IEEE R2 Student Activities Conference

Undergraduate Student Paper Competition

Prosthesis Electronics and Control Optimization for Energy Regeneration

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April 4, 2014

Acknowledgments:
This work was supported by the CSU Undergraduate Summer Research Program, the Wright Center for Sensor Systems Engineering, and National Science Foundation grant 0826124.
PROSTHESIS ELECTRONICS AND CONTROL OPTIMIZATION FOR ENERGY REGENERATION
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Abstract

Active above-knee prosthetic limbs consume a large amount of power and waste excess energy as heat. To remedy this issue, prostheses including supercapacitors are proposed here. A supercapacitor has the ability to charge and discharge a large amount of power quickly at low voltages. To allow for proper energy conversion between the high voltage knee motor and the low voltage supercapacitor, a modulated voltage source converter is examined. Results show that the supercapacitor is able to charge while tracking proper knee angle when the modulated voltage source converter is used.

1 INTRODUCTION

Active transfemoral (above-knee) prostheses have demonstrated the ability to restore a normal gait pattern through use of motors [4], [1], [5]. These motors have the disadvantage that they consume a large amount of energy and therefore have to balance operating time and battery size. It has been shown that during the gait cycle, periods (referred to as K-regions) exist when the knee velocity and torque are in opposite directions, resulting in a negative power at the knee. These K-regions are shown on the knee angle (Figure 1), and knee power (Figure 2). The negative K-regions are the regions in which the knee power is below the black line on Figure 2. The K-regions when the knee has negative power means that the prosthesis is required to act as a brake to maintain proper knee angle tracking [2], [3]. To meet this requirement, current active prostheses brake the knee by acting as a resistance, causing excess energy to be dissipated as heat [4].

Current studies are investigating prostheses with regenerative braking. Hydraulic prostheses solved this issue by using accumulators to store the excess energy [6]. Preliminary designs of an electrical prosthesis include a supercapacitor to store the excess energy [11]. Supercapacitors were chosen...
because they have the ability to store and release large amounts of charge at a fast rate. Supercapacitors, as opposed to ordinary capacitors, operate at low voltages. Low voltage supercapacitors can not be connected directly to the knee motor for two reasons: (1) the voltage produced by the knee motor is too high for the supercapacitors, and (2) the flow of energy requires a control system to allow the knee angle to track properly [9].

To allow for a proper connection between the supercapacitor and the knee motor in the electrical prosthesis, a modulated voltage source converter is chosen. Previous studies have demonstrated the feasibility of using a voltage source converter without a supercapacitor. It was shown that the prosthesis had an energy efficiency of 30% and was able to create the required impedance for the knee angle to track properly [5].

This research aims to check the possibility of including a similar voltage source converter circuit with a prosthesis that uses a supercapacitor, as
opposed to a normal capacitor, for energy storage. During this research, a control system for this converter circuit is designed so that the knee angle can track properly while also maximizing energy storage in the supercapacitor. Biogeography-based optimization, an evolutionary optimization algorithm, is used to optimize the design parameters and control signals that will be used in the prosthesis. This preliminary study is done through use of Simulink and Matlab simulations. An expanded version of this paper is available at [11].

2 VOLTAGE SOURCE CONVERTER

2.1 Hardware

The voltage source converter works on a similar principle to an H-bridge. A set of four switches, as seen in Figure 3, control the electric current flow in
the prosthesis. The H-bridge for this prosthesis works in four modes: motoring+, motoring-, generating+, and generating-. Motoring mode refers to the situation in which the knee has positive power and the energy stored in the supercapacitor is required to drive the motor while generating mode refers to the situation when the knee has negative power and requires braking to occur by storing excess energy in the supercapacitor. The signs on the generating and motoring modes describe the direction of the knee angle motion.

Figure 3: H-bridge voltage source converter circuit [5].

The control signals sent to the circuit decide which mode the circuit
is in. Once a mode is selected by the control system, the circuit begins to operate by having one diode conducting current in a forward-bias condition, having one MOSFET that remains on, and by having one MOSFET that is switched by a duty cycle determined by the control system. The diode and two MOSFETs that are in use are determined by the which mode was selected. Table I summarizes which circuit elements are used in each mode.

Table I: Circuit Elements Used in Each Mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>MOSFET on</th>
<th>Switching MOSFET</th>
<th>Operating Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor+</td>
<td>Q4</td>
<td>Q1</td>
<td>D2</td>
</tr>
<tr>
<td>Motor-</td>
<td>Q2</td>
<td>Q3</td>
<td>D4</td>
</tr>
<tr>
<td>Generator+</td>
<td>Q4</td>
<td>Q2</td>
<td>D1</td>
</tr>
<tr>
<td>Generator-</td>
<td>Q2</td>
<td>Q4</td>
<td>D3</td>
</tr>
</tbody>
</table>

Depending on which mode the voltage source converter is operating in, a different set of equations are used to describe the electrical states of the prosthesis. The equations are derived using Kirchoff’s voltage law around the loop for each mode. Due to the switching MOSFET in each mode, every mode that the voltage source converter circuit has requires two equations: one for the case when the capacitor is connected and one for the case when the capacitor is disconnected. Following the loop in Figure 3 for the generator+ mode the following equations are found for the cases when the capacitor is connected and disconnected, respectively:

\[ 0 = \epsilon - v_{Ra} - v_{D1} - v_{c} - v_{Q4} \]  \hspace{1cm} (1)

\[ 0 = \epsilon - v_{Ra} - v_{Q2} - v_{Q4} \]  \hspace{1cm} (2)
2.2 Control System

To achieve proper knee angle tracking, a control system is required to provide the correct amount of braking to the knee. The voltage source converter circuit is able to provide a variable brake by switching the supercapacitor in and out of the circuit in both generating and motor modes. As previously described, part of the voltage source converter’s operation involves switching a MOSFET on and off. According to the circuit shown in Figure 3, the switching of this MOSFET causes the motor to either be connected to the supercapacitor (switch signal of 0) or to have the motor leads shorted by the on resistances of the MOSFETs (switch signal of 1). In the motoring modes, the stored charge in the supercapacitor causes the knee angle to increase (motor+ mode) or decrease (motor- mode) when it is connected to the motor. The opposite happens when the supercapacitor is connected during a generating mode; the supercapacitor makes the knee brake because of the extra impedance it puts into the circuit. The switching is accomplished by a pulse-width modulated (PWM) switch signal generated by the control system. When the knee is in generating mode, the PWM signal modulates the voltage across the capacitor, while in motoring mode the PWM signal modulates the voltage across the motor.

In current simulations, mode switching occurs at specific times in the gait cycle determined by when the knee power becomes negative from reference gait data collected by the Cleveland Clinic Foundation [6]. Modulating between the supercapacitor being connected in the circuit (switch signal of 0) and disconnected (switch signal of 1) is done through a feedback system. In this system, the simulated knee angle is subtracted from the reference knee angle data. That error signal is then feed into a PID controller to create
a control signal. This control signal is then either added or subtracted to the previous control signal, depending on the mode that the prosthesis is operating in. The resulting control signal (duty cycle) is then sent through a comparator in addition to a triangle wave to create a PWM signal at a frequency of 10 kHz. The switching frequency for the PWM signal was set at 10 kHz because the simulation runs with a step size of $1 \times 10^{-5}$ seconds, causing the switching period to be a multiple of the simulation step size.

Deciding if the current control signal should be added or subtracted from the previous control signal is based on the operating mode of the prosthesis. When the prosthesis is operating in motoring+ mode, and the error signal is positive (meaning that the simulated knee angle is less than the reference data) the prosthesis is required to increase the knee angle. Increasing the knee angle is accomplished by connecting the capacitor so the stored energy can be used to power the motor, meaning that the switch signal should be 0. To be able to get the switch signal to be 0 for a longer period of time, the current control signal (created from a positive error signal) should be subtracted from the previous control signal. If the error were negative instead of positive (the simulated knee angle is larger than the reference angle) then the switch signal needs to be 1 more often so that the prosthesis will brake. Subtracting this negative control signal from the previous control signal will cause the switch signal to become 1 more often. Because both cases of error in the motoring+ mode require the current control signal to be subtracted from the previous control signal, then anytime the prosthesis is in motoring+ mode, the current control signal should be subtracted from the previous control signal. The logic for motoring- mode can be found in Appendix A.
Equations 3 and 4 describe the previously defined feedback system. $\Delta U$ is the control signal outputted from the PID controller, $K_p$, $K_i$, and $K_d$ are the PID proportional, integral, and derivative gains, $e(t)$ is the simulated knee angle subtracted from the reference knee angle, and $U_k$ indicates the control signal between times $(k-1)T$ and $kT$, where $T$ is the simulation step size ($1 \times 10^{-5}$ seconds).
3 BIOGEOGRAPHY-BASED OPTIMIZATION

Biogeography-based optimization is an evolutionary algorithm that was motivated by the study of migration of species [7], [8]. Each potential set of parameters is labeled as an island. The transfer of parameters between the islands is referred to as immigration when the parameters come into an island and emigration when the parameters spread across to new islands.

Islands that are near each other will experience immigration and emigration. Immigration and emigration of parameters occurs in nature through various means such as wind and water currents. After many years, the parameters will tend to concentrate themselves on islands that have more desirable features. The level of desirable features is defined by an island’s habitat suitability index (HSI). The habitat suitability index is a function of the parameter values in the island. Each parameter value is defined by a suitability index variable (SIV).

When an island has a high habitat suitability index because it has many species, its emigration rate, $\mu$ will be large. When the emigration rate is high, the immigration rate, $\lambda$ will be low because the island will not be able to support any more species due to a limitation of resources. For purpose of optimizing the voltage converter circuit and prosthesis, a linear relationship will be assumed between the migration rate and habitat suitability index. This relationship will hold for every island in the process of optimizing the voltage source converter circuit. A graphical representation of this relationship is shown in Figure 5.

Biogeography-based optimization seeks to maximize the habitat suitability index by probabilistically deciding whether to immigrate each suitability index variable in each island. If the suitability index variable is chosen to
Figure 5: Linear relationship for migration and habitat suitability index.

To quantify how desirable an island (solution) is, biogeography-based optimization requires a cost function to be evaluated for each possible solution. Since the goals of the modulated voltage source converter are to allow the prosthesis to maintain proper knee angle tracking and to store as much charge in the capacitor as possible, a cost function was created that includes both of these goals. Since the main objective of the prosthesis is to maintain knee angle tracking, a weighting factor is multiplied to make a tracking error less desirable than poor capacitor charge. Since the units for the root mean
Initialize population of potential solutions.

while not (desirable solution obtained)
    for each island $x_i$
        for each SIV $s$
            Use $\lambda_i$ to determine if immigration to $x_i$ occurs
            if immigration to $x_i$ occurs then
                Use $\mu$ to select emigrating island $x_i$
                $x_i(s) \leftarrow x_j(s)$
            end if
        probabilistically determine if mutation occurs
        next SIV: $s++$
    next island: $i++$
next generation

Figure 6: Pseudo code for the biogeography-based optimization algorithm.

square of the tracking error and capacitor charge are different, it is difficult
to determine a proper weighting factor and involves intuition and educated
guessing. A weighting factor of 2:1 was chosen for the root mean square of
tracking error to the increase in capacitor charge. Equation 5 shows the cost
function that was evaluated in the simulation where $\phi_k^d$ is the reference knee
angle, $\phi_k$ is the simulated knee angle, and $\Delta C$ is the change in capacitor
charge.

\[
Cost = \int [\phi_k^d(t) - \phi_k(t)]^2 dt - \frac{1}{2}(\Delta C) \tag{5}
\]

4 RESULTS

The regenerative prosthesis is able to track a reference knee angle while also
storing charge during a region of the gait cycle when knee power is negative
(requires braking). Figure 7 shows the knee angle tracking for this period. A root mean square knee angle tracking error of 1.53 degrees is achieved during preliminary simulation with only a few generations of biogeography-based optimization.

![Knee Angle Tracking](image)

**Figure 7:** Knee angle tracking with the modulated voltage source converter during K2 region from Figures 1, 2.

An increase in capacitor charge can be seen in Figure 8 during the same section of the gait cycle. The charge of the capacitor increased by 1.2 Coulombs during this simulation. The end of the simulation when the capacitor charge stays constant is due to the knee angle tracking. Because the simulated knee angle is below the reference knee angle, the control system disconnected the supercapacitor by setting the switch signal to 1 so that the knee would have less braking.
A modulated voltage source converter circuit was evaluated for the possibility of being used in a regenerative active above-knee prosthesis. Simulations were made to operate the prosthesis during a region of the gait cycle when knee power is negative, producing excess energy. It was observed that biogeography-based optimization was successful in optimizing the design parameters and control signals in the prosthesis.

The simulation for this research allows for future work in this system. Because the simulation demonstrated the ability to track a reference knee angle and the ability to absorb excess energy in a supercapacitor, the entire gait cycle needs to be simulated. Once the entire gait cycle is simulated, biogeography-based optimization may be used to optimize knee angle tracking and energy storage for the entire stride in the gait cycle.
Even further research includes creating the modulated voltage source converter circuit with an on-board control system through use of microprocessors or DSpace and integrating the circuit into a working prosthesis prototype. The prosthesis prototype may then be tested with the university’s hip robot to ensure desirable operation [10].

**APPENDIX A: CONTROL SIGNAL OPERATION FOR MOTOR- MODE**

When the prosthesis is operating in motoring- mode, and the error signal is positive (meaning that the simulated knee angle is less than the reference data) the prosthesis is required to increase the knee angle. Increasing the knee angle is accomplished by disconnecting the capacitor so the stored energy will not power the motor, meaning that the switch signal should be 1. This is shown on the right side of the black line in Figure 9. To be able to get the switch signal to be 1 more often than 0, the current control signal (created from a positive error) should be added to the previous control signal. If the error were negative instead of positive (the simulated knee angle is larger than the reference angle) then the switch signal needs to become 0 more often than 1 so that the knee motor will be powered by the capacitor so that the knee angle can decrease faster. Adding this negative control signal to the previous control signal will cause the switch signal to be 0 for a larger portion of time. Because both cases of error in the motoring- mode require the current control signal to be added to the previous control signal, then anytime the prosthesis is in motoring- mode, the current control signal should be added to the previous control signal.
Figure 9: Possible errors for motor-mode. The capacitor needs to be connected more frequently left of the black line and disconnected more frequently on the right side of the black line.

APPENDIX B: SYSTEM DIAGRAM

The current simulation is summarized by Figure 10. The simulation starts with initial conditions obtained from reference data inside the integral block. These initial integration conditions are used as input for the state space model of the prosthesis with the voltage converter circuit. The state space model outputs the derivative of the states, which are then integrated. The state of the knee position is then compared to the reference data to create an error signal to input into the PID controller. The output from the PID controller is then either added or subtracted to the previous control signal (as determined by the logic explained in Appendix A) to create a duty cycle. The duty cycle is then compared to a triangle wave at 10 kHz to produce a switching signal. The switch signal then determines which equations should be used in the state space model, repeating the process until the end of the
simulation.

Figure 10: Block Diagram of the prosthesis with modulated voltage source converter included.
References


