Embedded System Controlling Microwave Generators in Hyperthermia and Diathermy Medical Devices

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Abstract—Microwave Hyperthermia (MH) is a medical procedure of rising the human body tissue temperature between 41.5°C and 45°C using electromagnetic radiation and maintaining the desired temperature during the treatment period. In this paper we present a part of our embedded system that can drive a continuous wave (CW) 2450 MHz magnetron as well as a 915 MHz RF power generator for pulse-modulated waves operating mode, measuring and managing the patient’s skin temperature feedback. This embedded system is intended for use in microwave hyperthermia or microwave diathermy devices, with non-invasive regional or interstitial applicators.

Our paper is structured in four chapters. The “Introduction” is briefly presenting the microwave hyperthermia essentials: microwave propagation, penetration depth, SAR and microwave heating mechanism. The “Design configuration” part presents the structure of our hyperthermia device with basic microwave generators and auxiliary equipment used for thermal management. The “Embedded design” chapter presents, in two subsections entitled “Hardware” and “Software”, the principles used for controlling the microwave generators together with the implemented solution and the essential aspects of our firmware as program flow. In “Conclusions”, preliminary results are analyzed in agreement with the IEC60601 standards and with the requested directions for further developments.

I. INTRODUCTION

Microwave Hyperthermia (MH) is a medical procedure to rise the human body tissue temperature between 41.5°C and 45°C using electromagnetic radiation and to maintain it in this range for a requested period. MH is used in the management of superficial tumors as a stand-alone procedure or with conventional radiotherapy and chemotherapy. Microwave Diathermy (MD) is used in physical medicine and sports traumatology, heating the tissues of the body up to 41°C.

Microwaves are electromagnetic radiations in the frequency range of 300MHz and 300GHz (1) named also centimeter waves in a simple approach (2).

\[
\lambda_0 = c \cdot T = \frac{c}{F} \quad (1)
\]

where:
\( \lambda_0 \) open space wavelength [m]
\( c = 299792458 \) [m/s] the light speed
\( T = \) radiation period [s]
\( F = \) radiation frequency [Hz]

\[
\lambda_0[cm] = \frac{30}{F[GHz]} \quad (2)
\]

Radiations with wavelengths in the centimeter range have insufficient energy for biomolecule ionization, therefore microwaves are nonionizing radiation. While in open space, the microwave wavelength is described by (2); once the radiation penetrates the human body tissue, the wavelength becomes shorter (3):

\[
\lambda_h = \frac{v_0}{F} = \frac{1}{F \sqrt{i \epsilon}} \quad (3)
\]

where:
\( v_0 = \) wave speed in body tissue[m/s]
\( F = \) radiation frequency [Hz]
\( \epsilon = \epsilon_0(\epsilon' - j \epsilon'') \) body complex permittivity \( (4) \)
\( \mu = \mu_0 = 4\pi \times 10^{-7}[H/m] \) body magnetic permeability
\( \epsilon_0 = 1/c^2 \mu_0 = 1/36\pi \times 10^{-7}[F/m] \) absolute permittivity

The real part of the complex permittivity (4) is the dielectric constant (5), which characterizes the cell tissue polarisation capacity caused by the electromagnetic field.

\[
\epsilon_r = \frac{\epsilon'}{\epsilon_0} \quad (5)
\]

The imaginary part (6) of the complex permittivity (4) indicates the molecule oscillation, translation and vibration behaviour, caused by the interaction with the microwave field:

\[
\epsilon'' = \frac{\sigma}{i \omega \epsilon_0} \quad (6)
\]

where: \( \omega = 2\pi F \)
\( \sigma = 2\pi \sigma_0 e'' \) is the tissue electrical conductivity [S/m]

The dependence of the tissue electrical conductivity (characteristic of a human body and frequency dependant) on \( e'' \) indicates the existence of cell heating mechanism by ionic and dipolar displacement currents. Thus, dielectric loss (7) becomes a global term that characterizes the microwave absorption interaction with the biomass.

\[
tg\delta = \frac{\epsilon''}{\epsilon'} \quad (7)
\]

Microwave propagation (8) through a homogeneous biologic environment is attenuated with \( \alpha \):

\[
\gamma = \alpha + j\beta = \sqrt{[\alpha \nu(+\sigma+j\alpha \epsilon)]} \quad (8)
\]

where: \( \gamma = \) complex propagation coefficient
\( \alpha = \) attenuation coefficient[dB/m]
\[ \beta = \text{propagation coefficient} \]

Microwave penetration depth (9) in the biomass is the length measured from the body surface where the microwave power density attenuates with \( e = 2.71 \) (or 37% from the surface amplitude of the wave). Microwave penetration continues deeper than the penetration depth until total attenuation:

\[ d = \frac{2}{\mu_r \sigma} \]  

where \( \mu_r = 1 \) for a normal tissue.

The microwave power (10), the tissue temperature and local vascularity are heavily modifying the penetration depth. Once the cell temperature increases, the penetration depth decreases, because of an increase of the tissue conductivity:

\[ P = \pi \varepsilon \varepsilon_0 E^2 = \sigma \cdot E^2 / 2 \]  

where \( E \) is the microwave electric field intensity.

The characterisation of a specific biomass response to the microwave radiation is given by the Specific Absorption Rate (11) which becomes 13.5% from the surface value at the penetration depth.

\[ \text{SAR} = \frac{\sigma}{\rho} E_{rms}^2 \text{[W/kg]} \]  

where:

- \( E_{rms} \) = root mean square of microwave electrical field
- \( \rho \) = tissue density \([\text{kg/m}^3]\)
- \( \sigma \) = tissue electrical conductivity \([\text{S/m}]\)

SAR is a parameter which highly depends on the microwave applicator (antenna) and local characteristics (shape of the biomass, vascularity, wave reflections, body temperature, etc.).

The Pennes approximation (12) to biological heat transfer via diffused conduction and blood convection in tissue [1] provides useful insights into microwave-induced rises in tissue temperature.

\[ \rho c \frac{dT}{dt} = \text{SAR} + \zeta \nabla^2 T - V_s (T - T_0) \]

where:

- \( T \) = tissue temperature\([\text{C}]\)
- \( T_0 \) = environment temperature \([\text{C}]\)
- \( c \) = tissue specific heat \([\text{J/kg K}]\)
- \( \zeta \) = coefficient of heat conduction
- \( \zeta \nabla^2 T \) = heat conduction term
- \( V_s \) = product of flow rate and heat capacity of blood
- \( V_s (T - T_0) \) = convection heat exchange term

Since the heat conduction term describes a passive phenomenon which takes place slowly in the biological tissues and the convection heat exchange term serves to moderate temperature elevation in tissues because heat is transported away from the generating site, (12) becomes:

\[ \text{SAR} \equiv \rho c \frac{dT}{dt} \quad (13) \]

Equations (11) and (13) state that temperature variation in a tissue heated by a microwave radiation is proportional to the energy of the applied microwave field. However short pulsed microwave radiation can produce non-thermal effects (or minimal thermal effects) if the rising heat is transported by convection (12). Medical experiments [2] show that tumor destruction mechanism by heat is not entirely known [3]. Thus, specific combination between thermal and non-thermal microwave radiation patterns can produce beneficial effects [4].

**II. DESIGN CONSIDERATION**

A simplified scheme of our microwave hyperthermia device is presented in fig.1. The microwave circuit is designed around a microwave generator (1) which comprises a continuous wave commercial magnetron rated at 700-1200W output power at 2450MHz, or a semiconductor generator with 60W-100W output power at 915MHz (fig.2). Combinations of two such semiconductor amplifiers are possible. The CW magnetron is supplied from an IGBT inverter (2) at 3500...4000V max.0.35A. The semiconductor amplifier is using a linear power supply. The applicator (5) is a microwave coaxial antenna for 2450MHz or a microstrip or coaxial slot antenna at 915MHz. A medical grade IR sensor (8) is a component part of the coaxial or microstrip applicator. For the coaxial slot antenna, the temperature is measured using two thermocouples. Semiconductor amplifier output is connected to the load through a circulator (13) to minimize the voltage standing wave ratio (VSWR), by measuring the wave reflections on a load (14) through a detector and an analogic to digital converter (15).

Figure 1 Simplified scheme of our microwave hyperthermia device

An embedded master system is driving the microwave generator power supply (2) and measures the biomass (7) heated...
area temperature (7a). Some input/output parameters can be displayed on an alphanumeric LCD display (4) and programmed from a functional keypad and an encoder. An optoisolated USB (3a) can connect the embedded master with a PC, however connection with the PC is not mandatory during the treatment period. An embedded slave (12) is driving a Peltier-based thermostat (11) which heats deionized water in the warm side of the double chamber tank (10). A cold chamber of the tank is also available. Two temperature sensors (10a) share the same bus for measuring the warm and the cold water temperatures. Warm water (45°C) or cold water (20...30°C) is flowing through the bolus (6) in the fluid circuit, being pumped by (9). Two-way valves are switching the water circuit from/to the warm respectively from/to the cold chambers of the tank, as requested by the treatment procedure. The bolus (6) is also an impedance adapting circuit between the applicator (5) and biomass (7).

Two types of microwave generators (fig.2) can be driven by the embedded master. The 915MHz generator (B) is useful for local hyperthermia treatments using interstitial applicators (coaxial slot or microstrip) having higher penetration depth, while the 2450MHz generator is designed for regional hyperthermia of the skin, with a lower penetration depth. Specific penetration depth [5] of some tissues for the frequencies used by our MW generators is presented in table I.

<table>
<thead>
<tr>
<th>Tissue name</th>
<th>915MHz</th>
<th>2450MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry skin</td>
<td>3.99</td>
<td>2.25</td>
</tr>
<tr>
<td>wet skin</td>
<td>4.30</td>
<td>2.20</td>
</tr>
<tr>
<td>fat</td>
<td>24.23</td>
<td>11.70</td>
</tr>
<tr>
<td>breast fat</td>
<td>25.06</td>
<td>8.83</td>
</tr>
<tr>
<td>muscle</td>
<td>4.21</td>
<td>2.23</td>
</tr>
<tr>
<td>blood</td>
<td>2.76</td>
<td>1.61</td>
</tr>
<tr>
<td>bladder</td>
<td>6.11</td>
<td>3.31</td>
</tr>
</tbody>
</table>

Coupling the output radiation of two identical semiconductor MW generators is useful for hyperthermia of soft tissues having large volume. Controlling the phase of the microwave radiation in the 915MHz MW generators (B, fig.2) is compulsory for the correct heating of a zone deep in the tissue.

III. EMBEDDED DESIGN

We have started our embedded design based on an early control module concept developed for a laboratory equipment [6] which uses a 2450MHz CW magnetron as an MW generator. With the initial requirements well-defined as “design for manufacturability” of a medical equipment, knowing the medical basic standard [7] and some collateral standards [8-10] is indispensable.

III.A HARDWARE

The embedded master module is using an inexpensive RISC microcontroller PIC18F44J11 [11] (fig.3). Two 915MHz/60W MW generators are controlled through digital to analog converters (9,10) respectively (11,12) which are sharing the same Inter IC (I2C) communication bus. Both amplitude (14) and phase (13) of the microwave radiation can be controlled. VSWR feedback signals are measured with the microcontroller 10-bit internal analog to digital converter. The 2450MHz/700W MW generator is driven using an optoisolated digital control (20) if the magnetron power supply is an inverter, or by power control (21) if the magnetron power supply is based on HV transformer and voltage doubler. The power control is based on optoisolated solid state relays (19) synchronised with the main voltage into an optoisolated zero switch circuit (17). The necessary SSR used for microwave amplitude control are driven and conditioned using a multiplexer (18) playing a determinant position in the power-up sequence.
The temperature sensors (16) accepted by the embedded module through the interface (15) are medical IR sensors [12] using a system management (SM) bus and thermocouples with analog amplifiers.

The communication (23) between embedded master and embedded slave is using a separately I2C bus. The SD card (24) is interfaced on a serial peripheral interface (SPI) bus and is used only for storing the patient’s treatment variables. An optoisolated USB (7) is using a FTDI IC driver [13] which communicates with a PC on an USB interface after implementing a virtual COM port. Through the patient request interface (5) the patient discomfort during heating procedure is monitored, a warning lamp (6) showing the operator the level of the patient’s pain. A two elevation level button allows the patient to signalize or even to stop the microwave radiation at a higher pain level, prior to the operator command.

The alphanumeric LCD (2) is a 20x4 large character display where both the treatment variables and keypad functions during the actual treatment phase are displayed. The analogic encoder (4) is used only for fast updating of the variables (increase-decrease function).

The embedded master module (fig.4) is supplied entirely at 3.3V and has a lithium-ion battery backup to avoid any turn up of accidentally dangerous running sequences. Since the module can drive both CW magnetron supply types and only one 2450MHz MW generator is used in the hyperthermia device, the unused MW driving blocks of the module remain unpopulated on the PCB.

III.B. SOFTWARE

In programmable medical electrical subsystems (PESS) [9] all software routines must pass verification and validation procedures. Based on the affirmation above, the entire process of software writing, verifying and validation procedures is painful. Some software procedures have already been verified: the LCD displaying procedure, the procedures for reading the functional keypad, generating the real time clock, measuring the skin temperature with the IR sensor (fig.5) and the MW digital and power control procedures for microwave thermal (T) modulation. Different hardware configurations of the embedded module are loaded with different firmware versions. However, basic functions of the embedded module are insensitive to the MW generator type. One of such software routines is the body tissue temperature control. Based on medical observation that tissue temperature in a hyperthermia procedure may have a large variation from $T_1$ to $T_2$ with $T_1 \geq 42^\circ C$ [14], maintaining an extremely precise temperature near the tumoral boundary is not necessary. However, the hyperthermia treatment seems more effective at higher temperature doses [15],[16], the treatment time decreasing when average treatment temperature is near $T_2=45^\circ C$.

Two driving pulse sequences (fig.6) are software defined: - a pulse width modulated (PWM) (variable duty cycle pulse, in the 1-100% range) at a fixed frequency of 1Hz, named microwave thermal (T) sequence;

- a PWM variable duty cycle pulse (in the 1-30% range) selectable by the operator either in delta’ frequency range (1Hz-4Hz) or in alpha” frequency range (8Hz-13Hz), named microwave non thermal (NT) sequence.

Increasing the treatment temperature from $T_0=36^\circ C$ to $T_1=45^\circ C$ should occur in $t_{10}=6\text{min}$. The entire treatment time period is $t_{10}=30\text{min}...60\text{min}$ and it must comprise as many NT sequences as possible. Choosing between delta and alpha frequency range for microwave NT modulation is an experimental decision and depends on the patient’s response during the entire treatment.

1 Delta brain waves occur in deep sleep
2 Alpha waves occur in adults brain who are relaxed but alert
The implemented software controller is a proportional-derivative type (PD) for the starting treatment period $t_1-t_0$ (fig.6) avoiding temperature rise overshooting [17]. Once the temperature $T$ of the body becomes $T_1 \leq T \leq T_2$, a proportional control (P) is used. The flowchart (fig.7) describes programming steps for PD implementation of the thermal effect PWM (PWM_T). Input parameters are: temperature ($T_1$), programmed temperature increasing rate ($Tr_{prog}$), programmed duty cycle of the PWM (PWM_Tval), changing rate of the PWM duty-cycle (PWM_Trate), temperature measurement sampling interval ($t_{sample}$). The object’s temperature ($T_{obj}$) is measured every $t_{sample}$ which is precisely generated by a real time clock (RTC). On every measurement cycle, the temperature increase ($\Delta T$) is computed and the temperature rise ($Tr_{calc}$) is compared with the programmed temperature increase rate ($Tr_{prog}$).

A decision is taken based on the result of the comparison, and the duty cycle of the PWM_T is modified accordingly. To obtain $t_1-t_0 \leq 6\text{min}$, the programmed temperature increase rate is $1.5\text{C/min}$. If the temperature sampling interval is 10 seconds, PWM duty-cycle can be modified 36 times in the best circumstances until $T_2$ value is reached, so choosing the right programmed duty-cycle for the PWM_T initial value is extremely important.

The proportional control implementation of the non-thermal microwave effect (NT) is straightforward, being implemented with fast comparison at the $T_1$ and $T_2$ boundaries (fig.8). The input parameters are: temperature variation range ($T_1$ and $T_2$), programmed duty cycle of the PWM (PWM_NTval) and the frequency of the PWM (PWM_NTf).

IV. CONCLUSIONS

We have presented here a work in progress, describing a new method, as proposed by us, for implementation of a microwave-embedded device for use in hyperthermia or diathermy treatments. The novelty of the embedded device, which is pa-
tent pending [18], consists in its versatility of driving various types of microwave generators with pulse modulating signals. Such modulated microwave radiations are able to create both thermal and non-thermal effects when interacting with living tissues. Since the microwave hyperthermia treatment is a painful procedure, inducing a relaxation status to the patient during the entire procedure is a major bonus. The future activity will comprise various experiments on phantom tissue, preparing the field for human tissue tests.

REFERENCES


[7] IEC60601-1, Medical electrical equipment, Part I: General requirements for basic safety and essential performance


[10] IEC60601-2-6, Medical electrical equipment, Part 2-6: Particular requirements for the safety of microwave therapy equipment.


[12] MLX90615 IR thermometer datasheet


[18] V.Surducan, E.Surducan, C. Neamtu, “Driving module for microwave generators used in medical an laboratory apparatus” Romanian patent pending RO A00113/11.02.2010