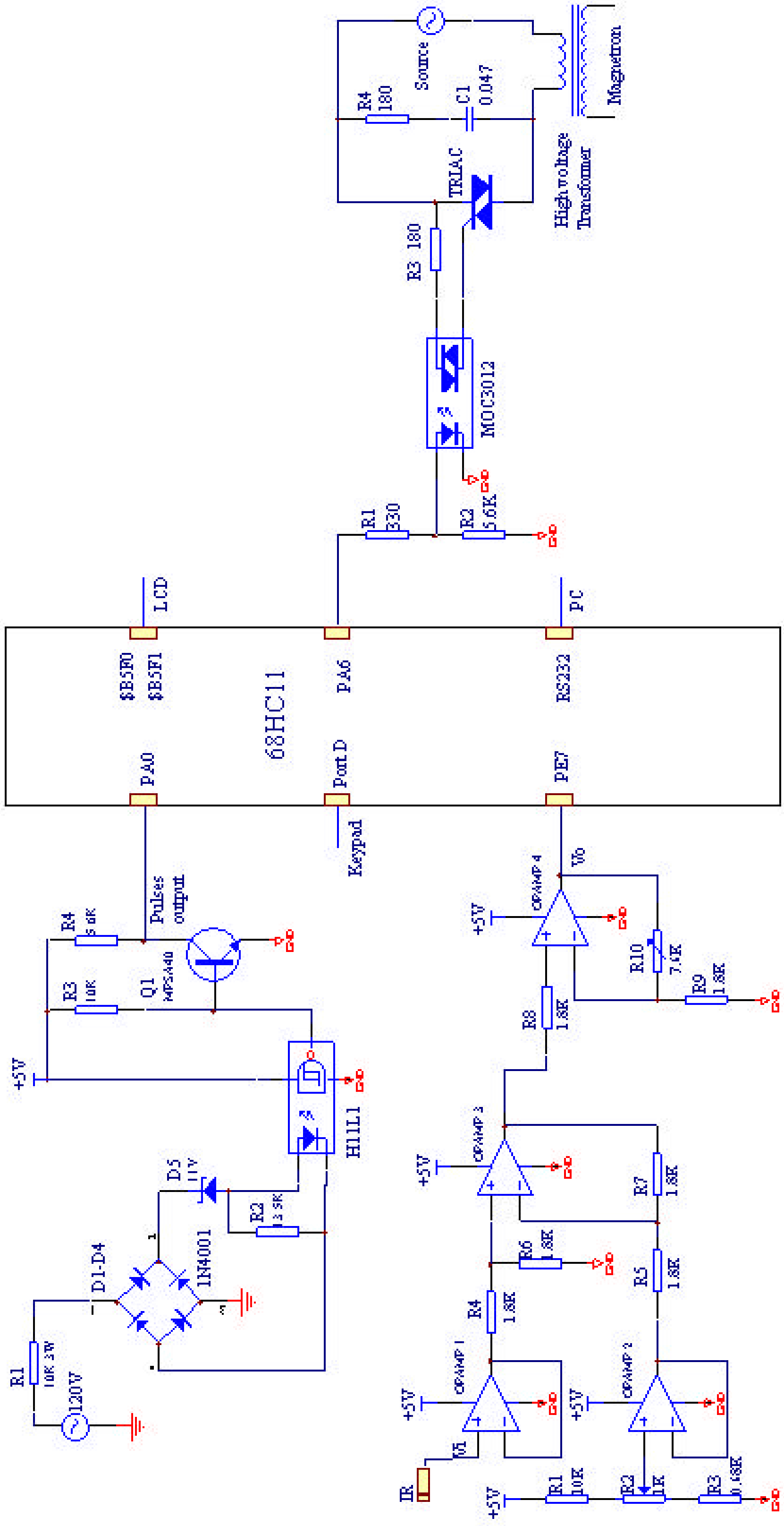
```
            LDAA   LCD_CMD          *LCD_CMD delay
            ANDA   #$80
            CMPA   #$00
            BNE    DELAY
            RTS
DELAY2
            LDY    #$000A           *LCD_DATA delay
DELAYLP
            DEY
            BNE    DELAYLP
            RTS
*Display selection
LOOPC
            LDAA  BUFC
            CMPA   #$00
            BEQ    LOP0
            CMPA   #$01
            BEQ    LOP1
            CMPA   #$02
            BEQ    LOP2
            CMPA   #$03
            BEQ    LOP3
            CMPA   #$04
            BEQ    LOP4
            CMPA   #$05
            BEQ    LOP5
            CMPA   #$06
            BEQ    LOP6
            CMPA   #$06
            BEQ    LOP6
            CMPA   #$07
            BEQ    LOP7
            CMPA   #$08
            BEQ    LOP8
            CMPA   #$09
            BEQ    LOP9
*Record selection
LOOPD
            LDAA  BUFD
            ANDA   #$0F
            CMPA   #$00
            BEQ    LOP0
            CMPA   #$01
            BEQ    LOP1
            CMPA   #$02
            BEQ    LOP2
            CMPA   #$03
```

```
                BEQ     LOP3
                CMPA    #$04
                BEQ     LOP4
                CMPA    #$05
                BEQ     LOP5
                CMPA    #$06
                BEQ     LOP6
                CMPA    #$06
                BEQ     LOP6
                CMPA    #$07
                BEQ     LOP7
                CMPA    #$08
                BEQ     LOP8
                CMPA    #$09
                BEQ     LOP9
* Display number
LOP0
                LDAA    #$30
                STAA    LCD_DATA
                RTS
LOP1
                LDAA    #$31
                STAA    LCD_DATA
                RTS
LOP2
                LDAA    #$32
                STAA    LCD_DATA
                RTS
LOP3
                LDAA    #$33
                STAA    LCD_DATA
                RTS
LOP4
                LDAA    #$34
                STAA    LCD_DATA
                RTS
LOP5
                LDAA    #$35
                STAA    LCD_DATA
                RTS
LOP6
                LDAA    #$36
                STAA    LCD_DATA
                RTS
LOP7
                LDAA    #$37
                STAA    LCD_DATA
```

```
            RTS
LOP8
            LDAA   #$38
            STAA   LCD_DATA
            RTS
LOP9
            LDAA   #$39
            STAA   LCD_DATA
            RTS
*
RECORD
            LDY     COUNT2          *Hex to Decimal
            LSL     BUFE            *for recording in Decimal
            LSL     BUFE
            LSL     BUFE
            LSL     BUFE
            LDAA    BUFE
            ADDA    BUFF
            STAA    00,Y
            INY
            STY     COUNT2
            RTS
*
            ORG     $FFFE           *reset interrupt address
            FDB     START
            END
```

Appendix B

Circuit diagram of the system


68HC11
PA0
Port D
PE7
$B5F0
$B5F1
PA6
RS232
LCD
PC
Keypad
Pulses output
Vo
MOC3012
TRIAC
Source
High voltage Transformer
Magnetron
H11L1
1N4001
D1-D4
120V
Q1
IR
OPAMP 1
OPAMP 2
OPAMP 3
OPAMP 4
R1 330
R2 5.6K
R3 180
R4 180
C1 0.047
+5V