Towards Impedance Optimised Transcutaneous Atrial Defibrillation

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Abstract

Impedance compensated transcutaneous atrial defibrillation may offer more cost effective and less painful treatment for patients with AF by facilitating arrhythmia detection and low-energy synchronized cardioversion in a non-acute care setting. However, the technological barriers to implementation remain significant. In this paper advancements towards the realization of an impedance compensated passive transcutaneous atrial defibrillator architecture are reported: high power transcutaneous inductive link for defibrillation energy transfer, low-power electro-cardiogram and impedance sensing for AF detection and optimised cardioversion management via an embedded microcontroller with RF communications link for overall system control. The transcutaneous inductive link has been reliably operated in two distinct modes; 'sense mode' offers a >5W continuous power transfer mode to enable AF-ECG processing and intracardiac impedance measurement prior to cardioversion while 'shock mode' facilitates the transcutaneous coupling of >150W during delivery of an impedance compensated rectilinear defibrillation shock waveform to the heart. Laboratory bench test and experimental results are presented to demonstrate proof of concept.

1. Introduction

Historically, the use of implantable defibrillator technology for the treatment of chronic AF has remained problematic for two main reasons: (i) the pain that results from the relatively large electrical shock (up to 20J) typically required for successful cardioversion and (ii) unit automaticity giving rise to significant patient anxiety in respect of cardioversion taking place at either an inappropriate time or setting. Optimisation of the electrical defibrillation shock waveform for the lowest possible energy to achieve successful cardioversion (to reduce pain and avoid the need for patient sedation) and the development of externally controlled battery free implantable atrial defibrillators for arrhythmia detection and synchronised cardioversion in a non-acute care setting are key challenges [1-10]. In this paper, several advancements towards the realization of an impedance compensated passive implantable transcutaneous atrial defibrillator are reported; a high power transcutaneous inductive link for energy transfer, a low-power ECG and impedance sensing system for AF detection and optimised cardioversion with integrated microcontroller and RF link for system control.

2. Methods

Fig. 1 shows a top-level schematic of the power transmitter (external) and power receiver (implant) architecture developed. The external power transmitter consists of a tuned parallel RLC resonant tank circuit energized via synchronous switching of an IGBT (IRG4PH40U) located in the current return path to ground; with a primary coil (L_T = 9.65μH: 30 turn spiral coil, inner diameter 20mm, 0.85mm copper wire) and a resonant capacitor (C_T = 17.41nF). The implantable power receiver consists of a series RLC resonant tank circuit; with a primary-secondary turns ratio of 1:1 (again L_T = 30 turn spiral coil, inner diameter 20mm, 0.85mm copper wire) and a resonant capacitor (C_T : 10nF). Both circuits (TX/RX) designed for maximum power transfer at approximately 185kHz. The output of the receiver coil is then rectified and filtered; with multiple regulators used to provide the range of voltages (6-18V) required for operation of the integrated control, measurement and communications circuitry. In sense mode, up to 5W of power is continuously transferred; while local temperature monitoring ensures that maximum implant operating temperatures are never exceeded. In this mode, an integrated ECG unit is also used to detect the presence of AF while a standard Howland bridge is used to measure the impedance of the heart and communicate this to the TX unit prior to cardioversion [12, 13]. In shock mode, up to 150W of power can be delivered as an impedance compensated biphasic chronosymetric amplitude asymmetric shock impulse to the patient.

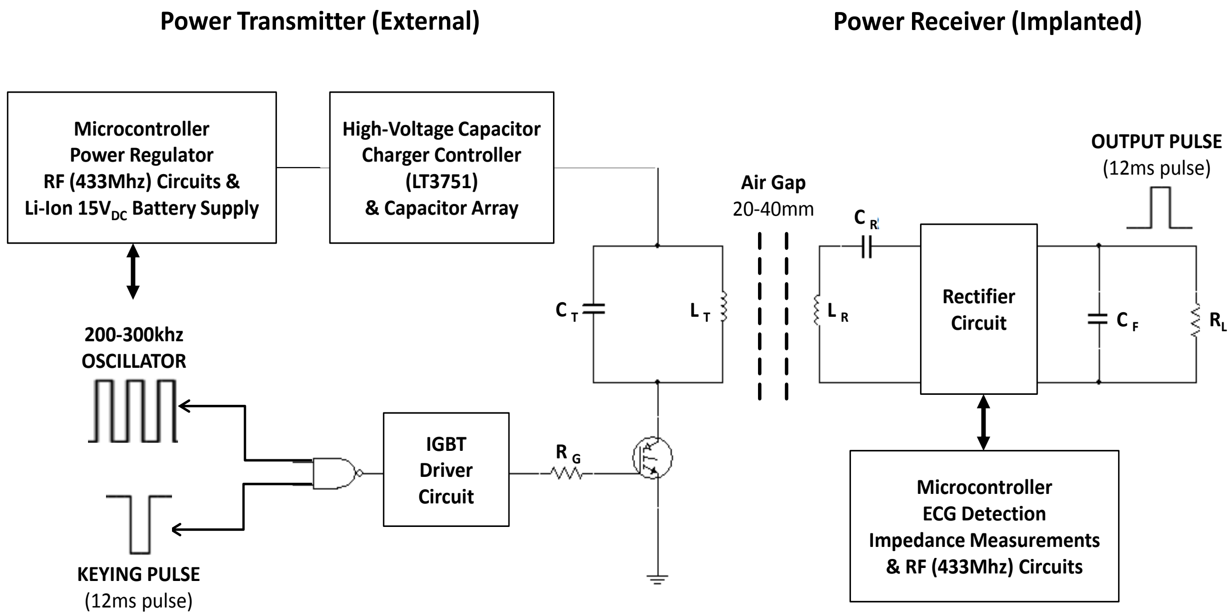


Figure 1. Implantable transcutaneous power link architecture.

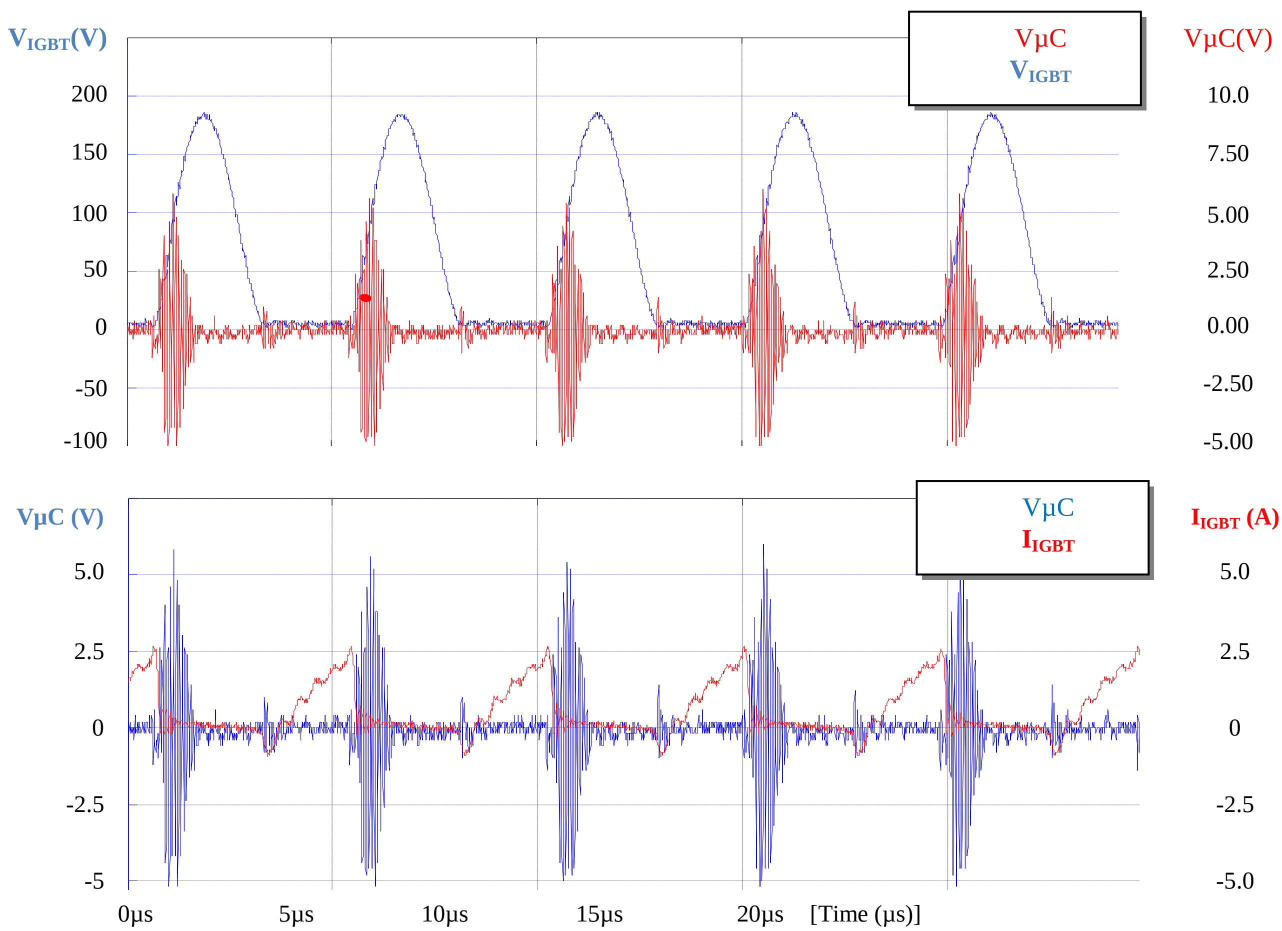


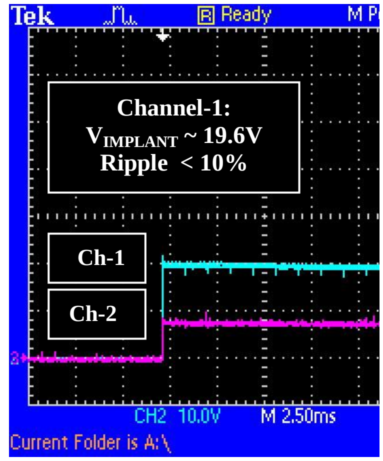
Figure 2. TX microcontroller (µC) control signals versus voltage (V) and current (I) across IGBT switching transistor.

3. Results

Architecture sub-systems were tested and characterized separately. Fig. 2 shows oscilloscope plots of the control signal from the microcontroller driving the power transmission resonant tank and the voltage and current waveforms that developed; where it can readily be observed that at a switching frequency of approximately 185kHz (T=5.4μs) the control signal (0-5V) modulates the tank voltage and current from 0-180V at 0-2.5A with a transmission efficiency of approximately 47.2% achieved. When operating in sense mode: Fig. 3 shows the oscilloscope plot taken from the implant side rectified and regulated output voltage where again for f~185kHz, V_{RX}=19.6V@0.36 A (7.1W continuous) while Fig. 4 provides an oscilloscope plot of the voltage waveform taken across a 50Ω dummy (resistive) load during the impedance measurement phase; demonstrating injection of a +/-98μA constant magnitude sinusoidal current at a frequency of 1kHz. In addition, the impedance measurement function was calibrated against a standard commercial instrument used to measure the inter-electrode complex impedance spectrum between the electrical contacts of two defibrillation catheters placed co-axially 4cm apart in a normal saline solution (containing 9g sodium chloride per litre with approximate ionic content of 150mmol/L sodium, 150mmol/L chloride at 25C). Measurement repeatability was found to be approximately 3%. When operating in shock mode: Fig. 5 shows an oscilloscope plot taken from the implant side rectified and regulated output voltage where f~185kHz, V_{RX}=98.4V @ 1.6A (>157W for a duration of 12ms) during shock delivery.

4. Discussion

In the context of the experimental test results achieved, overall functionality of the design was verified. Transcutaneous coupling of up to 5W continuous (sense mode) and up to 2.2J of energy (shock mode) was reliably demonstrated. The ability to reliably operate the transcutaneous link in both a continuous low power and a high power delivery mode is key to incorporation of low-power ECG, impedance measurement and RF communications circuitry. Further studies into advanced ECG detection techniques [12] and the potential advantages of shock sequencing [6,7,10] are being undertaken to investigate new low-energy cardioversion protocols that could avoid the need for sedation. Finally, in the present implementation, regulation of power delivery to the implant is controlled by the external unit; work is ongoing to develop a base-implant temperature feedback loop that will ensure maximum power transfer never exceeds local tissue heating constraints.

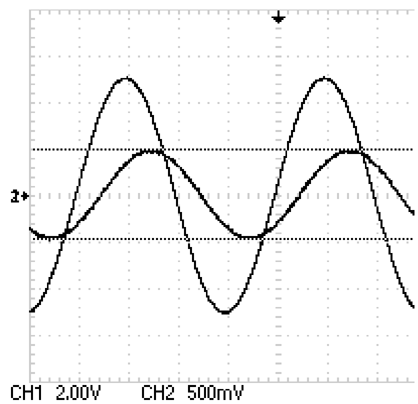


Y-Axis
Channel-1
$V_{IMPLANT}$
[10V/div]

Channel-2
$I_{IMPLANT}$
[0.5A/div]

X-Axis
Timebase
[2.5ms/div]

Figure 3. Implant side rectified and regulated output voltage and current. Sense mode: 19.6V (10V/div), 50Ω load, 0.36A [7.1W].

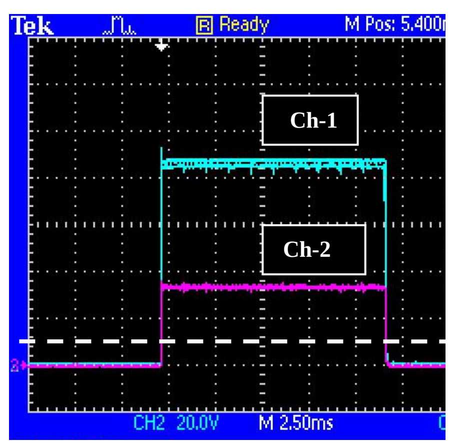


Y-Axis
Channel-1
V_{SOURCE}
[2V/div (x1)]

Channel-2
V_{LOAD}
[500mV/div (x100)]

X-Axis
Timebase
250μs/div
f = 1000Hz

Figure 4. Impedance measurement taken across a 50Ω resistive load at 1kHz; $V_{REF.}$ = +/-5V, V_{LOAD}=0.985V_{PP}



Y-Axis
Channel-1
V_{SHOCK}
[20V/div]

Channel-2
I_{SHOCK}
[1A/div]

x-axis
Timebase
[2.5ms/div]

Figure 5. Implant side rectified and regulated output voltage and current. Shock delivery mode: 98.4V (20V/div), 1.6A [157.4W, 2.2J over 12ms].

5. Conclusions

Impedance compensated transcutaneous defibrillation may allow cost effective pain free treatment of patients with persistent AF. In this work a number of key advancements towards a battery free low-energy impedance compensated passive implantable atrial defibrillator (IC-PIAD) system are reported. In particular, the proposed dual band / dual mode RF transmission architecture enables the possibility of efficacious low-energy impedance compensated passive implantable atrial defibrillation in an ambulatory setting. Further development of the system for pre-clinical trials is on-going.

Acknowledgements

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