2017 University of Waterloo Clean Snowmobile

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Abstract

The University of Waterloo's Clean Snowmobile Team has developed a zero-emission snowmobile by modifying stock, internal combustion snowmobile. The 2015 Polaris 800 AXYS PRO-X chassis has been implemented together with an 84V brushed DC motor, six 12V 4-cell batteries, and a 120V programmable permanent magnet motor controller together with regen. Safety features have been integrated into the system to resist cold weather conditions and prevent hazards from electrical components. The modified snowmobile is intended to appeal to researchers to travel to and from remote satellite camp facilities in environmentally sensitive locations.

Introduction

Snowmobiling is a popular winter recreational activity that has historically received substantial scrutiny for its environmental impact. Prior to the 21st century, snowmobiles were primarily powered by two-stroke engines with very little emissions control. As technology continues to advance, the movement shifts towards environmentally friendly technology, and moves away from using biofuels that continue to contribute to greenhouse gases and the depletion of nonrenewable resources.

Undergraduate engineering students from all over the world compete annually to modify current production snowmobiles into electric, zero-emissions ones. The Challenge has been inspired by the research conducted at Summit Station in Greenland, where the area is extremely sensitive to emissions from IC engines. ZE snowmobiles have then become the solution for researchers to travel to and from remote satellite came facilities. As battery technology continues to advance, the switch to ZE snowmobiles will hopefully become commercially available for all riders to switch to.

Design

Driveline

To transfer power directly from the motor to the jackshaft, a pulley system is chosen for simplicity purposes. The alternative choice is to drive the jackshaft using a chain and sprockets, but this system would require an additional chaincase for lubrication. In contrast, the pulley system does not require an additional mount, as it is driven by a belt. To further simplify the system, the exact belt length was purchased in order to avoid the need of a belt tensioner.

The transfer of power from the jackshaft to the driveshaft is handled using the stock chaincase, but with a modified gear ratio. The goal was to reach a speed of 40kph when the motor is delivering maximum power. From the power curve provided by the motor OEM, maximum power is reached at roughly 2000 rpm. From there, the pulleys and sprockets were chosen to achieve the desired speed, while maintaining practical sizes.

Table 1. Power transfer from motor to driveshaft

Max power motor speed (rpm)	2000
Drive pulley - teeth	28
Driven pulley - teeth	36
Pulley ratio	0.7778
Bottom sprocket – teeth	41
Top sprocket – teeth	21
Sprocket ratio	0.5122
Constant ($2\pi/60$)	0.10472
Cog shaft radius (m)	0.12
Speed (m/s)	10.01
Speed (kph)	36.04

Chassis

The chassis selected for the sled is a 2015 Polaris 800 AXYS PRO-X. Modifications to the sled have been made to accommodate for the electrical components, including the battery and battery container.

Motor

The Perm PMG-132 24-72V brushed DC motor has been selected to be the sled's motor. It has a very small power to weight ratio (24.8lbs), and the compact construction requires less space for it to fit in the sled.

The motor has a peak power of 34.3HP with a peak efficiency of 88.6% at 72V. The motor is designed to be used at a continuous current of 110A, withstanding a continuous 10 minute peak current of 200A. It has a rotational speed of 50.2RPM/V.

Motor Mount

A motor mount was designed and fabricated to mount the new motor onto the sled. It is also intended to minimize the vibrations felt inside the sled caused by the motor. Figure 1 shows the motor mounted to the ⅜" thick, lightweight and high strength aluminum alloy base frame. It mounts to the existing shafts and holes of the chassis, under the hood.

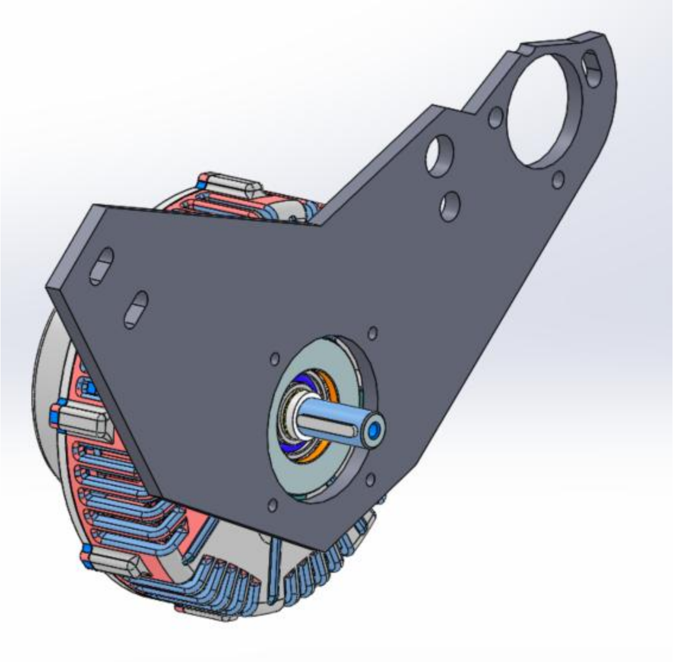

Figure 1. DC motor mounted to the motor mount

Motor Controller

The Kelly HPM12401C, a highly efficient, and permanent magnet DC motor controller, was selected to be the motor controller for the sled. It is rated at 400A at 120V, and can handle 400A for up to one minute.

The motor controller is fully programmable, allowing the settings to adjust accordingly to reach design objectives. It offers battery and thermal protection to warn, and shut down the system at configurable high and low battery voltages, and high temperatures, respectively.

Batteries

The battery pack used in this year's sled consists of six GBS 12V (4-Cell) 60Ah LiFeMnPO4 batteries. When put in series, the pack produces 72 volts (76.8 nominal) which sufficiently powers our motor. Using six separate batteries allows greater configuration of the overall battery back, which makes it easier to install in the sled. The batteries are the largest non-chassis component of the snowmobile, therefore it was critical to have modularity such that we could configure their locations in a way that fit well in our particular sled.

Lithium ion batteries were chosen because of their massive reduction in weight compared to lead acid. Because lithium ion packs are substantially lighter than equivalent lead acid, the overall mass of the system was drastically decreased, thus improving performance and efficiency.

Battery Container

The battery container consists primarily of 3mm thick aluminum sheet metal with smaller 6mm aluminum supports. The sheet metal is laser cut into the desired flat pattern and then bent in order to compose the final shape of the container. The 3mm aluminum provides sufficient housing for the batteries and acts as a firewall for the driver in case of thermal runaway. It is designed in a rough 'T' shape as seen in Figures 2 and 3 below. Two of the batteries are located under the driver's seat and the remaining four are located in the front engine compartment. Despite the odd shape, all batteries are enclosed in one single container.

The reason for this design was modularity and security. The batteries compose the largest non-chassis component of the snowmobile and required extensive planning regarding their location. The 'T' design allowed all six batteries to remain within one container, to not interfere with the motor or other components whose locations were pre-set, and by keeping them all on the same plane and keeping the bulk of the batteries within the engine compartment, a low and frontwards center of gravity was maintained. As well, dividers were easily put between each set of two batteries, ensuring each battery container section does not exceed the maximum MJ limit.

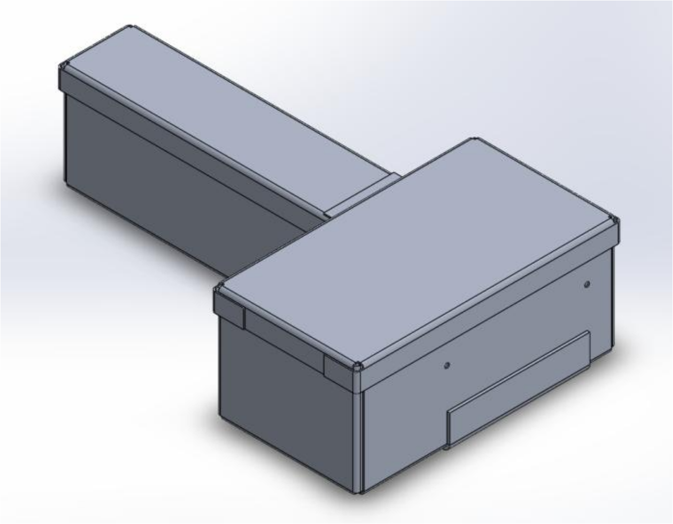

Figure 2. Battery container (on its own)

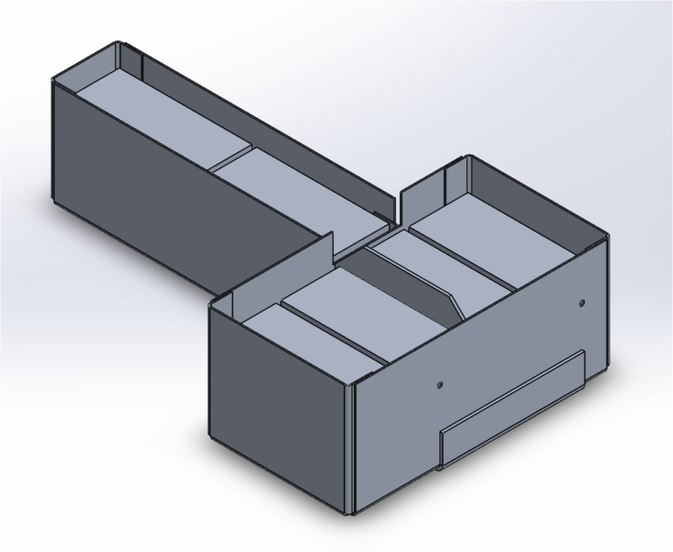

Figure 3. Battery configuration

Insulation of the battery box is achieved using Nomex 410 Insulation Paper and Nomex High Temperature Adhesive Insulating Paper Tape. The specific paper in use is 5 mil thick; each mil of thickness is rated to insulate for 40 V, thus the 5 mil is rated for up to 200 V. This far exceeds our 76.8 V tractive system nominal voltage, thus ensuring proper insulation and the safety of the operator.

An additional reason for the design of the battery container is to enable it to withstand 20G (horizontal) and 10G (vertical) of acceleration. Keeping the bulk of the batteries within the engine compartment ensures that a multitude of supports are available to the container in all directions. By securing the container at many different points and by reinforcing the aluminum sheet metal at critical locations, we were able to ensure the container is able to withstand extreme deceleration.

SolidWorks Simulation was used to run the deceleration simulations and their effects on the structure of the container. Fasteners were attached where they occur in the actual sled, and forces were applied to the walls of the container to simulate the dynamics of deceleration between the container itself and the batteries. An example of how a force was calculated can be seen in the following steps.

$$20 \text{ g-unit} = 196 \text{ m/s}^2,\ m_{battery} = 9.2 \text{ kg}$$

$$F_{front\ wall} = mg = (9.2 \text{ kg}) \times (196 \text{ m/s}^2) = 1803.2 \text{ N}$$

The above calculation is used for the force applied by a single battery when decelerating at 20G. Additional forces are calculated to simulate the other batteries, components, and factors acting on the system.

When simulations were first run, critical locations were addressed and supported by additional plates of aluminum. Reinforcing these locations ensured the material would not yield and that the container would be able to withstand 10G and 20G acceleration. As we continued to run simulations, we continued to modify our design to ensure the best results possible. An example of this can be seen in Figure 4, where we reinforced the joining of the two large sheet metal components to ensure that the principal stresses at those locations did not exceed the yield strength of the aluminum being used. Some supports were made out of sheets with greater thickness, such as 6mm, to increase strength of the components.

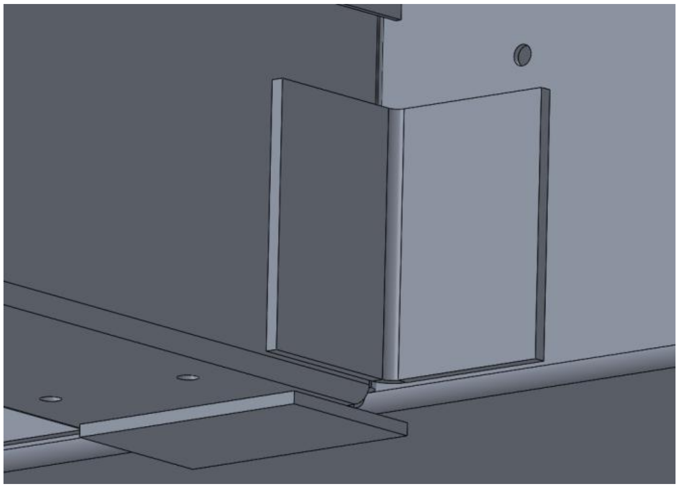

Figure 4. Corner reinforcement of battery container

Figure 5 below shows results from one of the simulations as an example. The color gradient represents the first principal stress in the material. It starts and zero (dark blue) and continues upwards to 28 MPa, the yield strength of aluminum and what we consider failure in this case.

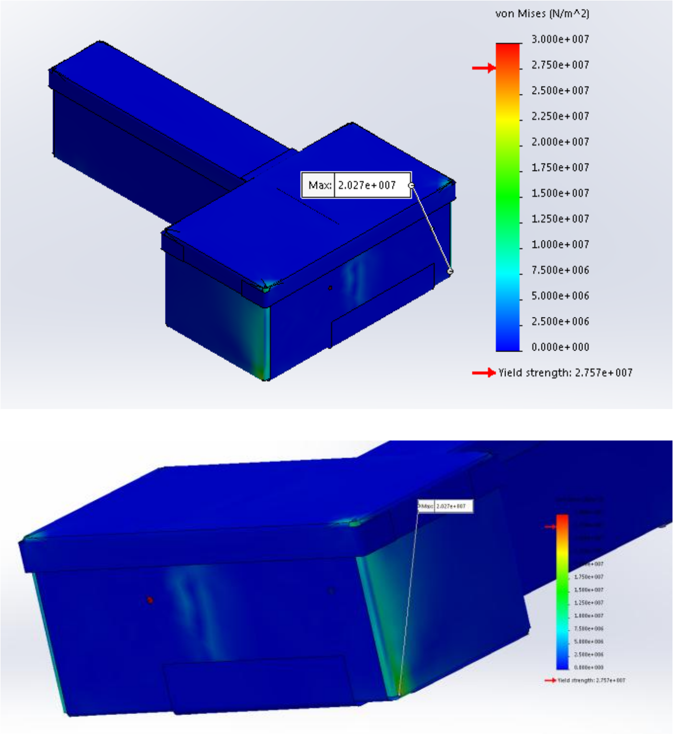

Figure 5. Simulation results example, 20G, horizontal, forward

As is visible in the figure by the von Mises stress, the battery container is capable of withstanding the specified deceleration, maintaining a factor of safety of approximately 1.36.

Electrical Safety

Shutdown Circuit

The shutdown circuit comprises multiple interlocks and switches that monitor the tractive system and allow the user to quickly and safely disconnect any high voltages outside of the battery box. The shutdowns are all wired in series so that if any of them fault, the BIRs will open.

Manual Shutoffs

The manual shutoffs consist of the key, tether switch, kill switch, HVD, and TSMS. The first three of these are consistent with shutoffs for stock IC snowmobiles so that any rider can instinctively know how to shutdown the tractive system. In addition to these, the HVD can be used to deenergize the tractive system. Removing the HVD plug simultaneously breaks the high current path between two battery segments and the shutdown circuit. Removing the HVD plug does not expose any HV contacts that can be accessed by fingers. The last manual shutoff is the TSMS. It is located at the back of the snowmobile and when off does not allow the BIRs to be closed.

In addition to these shutdowns there is also an interlock that will break the current to the BIRs if the lid of the battery container is not closed.

Automatic Shutoffs

There are three automated shutoffs incorporated into the shutdown circuit. They are the BSPD, IMD, and BMS. If any of them fault, the shutdown circuit is broken and the BIRs will open.

The BSPD faults if the hydraulic brakes are activated at the same time as acceleration is being requested from the throttle lever. The device uses duplicate sensors for redundancy. If the BSPD faults it must be manually reset.

The IMD used in the snowmobile is the Bender A-Isometer IR155-3204. It monitors the HV system to ensure that it is isolated from the GLV system. The IMD also needs to be manually reset if it faults.

The last automated shutoff is the BMS. The BMS will break the shutdown circuit if it determines that batteries are no longer within safe operating conditions. This can be a low cell voltage or high temperatures.

Cost

The MSRP document outlines the modifications made and the parts installed onto the snowmobile. Based on the Clean Snowmobile Challenge MSRP guidelines, the retail price of a ZE snowmobile is a total of $16402.77 USD, reflecting the manufacturing quantities of 5000 units per year.

Conclusions

For the past 16 years, the University of Waterloo Clean Snowmobile Team has participated in the IC category of the CSC. This is the first year that the team has entered the ZE category. Our team has gained confidence and experience on designing electric snowmobiles, and will continue to make modifications to increase performance and range.

There are improvements to be made in the future, including implementing two motors and coupling them to achieve better pull performance, and replacing the motor controller with one that better suits our future design specs and objectives.

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Acknowledgments

The University of Waterloo Clean Snowmobile Team would like to thank our sponsors, without whom this project would not have been possible:

Polaris Industries
SolidWorks
Waterloo Engineering Dean's Office
Waterloo Engineering Endowment Fund
University of Waterloo Engineering Society
Electric Motorsport
Department of Mechanical and Mechatronics Engineering
Ontario Federation of Snowmobile Clubs

We would also like to thank our Faculty Advisor, Professor Peter Teertstra, and our Electrical Faculty Advisor, Professor Mehrdad Kazerani for their guidance and overseeing the design work on the mechanical and electrical design phases.

Finally, we would like to thank the organizers of the competition, SAE and MTU KRC, especially Jay Meldrum, who gave us advice on how to succeed in our first ZE competition. We also want to thank all the other participating MTU KRC staff members.

Definitions/Abbreviations

BIR	Battery Isolation Relay
BMS	Battery Management System
BPSD	Brake System Plausibility Device
CSC	Clean Snowmobile Challenge

DC	Direct Current
GLV	Grounded Low Voltage
HV	High Voltage
HVD	High Voltage Disconnect
IC	Internal Combustion
IMD	Insulation Monitoring Device
LV	Low Voltage
MSRP	Manufacturer’s Suggested Retail Price
TSMS	Tractive System Master Switch