ResearchSpace@Auckland

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage. http://researchspace.auckland.ac.nz/feedback

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form and Deposit Licence.

Note: Masters Theses

The digital copy of a masters thesis is as submitted for examination and contains no corrections. The print copy, usually available in the University Library, may contain corrections made by hand, which have been requested by the supervisor.
An Effective Transcutaneous Energy Transfer (TET) System for Artificial Hearts

Thushari D. Dissanayake

Supervised by: Dr. David Budgett, Dr. Patrick Hu and Associate Professor Simon Malpas

A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy in Bioengineering
The University of Auckland, New Zealand
April 2010
Abstract

Smart implantable medical devices such as cochlear implants, cardiac pacemakers and artificial heart pumps, consume electrical energy for the lifetime of the patient. The method of power delivery in these devices is principally dependent on their power requirements. Low power implantable devices, such as cardiac pacemakers requiring power in the range of 30 - 100 μW and can be operated from an internal battery for up to 10 years before exhaustion. However, high power implantable medical devices such as artificial hearts can require up to 30 W which is not suitable to be supplied from a battery. These devices are currently powered by an external power supply consisting of a wire passing through the skin and directly connecting to the artificial heart. However this method of power delivery introduces a substantial risk of infection which contributes to 40% of serious adverse events for Left Ventricular Assist Devices (LVADs).

This thesis focuses on developing a wireless power supply solution for artificial hearts and LVADs. Transcutaneous Energy Transfer (TET) systems use magnetic fields to transfer power across the skin without direct electrical connectivity. This offers the prospect of lifetime operation and overcomes the infection risk associated with wires passing through the skin. The major issues relating to TET are the heating of tissue and the variable nature of the alignment between a primary coil located near the skin surface and a secondary coil located under the skin. The work carried out in this thesis uses a novel frequency control approach that allows for wide tolerance in the alignment between coils with separations and lateral displacements of 10 mm to 20 mm, with relatively small size (50 mm diameter) and enables the transfer of up to 25 W of power.

Thermal and alignment performance was verified using a sheep experimental model. The secondary coil was implanted under the skin in six sheep and the system was operated to deliver a stable power output to a 15 W load continuously over four weeks. The maximum surface temperature of the secondary coil increased by a mean value of 3.4 ± 0.4 °C (Standard Error of Mean). The highest absolute mean temperature was 38.3 °C. The mean temperature rise at 2 cm from the secondary coil was 0.8 ± 0.1 °C. The efficiency of the system exceeded 80% across a wide range of coil orientations. Histological analysis revealed no evidence of
tissue necrosis or damage after four weeks of operation. In a bench-top experiment, the TET system was used to power the MicroMed’s DeBakey HA5 LVAD. The contributions from this thesis include the development of an efficient TET system with frequency based power regulation and the implementation of the system in a non-compliant animal to carry out a full thermal and coupling study. It is concluded that the developed TET system demonstrates all key performance criteria as required for a power delivery system suitable for an implantable heart pump and eliminates the risk of driveline infections.
Acknowledgement

I would like to express my sincere gratitude towards my supervisors Dr David Budgett, Dr. Patrick Hu and Associate Professor Simon Malpas for their enormous efforts giving guidance and encouragement throughout the course of this project.

I wish to gratefully acknowledge, Dr. Andrew Taberner, Associate Professor Laura Bennet, Associate Professor Poul Nielsen, Dr. Lindsea Booth, Dr. Susan Pyner and Sarah-Jane Guild for their advice and assistance.

I would specially like to express my gratitude to VJU team leader of the sheep lab in Department of physiology, Maree Schollum, and workshop manager in Auckland Bioengineering Institute, Peter Blyth, for all their support during experimental work carried out in this project.

I am grateful for the financial assistance from Foundation of Research Science and Technology and Telemetry Research Ltd. Also I would like to thank all the employees of the Telemetry Research Ltd, particularly Dr. Robert Kriton, Mathew Lim, Masahiro Kondo, and Wayne Pallas, for their technical and moral support.

I am also very thankful for advice from my fellow PhD students and post doctoral researchers from the Implantable Medical Devices group, Daniel McCormick, Yanzhen Wu, David Russell, Alex Leung and Bob Wang. Last but not least I wish to thank my fellow postgraduate students and administrative staff at the Auckland Bioengineering Institute for providing a collegial atmosphere.
# Table of content

Abstract...........................................................................................................................................i  
Acknowledgement.......................................................................................................................... iii  
Table of content...............................................................................................................................iv  
List of figures........................................................................................................................................vii  
List of tables.........................................................................................................................................xiii  
Nomenclature ......................................................................................................................................xiv  

1 Introduction......................................................................................................................................1  
1.1 Power supplies for implantable medical device.................................................................2  
1.2 Applications of TET systems.................................................................................................5  
1.2.1 Cochlear implants ..............................................................................................................5  
1.2.2 Cardiac pacemaker .............................................................................................................6  
1.2.3 Implantable telemetry unit .................................................................................................7  
1.2.4 Retinal prosthetic devices .................................................................................................8  
1.2.5 Functional electrical simulators .........................................................................................8  
1.3 LVADs and artificial heart systems.........................................................................................9  
1.4 TET application summary.......................................................................................................14  
1.5 Challenges associated with TET systems ...........................................................................15  
1.6 TET Overview .......................................................................................................................17  
1.7 Objective and scope ...............................................................................................................20  

2 Thermal study of skin tissue ........................................................................................................23  
2.1 Thermal properties of skin tissue...........................................................................................24  
2.2 Simulating the temperature distribution of a TET system ..................................................26  
2.3 Experimental temperature study using bench tests............................................................28  
2.4 Temperature calibrations .......................................................................................................33  
2.5 Model validation using a short term experimental study in sheep .....................................37  
2.6 Summary ...............................................................................................................................41  

3 Magnetic coupling analysis and design of internal and external coils .............................43  
3.1 Mutual inductance and coupling coefficient .......................................................................44  
3.2 Significance of coupling in TET systems ............................................................................45  
3.3 Coil designs for high power TET systems in literature .....................................................50
3.4 Methods of determining coupling coefficient

3.4.1 Analytical model

3.4.2 Simulated model

3.4.3 Experimental measurements

3.4.4 Model validation

3.5 Comparison of analytical, numerical and practical coupling coefficients

3.6 Design and construction of an improved coil set

3.6.1 Construction of coils

3.6.2 Inductive coil design

3.7 Alignment tolerance of primary and secondary coils

3.8 General guideline for designing coils

3.9 Coil encapsulation and moulding

3.10 Summary

4 Power loss evaluation of the TET system

4.1 Self-sustained current-fed push-pull converter

4.2 Secondary power conditioning

4.3 Power loss components

4.3.1 Categorisation of power loss components

4.3.2 Power loss in the primary circuit

4.3.3 Power loss in the secondary circuit

4.4 Experimental loss analysis of the self-sustained push-pull converter

4.5 Methods of improving the existing system

4.6 Current-fed push-pull converter with an external controller

4.7 Current-fed push-pull converter with ZVS feedback

4.7.1 System performance

4.7.2 Experimental power loss analysis

4.8 Operating frequency

4.9 Discussion

5 Implementation of closed loop control

5.1 Power regulation techniques

5.1.1 Magnitude control method

5.1.2 Frequency control method

5.2 Switched capacitor control method

5.3 Implementing open loop frequency control
5.4 Implementing closed loop control ................................................................. 142
5.5 System response ............................................................................................ 145
   5.5.1 System response to variation in coupling ................................................. 145
   5.5.2 System response to variation in loading .................................................... 146
5.6 Power loss analysis with frequency control .................................................... 147
5.7 Discussion ....................................................................................................... 152

6 Sheep experimental study ................................................................................. 155
   6.1 Experimental protocol ................................................................................... 156
   6.2 Experimental preparation .............................................................................. 158
   6.3 Sheep surgery ................................................................................................. 160
   6.4 Experimental setup ...................................................................................... 163
   6.5 Sheep experimental Results ......................................................................... 165
      6.5.1 Power transfer capability ......................................................................... 165
      6.5.2 Coupling variation .................................................................................... 168
      6.5.3 Temperature changes ............................................................................... 169
      6.5.4 Histological study .................................................................................... 172
   6.6 Discussion ....................................................................................................... 175

7 TET integration into an existing heart pump ....................................................... 178
   7.1 Main components of the MicroMed’s Debakey HA5 VAD ............................. 179
   7.2 Incorporating TET ......................................................................................... 181
      7.2.1 Implantable rechargeable battery technology .......................................... 181
      7.2.2 Miniaturising the primary and the secondary circuits .............................. 184
      7.2.3 Demonstration unit ................................................................................. 186
      7.2.4 Pump performance with the TET system ............................................... 187
   7.3 Steps towards human trials ............................................................................ 188

8 Conclusions and future work ............................................................................ 191
   8.1 Contributions of this thesis .......................................................................... 194
   8.2 Recognition ..................................................................................................... 195
   8.3 Future work ..................................................................................................... 197

References ............................................................................................................. 200
List of figures

Figure 1-1: Adverse events from LVADs [8] ................................................................. 4
Figure 1-2: Block diagram of a TET power supply system ........................................ 4
Figure 1-3: TET system used in cochlear implants ..................................................... 6
Figure 1-4: A flowchart of a system measuring the electroneurogram signals in rabbits [21] .. 8
Figure 1-5: Functional electrical simulators [27] ............................................................ 9
Figure 1-6: The proposed fully sealed HeartMate II system [40] ................................. 11
Figure 1-7: Primary and the secondary coils of the LionHeart TET system [37] .......... 12
Figure 1-8: Abicor artificial heart system [31] ............................................................... 13
Figure 1-9: Circuit structure of a TET system ............................................................... 18
Figure 1-10: Full bridge and half bridge voltage fed converters .................................. 19
Figure 2-1: Cross sectional view of the placement of the primary and the secondary coil with in skin tissue .............................................................................................................. 25
Figure 2-2: 2D model of the primary and secondary coil within skin tissue meshed in COMSOL ................................................................................................................................. 26
Figure 2-3: Heat distribution of the primary and the secondary coils when delivering 15W of power to the load ........................................................................................................... 27
Figure 2-4: Measured temperature rise in three sets of primary and secondary coil designs .. 29
Figure 2-5: Temperature distribution around the Coil set 2 in air when simulated with a piece of insulator between the primary and secondary coils .................................................... 30
Figure 2-6: Temperature distributions around the primary and secondary coils in air without insulation ........................................................................................................................................... 31
Figure 2-7 : Temperature distributions around the primary and secondary coils in air with a polymer heat sink ........................................................................................................... 32
Figure 2-8: Maximum temperature in the TET system at different room temperatures ........ 33
Figure 2-9: Temperature calibration graph of 7 thermistors and an RTD .......................... 36
Figure 2-10: Heat distribution of the primary and the secondary coils when delivering 15W of power to the load [62] .................................................................................................. 38
Figure 2-11: Placement of the sensors in and around the internal coil .............................. 39
Figure 2-12: The coils placed in the sheep during surgery [62] ........................................... 40
Figure 2-13: Temperature rise in the primary and secondary coils when delivering various loads ................................................................. 41
Figure 3-1: Mutual inductance between two circular loops ........................................... 44
Figure 3-2: TET system implanted in the (a) abdominal area and (b) in the chest area .... 47
Figure 3-3: Coil displacements of primary and secondary coils .................................. 48
Figure 3-4: Equivalent circuit diagram of a parallel tuned TET .................................... 48
Figure 3-5: Impedance plot of equivalent circuit model at k=0.1 ................................. 49
Figure 3-6: Impedance plot of equivalent circuit model at k=0.4 ............................... 50
Figure 3-7: Placement of the primary and secondary coils in the TET system designed by NEDO artificial heart project [70] ................................................................. 51
Figure 3-8: Axially aligned separation between the primary and secondary coils ......... 53
Figure 3-9: Relationship between mutual inductance and the ratio of separation and primary coil radius ........................................................... 55
Figure 3-10: Primary and secondary coils laterally displaced by $x$ ............................. 55
Figure 3-11: Relationship between axially aligned separation and lateral displacement .... 56
Figure 3-12: Secondary coil rotated by an angle $\alpha$ on its centre axis ......................... 57
Figure 3-13: Relationship between axially aligned separation and angular rotation with mutual inductance .................................................................. 58
Figure 3-14: A mesh of primary and secondary coils generated in JMAG ............... 59
Figure 3-15: Magnetic field distribution generated by primary coil when the secondary is laterally displaced by 20 mm for a separation of 10 mm ......................... 60
Figure 3-16: Magnetic field distribution generated by primary coil when the secondary is laterally displaced by 10 mm for a separation of 15 mm ......................... 60
Figure 3-17: CAD model of physical test rig used to hold primary and secondary coils in known physical orientation ...................................................... 61
Figure 3-18: The effect of lateral displacement on coupling at 10 mm separation ........ 62
Figure 3-19: Effects of separation between coils on coupling when the coils aligned axially 64
Figure 3-20: Effects of lateral displacement on coupling at 10 mm separation between the coils .................................................................................... 64
Figure 3-21: Effects of lateral displacement on coupling at 10 mm separation between the coils .................................................................................... 65
Figure 3-22: Type 1 and 2 Litz wire from New England Litz wire manufacturers [72] ..... 66
Figure 3-23: Relationship between Resistance and wire gauge [73] ............................ 67
Figure 3-24: Wire gauge recommendations for different frequencies [74] ................. 68
Figure 3-25: Structure of spiral and concentrated coils .................................................69
Figure 3-26: Various coil geometries simulated on JMAG ............................................70
Figure 3-27: Various primary and secondary coil designs considered ..........................71
Figure 3-28: Coil dimensions ..........................................................................................72
Figure 3-29: Coupling coefficient over different external diameters for various coil
configurations .................................................................................................................72
Figure 3-30: Coupling coefficient at axially aligned separations ....................................72
Figure 3-31: (a) Coupling coefficient at axially aligned separations for practical coils; (b)
Coupling coefficient at lateral displacements for practical coils ...................................75
Figure 3-32: Tether length between a set of primary and secondary coils .......................76
Figure 3-33: Primary and secondary coils of coil set 1 and 2 [76] ...................................77
Figure 3-34: Displacement profiles of two sets of primary and secondary coils [76] ........78
Figure 3-35: Flow diagram of a design methodology for primary and secondary coils ......82
Figure 3-36: Primary and secondary coils moulds .......................................................85
Figure 3-37: The moulded primary and secondary coils ................................................85
Figure 4-1: TET system based on a self-sustained current-fed resonant push-pull converter. 89
Figure 4-2: Simulated waveforms of the collector-emitter voltage of the two BJTs and the
corresponding resonant waveform across the primary coil ............................................91
Figure 4-3: Secondary power conditioning circuitry ......................................................92
Figure 4-4: Categorization of power loss components .......................................................93
Figure 4-5: Switching voltage and current wave forms under non-ZVS condition ..........96
Figure 4-6: Distribution of losses in the autonomous push-pull converter .......................99
Figure 4-7: Switching voltage and current for a 10W load ............................................100
Figure 4-8: (a) Current and voltage waveforms during the turn-on time period; (b) Current
and voltage waveforms during the turn-off time period ................................................101
Figure 4-9: (a) Collector current waveform during the turn-on; (b) Collector voltage during
the turn-on ......................................................................................................................102
Figure 4-10: A cost benefit analysis of the power loss in the autonomous system ..........104
Figure 4-11: Current-fed push-pull converter with an external controller .........................106
Figure 4-12: Simulated waveforms of the current-fed push-pull converter with an external
controller .......................................................................................................................107
Figure 4-13: Voltage waveform across the resonant tank ..............................................110
Figure 4-14: Power loss analysis of a TET system with an external controller ...............111
Figure 4-15: Current-fed Push-pull converter with ZVS feedback ..................................113
Figure 4-16: (a) Resonant signal across the primary resonant tank; (b) Output voltage signals from the quad NAND gate; (c) The signals driving the switches S1 and S2.

Figure 4-17: Power loss contributions of the improved TET system with ZVS feedback.

Figure 4-18: Power efficiency and input voltage at various separations.

Figure 4-19: Power loss at various separations.

Figure 4-20: Power loss at various loading conditions.

Figure 4-21: Increase in ESR of inductive coils with frequency.

Figure 4-22: Relationship between power loss and operating frequency.

Figure 5-1: Basic structure of magnitude controlled TET system.

Figure 5-2: System based on primary frequency control.

Figure 5-3: Relationship between power flow and frequency of the system [97].

Figure 5-4: Relationship between phase angle and frequency.

Figure 5-5: Variable frequency current-fed push-pull converter.

Figure 5-6: Phase control structure.

Figure 5-7: Waveforms of the phase control circuitry.

Figure 5-8: Frequency control circuitry of the system.

Figure 5-9: (a) Frequency control waveforms for SV1; (b) Frequency control waveforms for SV2.

Figure 5-10: (a) Current through CV1; (b) Voltage across CV1.

Figure 5-11: The system’s waveforms at 164 kHz when it is 95% detuned.

Figure 5-12: The system’s waveforms at 172.8 kHz when it is 78% detuned.

Figure 5-13: The current and voltage waveforms of the tuning capacitor when the system is fully detuned and tuned.

Figure 5-14: Frequency variation and effective capacitance for different separations when delivering 7 W of power to the load.

Figure 5-15: Frequency variation and effective capacitance for different separations when delivering 15 W of power to the load.

Figure 5-16: TET system with wireless control [98].

Figure 5-17: Control Algorithm [99].

Figure 5-18: Response of the system to change coupling conditions.

Figure 5-19: Response of the system to change in loading conditions.

Figure 5-20: Categorization of power loss components including frequency control circuitry.

Figure 5-21: Power loss contributions at different stages of the frequency control circuitry.
Figure 5-22: Power spectrum across the resonant capacitor for ZVS condition in (a) Linear and (b) Logarithmic scale ................................................................. 151
Figure 5-23: Amplitude spectrum of the resonant capacitor when the system is fully tuned in (a) Linear and (b) Logarithmic scale ................................................................. 151
Figure 5-24: Amplitude spectrum across the resonant capacitor when the system is fully detuned in (a) Linear and (b) Logarithmic scale ................................................................. 152
Figure 5-25: Relationship between \( C_v \) and frequency control range ................................................................. 153
Figure 5-26: Amplitude spectrum across the resonant capacitor when \( C_v > C_p \) ................................................................. 154
Figure 6-1: The experimental setup of the sheep experiment [101] ................................................................. 157
Figure 6-2: The experimental setup of the sheep experimentation ................................................................. 158
Figure 6-3: Placement of the temperature sensors around the implanted coil [102] ................................................................. 159
Figure 6-4: Form of the implanted coil just before implantation in to a sheep ................................................................. 159
Figure 6-5: The area of shaved skin of on of the sheep before the application of iodine of sterilization ................................................................. 160
Figure 6-6: The exit point of the power leads and the thermistors out of the insertion point being sutured in place ................................................................. 161
Figure 6-7: Metabolic cages that sheep were kept in during experimentation ................................................................. 162
Figure 6-8: The placement of the primary coil over the sheep’s skin [99] ................................................................. 162
Figure 6-9: Block diagram of the data acquisition program on LabView ................................................................. 163
Figure 6-10: Graphical interface of the data display window on LabView ................................................................. 164
Figure 6-11: Experimental set up of the data acquisition units and the external circuitry in the control room ................................................................. 165
Figure 6-12: Mean power (±SEM) delivered to the 6 sheep over 28 day period [102] ................................................................. 166
Figure 6-13: Coupling variation over 24 hours in one sheep ................................................................. 167
Figure 6-14: Images captured on the QuickCam within 1 minute and 11 seconds ................................................................. 168
Figure 6-15: Variation in power transfer and coupling over 24 hours in Sheep 1 and 2 [104] ................................................................. 169
Figure 6-16: Transient temperature profile around the secondary coil from base line in Sheep 6 ................................................................. 170
Figure 6-17: Temperature rise of the sensor placed above the secondary coil under the skin over 28 days for six different sheep when delivering 15W of power to the load ................................................................. 171
Figure 6-18: The external view of the skin tissue once the coils were removed after one month. Image A corresponds to the active region and image B corresponds to the inactive region ................................................................. 172
Figure 6-19: 10x10 tissue sample being taken out directly above the center of the secondary coil.

Figure 6-20: Histological results of the tissue on the active and inactive region.

Figure 7-1: The MicroMed Debakey VAD system [34].

Figure 7-2: The MicroMed Debakey VAD controller [34].

Figure 7-3: Structure of the TET system following the integration of the Debakey VAD [106].

Figure 7-4: Energy density of Lithium ion battery is much higher than Nickel based batteries [109].

Figure 7-5: Physical TET circuits and VAD set up.

Figure 7-6: Demonstration unit.

Figure 7-7: Performance of the Debakey VAD with a standard dc power supply and the TET system.

Figure 7-8: Flow chart of development of a TET system towards human trials.
List of tables

Table 1-1: Typical coil separations and power requirements of TET systems .................. 14
Table 1-2: Characteristics of existing VAD systems [49] ............................................. 15
Table 2-1: Coil dimensions of three coil sets ................................................................... 28
Table 2-2: Calibration equations for a set of thermistors .................................................. 36
Table 3-1: Characteristics of primary and secondary coils ............................................. 63
Table 3-2: General coil parameters of primary and secondary coils ................................ 71
Table 3-3: General coil parameters of primary and secondary coils ................................ 74
Table 3-4: Coil dimensions of two coil sets ..................................................................... 77
Table 3-5: Coil designs for different power transfer and coupling conditions ............... 84
Table 4-1: Loss analysis of the autonomous push-pull converter .................................. 99
Table 4-2: Methods of improving power loss ................................................................. 103
Table 4-3: Loss analysis of the push-pull converter with an external controller ............. 111
Table 4-4: Loss analysis of the ZVS feedback TET system ........................................... 116
Table 6-1: Temperature distribution around the secondary coil over 28 days, data shown as mean ±sem of temperature rise and absolute temperature at different locations for six sheep .................................................................................................................. 171
## Nomenclature

### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac</td>
<td>Alternating current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>AWG</td>
<td>American Wire Gauge</td>
</tr>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analogue Converter</td>
</tr>
<tr>
<td>dc</td>
<td>Direct current</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>emf</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>EMC</td>
<td>Electromagnetic Compatibility</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>ESR</td>
<td>Equivalent Series Resistance</td>
</tr>
<tr>
<td>FES</td>
<td>Functional Electrical Stimulator</td>
</tr>
<tr>
<td>Li-I2</td>
<td>Lithium Iodine</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium Ion</td>
</tr>
<tr>
<td>Li-MnO2</td>
<td>Lithium Manganese Dioxide</td>
</tr>
<tr>
<td>Li-SO2</td>
<td>Lithium Sulfur Dioxide</td>
</tr>
<tr>
<td>LVAD</td>
<td>Left Ventricular Assist Device</td>
</tr>
<tr>
<td>ME</td>
<td>Medical Electrical</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Silicon Field Effect Transistor</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Nickel Cadmium</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>Nickel-Metal Hydride batteries</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PCE</td>
<td>Patient Carried Electronics</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>rms</td>
<td>Root mean square</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistive Temperature Device</td>
</tr>
<tr>
<td>SNA</td>
<td>Sympathetic Nerve Activity</td>
</tr>
<tr>
<td>LTSPICE</td>
<td>PC simulation program with integrated circuit emphasis</td>
</tr>
</tbody>
</table>
SEM - Standard Error of Mean
TAH - Total Artificial Heart
TET - Transcutaneous Energy Transfer
VAD - Ventricular Assist Device
ZCS - Zero Current Switching
ZVS - Zero Voltage Switching
2D - Two dimensions
3D - Three dimensions

**Symbols**

C - Capacitance (Farads)
f - Frequency (Hz)
ω - Angular frequency (Radians/s)
i - Instantaneous current (Amperes)
I - Current (Amperes)
j - Complex operator (\(\sqrt{-1}\))
k - Magnetic coupling coefficient
L - Self-inductance (Henrys)
M - Mutual inductance (Henrys)
P - Power (Watts)
Q - Quality factor
R - Resistance (Ω)
v - Instantaneous voltage (Volts)
V - Voltage magnitude (Volts)
θ - Phase angle, switching angle (degrees)
t - Time (seconds)