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TRANSCUTANEOUS POWER TRANSMISSION IMPLANT
FOR LEFT VENTRICULAR ASSIST DEVICE

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Abstract

The left ventricular assist device (LVAD) is a device used to assist a weak heart in pumping blood through the body. Currently, the LVAD system is powered by an external battery by wires that pass through the skin. The high probability of infection occurring is the leading cause of failure for the current LVAD system.[5] In an attempt to improve on the blood pump device, a wireless power transmission device was proposed. The proposed device was to use a motor-generator system that was coupled through magnets across a gap representing power being transmitted through a medium. The basics behind the device are that the motor would be provided power from an outlet and would rotate a disk that had magnets along the outer diameter. Then on the generator side a similar magnetic disk would rotate the generator which would provide power out that would then be regulated to usable DC voltage. This DC voltage would then be used to charge the battery of the LVAD system.

Nomenclature

AC - Alternating Current
Armature – Disk with magnets
COTS – Commercial off-the-shelf parts.
DAQ – Data acquisition unit
DC - Direct Current
Generator – Device which converts mechanical energy into electrical energy
LVAD – Left Ventricular Assist Device
Motor – Device which converts electrical energy into mechanical energy
Receiver – Generator side of the system
Rectifier – Converts the electrical signal from the generator into DC voltage
Regulator - Steps down voltage and provides about the same power input and output
RPM – Revolutions per minute
Transmitter - Motor side of the system

Introduction

This project is a part of the LVAD lab's ongoing goal of improving blood pump devices in the medical field. An LVAD is commonly used to assist he heart in pumping blood during heart failure.

One of the drawbacks of the LVAD is that it has a large power demand. Even the most efficient LVAD devices will, at regular intervals, require external power either from a surgical battery replacement or a pair of wire leads that can recharge the battery directly. Surgeries at regular intervals increase patient risk of infection at the incisions, and likewise do external wire leads.

This project's end goal is the first iteration of a wireless power transmission system that can bypass the risk of infection. This can be done with a passive magnetic coupling system, patented by Dr. Coley Duncan.

Inductive coil systems, over this distance, have a large energy loss associated with them, rejecting the lost energy as heat. This heat may increase the temperature of surrounding tissue to dangerous levels.

This project is founded on the goal of making a high-efficiency system that removes the risks of overheating, electrocution, and infection. This can be done using a paired motor-generator system with passive magnetic coupling.

Methodology

This project was divided into two main sub-assemblies, transmitter and receiver. The transmission portion consists of motor controller, motor housing, motor, magnetic armature. The receiver consists of receiving magnetic armature, generator, rectifier, and voltage regulator.

Figure 1: *General System diagram*

Motor Controller

The motor controller's main purposes in this project is to provide the proper signal and enough electrical power to spin the motor to our desired speed and torque range, namely ~10000 RPM and ~36.8 mNm of torque, and also to maintain the magnetic linkage between the motor and generator through soft/slow acceleration. The motor controller chosen was the Castle Creations Phoenix 35 motor controller for the fact that it was readily available and was already used to power and drive our motor, the EC i-40. There was another option to drive our motor with, and that was the reference design kit (RDK-BLDC) from TI/Stellaris. This option, however, was deemed unfeasible because it did not have the ability to reach the RPM that we wanted due to too low of a switching frequency and the unusually high number of poles (7) of the EC i-40. In the future, if a motor was matched with the specifications of the TI RDK-BLDC, this micro/motor controller could be utilized to provide sensored motor control, current limiting, and various other programmatically available features that the Phoenix 35 does not have.
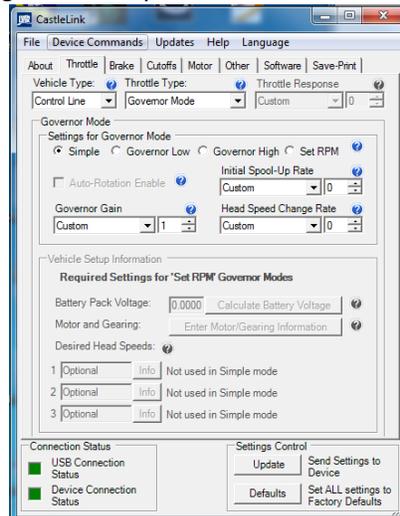
Figure 2: *A screenshot of the Castle Creations CastleLink interface.*

A feature of the Phoenix 35 was its ability to be programmed with certain control modes and various other settings through the CastleLink interface to a PC via USB adapter, and this feature was used frequently. The Phoenix 35 was able to spin the EC i-40 up to ~9000 RPM with the generator spinning and a load drawing power from the generator. More importantly, it was able to slowly ramp up the speed from 0 to 9000 without breaking the link (adjusting the constant for spool-up rate in Castle Link), all while drawing load. Also, as an unexpected bonus of using a motor controller normally used for radio controlled airplanes and helicopters, the control type could be set to a "governor mode," which actively adjusts its power output to hold the motor at a certain set RPM to the best of its abilities. The main purposes maintaining a high speed and torque output, as well as avoiding magnetic link breakage was achieved.

Motor Housing

The motor needed to be enclosed by a case that was able to withstand everyday use. The motor housing needed to be made out of a light weight, low thermal conductivity, and non-ferrous material to accommodate for everyday use. Plastic was determined to be adequate for our requirements in strength, thermal conductivity, and weight. The plastic chosen was a clear polycarbonate to allow for visibility of the interior components. The polycarbonate was used for the Generator Housing because this material is bio-compatible. The housing case needed to be within a customer specification of less than one and an eighth inches in diameter with a height of less than two inches. The motor housing needed to be able to accommodate a motor, motor mounting mechanism, and the transmitting magnetic armature. Furthermore, the housing needed to allow for an easy access to internal components. The motor housing was machined manually between a combination of lathe and milling machines.

Magnetic Armature and Receiver (Transmitting and Receiving)

The design of the matching armatures was chosen from the results gained from magnetostatic simulation in COMSOL Multiphysics and experimental verification. Multiple configurations and magnet shapes were explored; the end result of six cylindrical magnets was chosen as a compromise between torque transmission capability, COTS cost, and design feasibility.

Properties for the neodymium magnets used in simulation were gathered from spec sheets from manufacturers. The range for magnetic remanence gave a wide range of torque values, so this property was experimentally gathered using data gained from the pull test (Figures 3 and 4 below).

Figure 3: *Magnet Pull Force Setup*
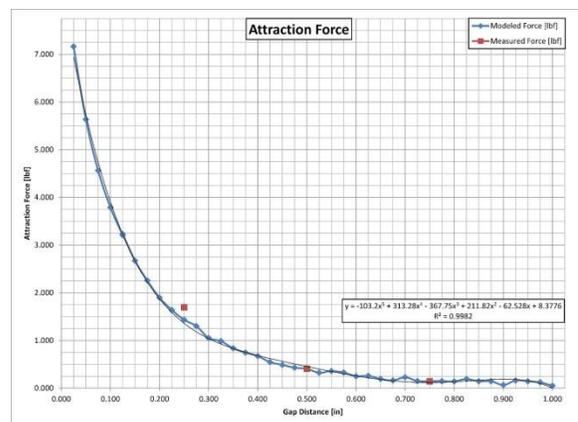
Figure 4: *Magnet Pull force Results*

Simulation data was verified with a bench top dynamometer; there was a correlation between results with less than 10% error.

The magnetic armatures were expected to be spinning at 20000 rpm. This armature was also designed to be thin, 0.300 inches, with a diameter of 2.875 inches. Since the disk would be spinning at a high rpm, a check of stress failure was required. ANSYS was used to model the disk and do a finite element analysis on the part. The

part was modeled with the material properties of polycarbonate. The max stress polycarbonate was able to withstand before yielding was 44MPa. The ANSYS results shown in Figure 5 show that the disk would see a max stress of 8.5 MPa
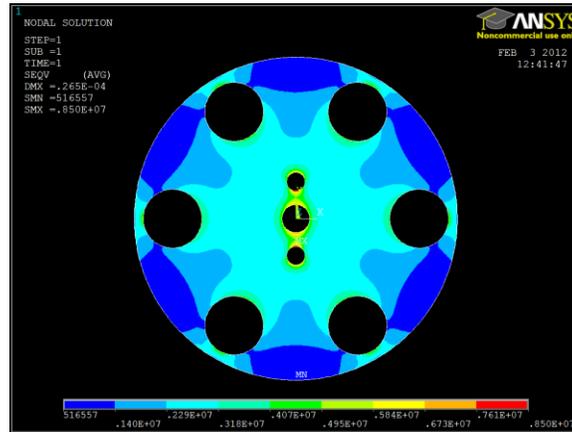

Figure 5: ANSYS stress (Pa) model of rotating disk at 20000 rpm.

Generator

For the purposes of this project, a generator that will meet the requirements of our design limits must be correctly chosen. The design limits for the generator are: (a) ability to fit into a case the size of a hockey puck (3 inch diameter and 1 inch thickness) and still allow room for rotating magnets, electronics, etc., (b) ability to use the available torque (breaking torque of magnetic link or maximum (nominal) torque of motor, 38.6 mNm and 36.8 mNm respectively) and speed provided by the motor to generate the required power (30 W), (c) emit less than 6 W of energy as heat so as to meet our minimum heat generation specification (40mW/cm2), (d) must be able to reliably perform its task for at least one year. It must also be noted that commercial generators are usually referring to large wind turbine or gas generators that generate a much greater power that we need, so we were essentially looking for "motors" that could potentially be run as generators. The difficulty is that companies are not then selling you generators, and their literature and specifications will not be conducive to would-be generator buyers.

Although each design limit logically eliminated potential candidates for generator (the size specification eliminated large motors, the torque and speed limits eliminated motors that did not spin as fast nor had non-matching constants, etc.), there were still a large amount to choose from and there had to be a way to quantify the differences. From here, it was decided to choose one motor/generator out of one catalog (Maxon), and that the analysis would be conducted with MATLAB for flexibility and repeatability. The document, "MATLAB Generator Characterization Documentation" could be referred to for more in-depth technical details, excerpts are copied below.

From "MATLAB Generator Characterization Documentation":
Introduction

This MATLAB implementation was the result of a need for a way to characterize commercial motors as generators. Commercial motors are usually supplied with a data sheet that includes numerous constants that define each individual motor. Additionally, some companies will provide literature in helping novices in energy conversion machines distinguish between their motors and also the principles behind how their products work. Through careful reading of such literature, a method was devised to calculate how a motor would behave as a generator. Implementing this analysis in MATLAB was common sense from the start since there were numerous calculations to be done for each individual motor, then multiply that by the amount of motors we would like to compare against each other and we have even more calculations. Numerically and programmatically solving this problem meant that results were fast, precise and repeatable. It also ensured that meaningful graphs and figures could be created and distributed easily.
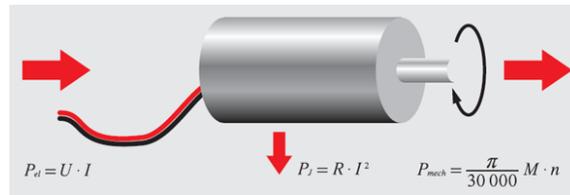
Theory

Figure 6: Motor Operation.

The motor accepts Pel, which is electrical power, in as a product of voltage and current. The motor also outputs Pmech, which is mechanical power out as rotation of the shaft. In the process of converting this electrical energy to mechanical energy, heat is dissipated due to joule heating losses and friction losses (not shown above since it manifests as a reduction in Pmech).

$$\eta = \frac{\pi}{30\,000} \cdot \frac{n \cdot (M - M_R)}{U \cdot I}$$

Figure 7: Efficiency.

Efficiency, as defined by Maxon literature, for a motor is the ratio between the total mechanical power out divided by the electrical power in.

If we isolate the term MR from the equation in Figure 7, we can see that the term signifies a loss in mechanical power (subtracted from the *theoretical* mechanical power out). It is known as the friction loss arising from iron loss in the commutation system (in the case of the electrically commutated motor, a.k.a. brushless).
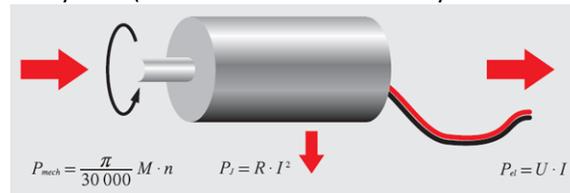

Figure 8: Generator Mode.

In generator mode, we can look at the known mechanical power going into the generator, the same joule heating losses from the motor copper wire windings, and the theoretical electrical power out. What is left out is the same friction torque, MR that arises from the commutation system.

Instead of taking the theoretical electrical power out and dividing over the mechanical power in to find the efficiency, the efficiency of the generator was calculated as thus:

$$\eta = \frac{P_{mech} - P_{friction} - P_J}{P_{mech}}$$

$$\eta(n, M, T) = \frac{\frac{\pi}{30000} n(M - M_R) - R_{25}\left(1 + \alpha_{Cu}(T - 25^o C)\right)I^2}{\frac{\pi}{30000} n * M}$$

Figure 9: Generator Efficiency.

This was deemed to be a more conservative estimate of the efficiency since we are estimated known losses and using them to determine efficiency. Additionally, the resistance of the generator/motor is dependent on temperature and is represented as thus above. The friction torque was also deemed to change with temperature but the literature did not give a clear way to estimate that so it is only speed dependent.

Omitted from the document are MATLAB code explanations and actual MATLAB code.

Using the method described above and keeping all things in consideration, the Maxon "EC45 flat" was chosen.

In terms of heat, any power lost between input electrical power to the motor and output electrical power of generator is considered heat. With that in mind, we can trace the energy transfer in stages to determine the heat output of separate groups of components. The reliability of Maxon EC motors are limited by the bearing life and from the Maxon catalog, their bearings are "designed for tens of thousands of hours" but ultimately, "service life is affected by maximum speed, residual imbalance and bearing load". Coincidentally, if we take the lower end of the range "tens of thousands" we get 10,000 hours ~= 1.14 years. However, we do not really know how long it will last since the residual imbalance and other factors affecting service life were not analyzed.

Additionally, a flaw was discovered in the analysis which did not match real world expectations. The analysis assumed 0 bearing friction in terms of power generation when in fact bearing friction as well as air friction of spinning armature (plastic disk holding magnets) would decrease the amount of torque being directly converted into current draw. This issue will be fully quantified and explained in the results section.
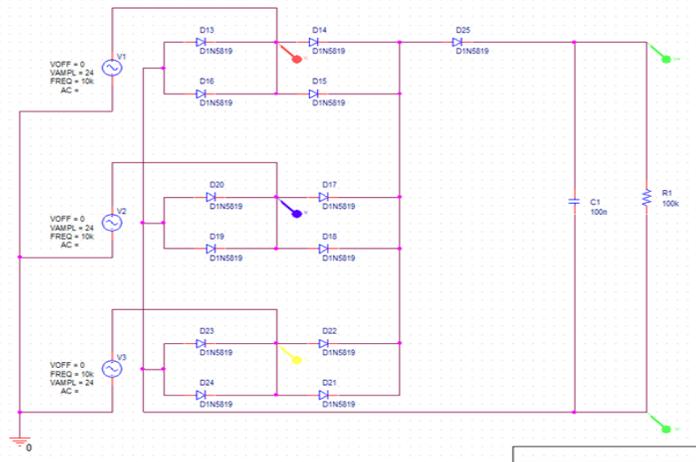
Rectifier

The generator will output supply a three phase alternating current (AC) signal. This signal will need to be converting into a direct current(DC) signal. The LVAD system runs off a DC power supply and needs the same signal to supply it. Rectification is the process from changing an AC signal into a DC signal. Diodes are used for rectification.

Diodes contain two junctions, a positively doped material and a negatively doped material. In order to allow a flow of electrons from one junction to another, the positive doped material needs to be at a higher potential than the negative doped junction. This means the junction will stop the flow from reverse currents and only let one signal flow of current. Since AC allows flow of current in two directions, that flow is stopped to a single flow in one direction.

There are many different diode types and junction types. The diodes chosen for this particular design was Schottky diodes. Schottky diodes have a fast recovery rate. The frequency of the signal will affect the diode's time to turn the junction on and off. Schottky diodes have a lower forward voltage (drop across the diode) as well. The power dissipated over the diode is the forward voltage multiplied by the current through the system. The lower the forward voltage, the lower the power dissipation, was making the system more efficient.

The rectifier configuration used was a full wave bridge rectifier. This rectifier configuration allows us to combine all three phases and clip the signal at a reference voltage. The reference voltage is taken to be ground. Figure 10 shows a cadence PSPICE schematic of the rectifier.[3]

Figure 10: *Three-phase rectifier.*

Voltage Regulator

A DC battery needs a consistent flow of current at a set voltage. The spec for the voltage was to be set at a range from 12 volts DC to 15 volts DC. The current flow would be set at what the DC power needed to supply the

system. Using the electrical power equation, P=IV, the current was found to be a range from 2A to 2.5A. This will achieve a consistent power of 30W to the external system.

In order to keep this voltage and current as steady as possible, a voltage regulator was used after the rectifier. The rectifier supplied a certain voltage and the regulator stepped down the voltage. When the voltage is stepped down, the current is equivalently stepped up with inefficiencies accounted for. Since the generator outputted a high voltage and low current, the regulator shifted those ranges to a more usable range.

For the ranges, the generator and rectifier supplied, a synchronous buck step down regulator was chosen. Buck converters are high efficient controllers that can operate at high voltage ranges and high frequencies. The generator was able to output frequencies up to 1.3kHz. The LM5116 was able to fulfill all the requirements needed to step down the voltage and step up the current from the input given from the rectifier. The circuit components for the accompanying circuit for the regulator can be calculated from the LM5116 data sheet.

INTEGRATION

A test rig was built to measure different parameters of the device. The devices needed to be able to fit and function inside the test rig. The device had to supply the test with long enough leads to feed into a DAQ. This allowed the test rig to characterize electrical power in and out and RPM from the hall effect sensors of the motor and generator. Each case had to provide internal thermocouples to the DAQ, for testing of temperature spec. The rig was able to measure external surface temperatures of each case. The test rig tested contact pressure between the two cases and casing torque. Finally the test rig was able to implement a method to vary separation distance.

RESULTS AND DISCUSSION

Dimensions and masses met the planned specifications. The only exception to this was the implant diameter, which required a diameter expansion to accommodate the rectifier circuitry.

Contact pressures met and exceeded specification. The original contact pressure required that the devices, across a 20mm gap, should not exceed 3.5kPa in axial pressure.[4] At 20mm, the device caused 0.40kPa in pressure.

The implant case was fully sealed and ingress protected, using an ingress protection rating of 68. The case was submerged for up to 12 hours with no water leaking into the case.

Voltage and output power did not meet specifications. Loading the generator with too much current resulted in a loss of coupling in the armature-receiver pair. Furthermore, by the end of the project, the voltage regulator circuit was damaged and unavailable. It is expected that the power and voltage will be closer to specification upon the use of the voltage regulator circuit.

Design life and reliability calculations from all components were difficult to make, due to the lack of numerical values on some of the components, and only a basic prediction of how the device would be used. It was estimated that the design life for the motor and generator were both 6 years, passing our specification for the motor and failing our specification for the implant. Reliability was not able to be calculated.

The power for the system was characterized as functions of output power. Figure 11 shows that system efficiency increases with an increase in output power, and Figure 12 shows that this reduces heat output.
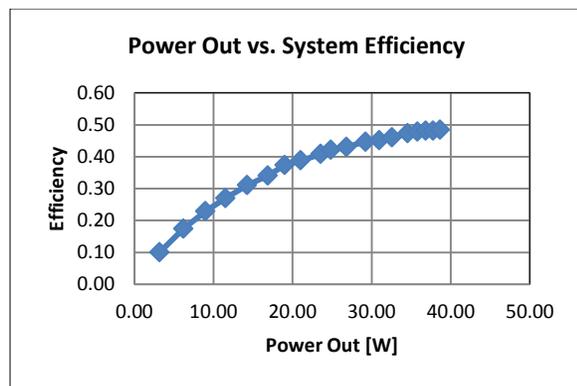

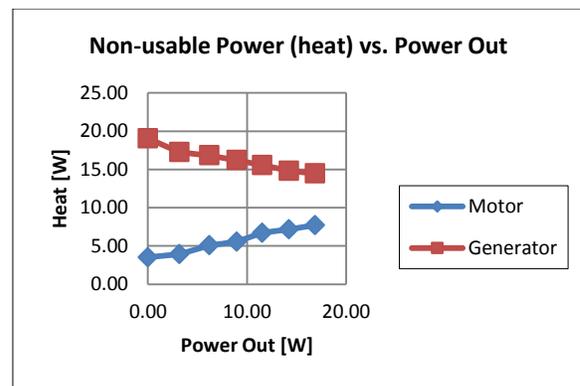**Figure 11:** *Efficiency increases as output power*

Figure 12: *Heat is reduced for the generator at*

Increases. *higher power.*

Output Power vs. Input Power
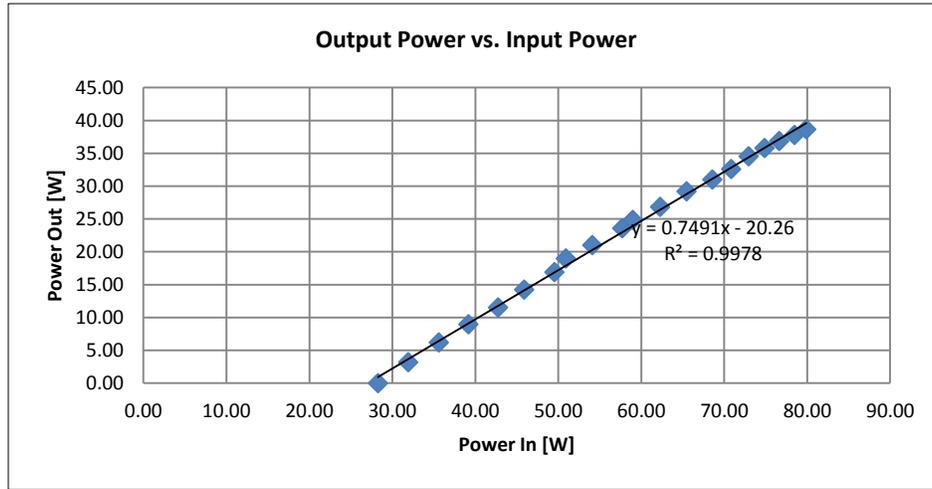
$y = 0.7491x - 20.26$
$R^2 = 0.9978$

Figure 13: *Characterization of efficiency for the system.*

Figure 12 displays the overall system efficiency. The slope of the line indicates that the system efficiency approaches 75% with higher power inputs, but the offset of -20 prevents this from happening in the specified operating range. The rest of the power is dissipated as heat.

CONCLUSION AND RECOMMENDATIONS

It was shown that power can be transferred wirelessly using passive magnetic coupling. The device offers significant potential in the medical device industry as an alternative to transcutaneous wiring and/or inductive loop systems. The device had no observable ill effects on biological tissue.

Future iterations of this design should involve a smaller casing, a greater power transfer, and a higher efficiency motor-generator set. The next iteration should also look into the possibility of a frameless motor at the base of the generator-side design. Furthermore, it is recommended to have a feedback circuit to detect a break in the magnetic link.

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