2009 Clarkson University Electric Snowmobile

Leif Amber
Jonathan DiGiacomandrea
Scott Keefe
Peter Kudrewicz
Josh Gale
Brian Loggi
Tom Masse
Jeannie Piekarz
Tim Swyka
Clarkson Electric Knights

ABSTRACT

The Clarkson University Electric Knights has taken a 2008 Polaris 600RR and converted it to a fully electric snowmobile for the 2009 SAE Clean Snowmobile Competition. This snowmobile features a battery system that provides 37kW to the motor and a battery management system to efficiently discharge and equalize the battery system. Decreased snowmobile weight of 7-8kg from the 2008 Clean Snowmobile Challenge will aid in traveling a longer range as the snowmobile will now weigh 278kg. Increased traction through track lug length and gear reduction will help improve towing capacity. These modifications were made without compromising rider comfort when compared to a stock 600RR.

INTRODUCTION

With important ongoing research regarding the global cycling of atmospheric chemicals at Summit Station on the Greenland Ice Cap, the National Science Foundation is looking for a zero emissions vehicle capable of transporting equipment and staff to and from research sites. Traditionally, electric vehicles were limited by factors such as range, but continued advancement in battery technology is providing increased viability of such vehicles. The Society of Automotive Engineer's Clean Snowmobile Challenge strives to address this issue in an attempt to provide an alternative mode of transportation that will not skew research data due to emissions discharged by internal combustion vehicles.

DESIGN STRATEGY

Based on the 2008 Clean Snowmobile Challenge results, the team brainstormed ideas for realistic improvements and designs that would allow the snowmobile to gain position on other teams in various competition events. This would enable the team to become a top competitor.

One goal, not pertaining to competition evaluations, was to keep the external aesthetics of the snowmobile the same so as to make it visibly indistinguishable from an internal combustion snowmobile. This would help ensure a similar rider comfort to the original stock Polaris 600RR by keeping the weight distribution relatively the same rather than adding battery boxes to the back of the snowmobile.

The second goal was to increase speed and reduce torque through the use of a new motor controller that would allow more power to pass from the main battery system to the motor and by reducing the gear ratio. Reducing the gear ratio would help to increase speed to the drive shaft thus reducing torque output according to Figure 8 as seen under the section on the drive system.

The main power system involves a large quantity of cells that it was desirable to be able to regulate that system through a Battery Management System or BMS. This system would help equalize each individual cell preventing any cell from sinking below minimum operating voltage. By not allowing cells to fall lower than this critical voltage, no one battery can cause the entire battery system to perform poorly.

Through past results in the Clean Snowmobile Challenge, snowmobile weight seems to increase from year to year when the same chassis is used due to the implementation of additional batteries. With weight in mind, the team sought to reduce weight where possible on new and existing components on the snowmobile. Being weight conscious, creates a sense of practicality of design and prevents over-engineering but safety still has to remain a priority in order to prevent harm to the rider.

BATTERY SELECTION

The main goal of the electrical system is to provide enough energy to power the sled using batteries. This required deliberation over which batteries would provide enough power to the sled while maximizing safety, rider comfort, ease of handling, and operation in a cold environment. Several factors were used in the analysis of possible batteries for the electrical system including: battery chemistry, operating temperature, energy density, price, and safety.

One way to classify batteries is disposable batteries vs. rechargeable batteries. Disposable batteries, due to their chemistry, can only be used once. Rechargeable batteries can be used many times before their useful lifespan expires. A battery's useful life span is a measure of how many times the battery can be charged and discharged before it is no longer able to function correctly. Rechargeable batteries with a lifespan equal to that of the sled would be optimal. This would produce a sled that would be cost-effective for the user, as it would not require an expensive replacement of the batteries during the lifetime of the sled.

snowmobile, they would need to be able to operate in sub-freezing temperatures.

The next major aspect of batteries is energy density. Energy density is the amount of energy stored in a given unit of mass. Each battery chemistry has a different energy density, and therefore more batteries of low energy densities would be required to provide the same amount of energy as a battery of high energy density. Based on the data in Table 1, for example, it takes approximately two to six kilograms of nickel metal hydride batteries to provide the same amount of energy as a lithium ion battery. A type of battery that has a high energy density allows for a lighter snowmobile.

Another important characteristic of the batteries is price. Although the final price of the sled must be affordable for those who want to use them, eliminating the need for gasoline would help offset the cost of the batteries. Therefore, batteries that suited the needs of the snowmobile could be chosen with less regard for price.

The final requirement for the batteries is safety. Safety is always of the utmost importance, and therefore batteries that can withstand the vibrations and movements of the sled needed to be chosen.

A summary of these characteristics for four plausible types of batteries is given in Table 1. Batteries with a lower energy density such as lead acid and nickel metal hydride would be cost effective, but the huge mass and volume of these batteries would need to be incorporated into the snowmobile design. The large mass and volume would have extremely adverse effects on major goals such as weight, aesthetics, handling, and rider comfort.

Battery Type	Energy Density (Wh/kg)	Price ($US)	Disadvantages	Recharge Cycles	Peak Discharge Rate Times Cell Capacity (A)	Operating Temperature (ºC)
Lead Acid	30-40	5-8	Weight, Short Life Span	500-800	3.5x	-40 to +60
Nickel Metal Hydride	30-80	1.37	Weight, Low Discharge Rate	1000	2.3x	-30 to +60
Lithium Ion	160	2.8-5	Volatile, Cost, Low Discharge Rate	1200	2x	-20 to +60
Lithium Polymer	130-200	2.8-5	Cost, Short Life Span	500	5x	-10 to +60

Table 1: Battery Types & Energy Densities

The second consideration for the batteries was the temperature at which they could effectively operate. Since the batteries were to be incorporated in a

This left the decision between lithium ion and lithium polymer. Due to the safety concerns with lithium ion batteries, lithium polymer batteries were chosen on the behalf of the safety of the rider. Although these batteries would have a high price tag and a more limited life span, they would be small, lightweight, safe, and able to operate in a cold environment.

Once lithium polymer batteries were chosen, the team began looking at the offerings of several manufacturers. BatterySpace was chosen as the battery provider, as they offered the right size battery at a reasonable price. The cells chosen were 3.7V cells with a storage capacity of 10000mAh. These cells have an energy density of 171Wh/kg, and each cell weighs 210 grams. Two hundred such cells were purchased and assembled into the main power system. A photo of the cells can be seen in Figure 1.

Figure 1: Lithium Polymer Battery

MAIN POWER SYSTEM - The 200 cells purchased from BatterySpace provide the power to drive the motor and make the snowmobile move. Each battery is rated for 3.7 Volts with a storage capacity of 10 Amp-hours. Since the motor chosen requires a 144 Volt nominal supply, there are forty packs wired in series to provide 148 Volts. Each battery pack consists of five batteries wired in parallel that provides a maximum current of 250 Amps to the motor. This allows the motor to be supplied with a maximum of 37kW. Figure 2 illustrates the battery setup with the motor controller.

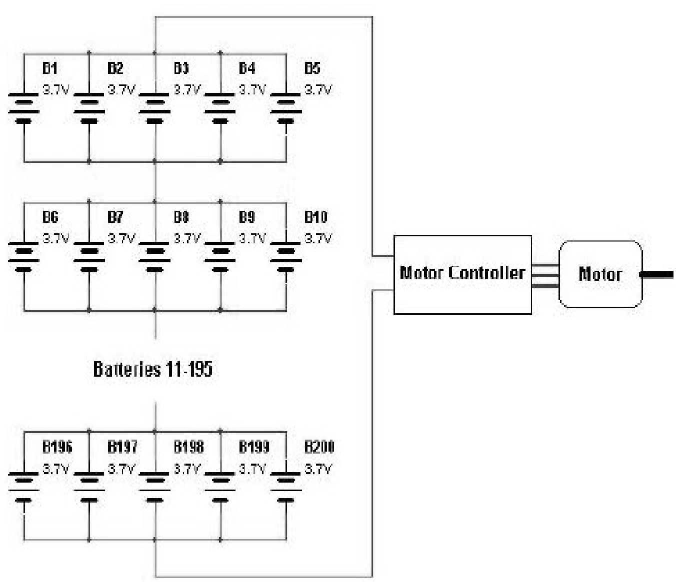

Figure 2: Battery Wiring Diagram

After designing the battery system, each battery was wired together with the batteries in its pack. The batteries purchased had small, fragile .004” nickel battery tabs, which would make wiring them together difficult. Therefore, the team could either weld or solder extensions on each battery. After attempting to weld the tabs together with little success, the team looked into soldering the batteries. Although there was some risk to the batteries in heating the tabs for soldering, this seemed the only option. Therefore, each tab was attached using as little heat from the soldering iron as possible to reduce the risk of harm to the batteries. Holes were then made on the end of each battery tab so the battery tabs in each pack could be bolted together to easily connect the cells in parallel. Finally, each battery pack was wired in series and encased in a protective box as shown in Figure 3.

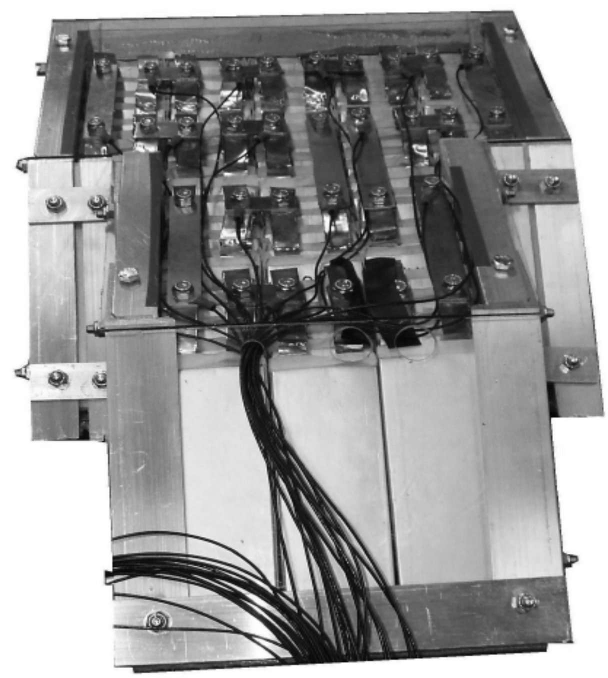

Figure 3: Battery Tabs and Connections

BATTERY MANAGEMENT SYSTEM

The pack of 200 batteries presented a tremendous challenge. All of the batteries were of the same chemistry; however no two batteries are identical. Some discharge faster than others whereas others drain slower. If all of the batteries are not discharging the same amount of power to the sled, it creates a dangerous situation for the batteries as a whole, and the sled is not running as efficiently as possible. To solve this problem, a battery management system (BMS) was created. A “Switched Capacitor System for Automatic Series Battery Equalization” was used[1]. An optimal BMS uses little to no power to use and is completely self sustained.

Instead of charging all of the 200 batteries separately, 40 packs of five were balanced. Each pack of batteries was wired in parallel and would cause each other to balance naturally. The forty packs of batteries were wired in series to reach maximum voltage. In order to balance the packs of batteries, a printed circuit board was designed to simplify and to compact the overall BMS dramatically. A block diagram of the entire circuit is shown in Figure 4. The design used can be wired to the batteries while they're being charged, used, or while in storage. The circuit only balances the batteries, so when the batteries are balanced, the circuit uses negligible quiescent power[1].

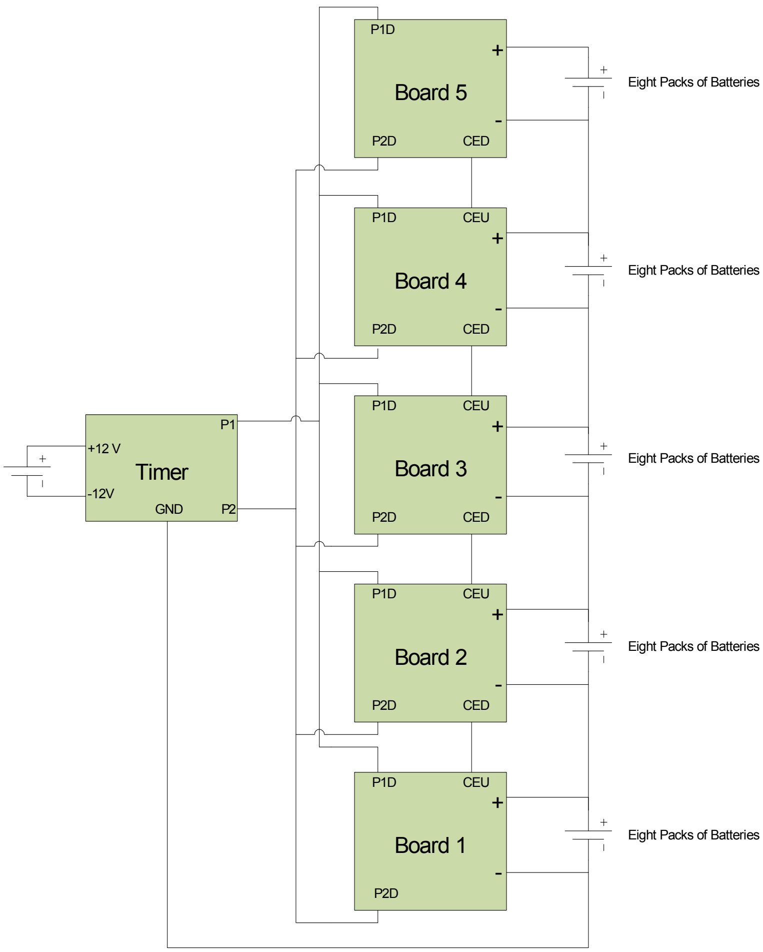

Figure 4: Entire BMS Circuit Diagram

Each board contains eight "Type Two Cells". Each cell is comprised of two MOSFETs, capacitors, zener diodes, and passive circuit elements as shown in Figure 5. A populated board is seen in Figure 6. Every battery pack was connected to the board as shown in Figure 4, labeled as "B". The MOSFETs (T1 and T2) were used in conjunction with a clock generator to switch on and off like an SPDT (single-pole double-throw) switch[1]. The zener diodes (DZ_{1a}, DZ_{1b}, DZ_{2a}, DZ_{2b}) are connected to the MOSFETs to protect them from any kind of unwanted voltage levels or incorrect current directions[1]. RPx and RSx are used as current limiting resistors and the CPx is used to make sure that the signal is not slowed down by these resistors[1]. D1 and D2 maintain DC biasing and RD1 and RD2 protect them from any problems in the signal such as spikes and noise. P1 and P2 are connected to the clock circuit. All of the boards' clock signals are connected in series. However, each board is connected in parallel with the clock to maintain a clean signal.

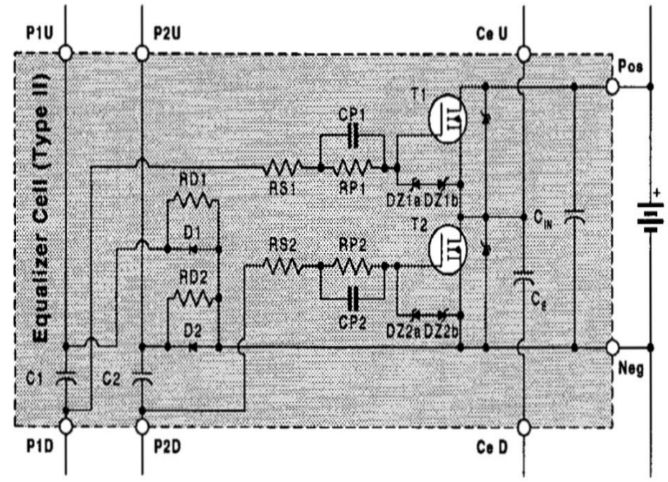

Figure 5: Battery Management System Board Schematic

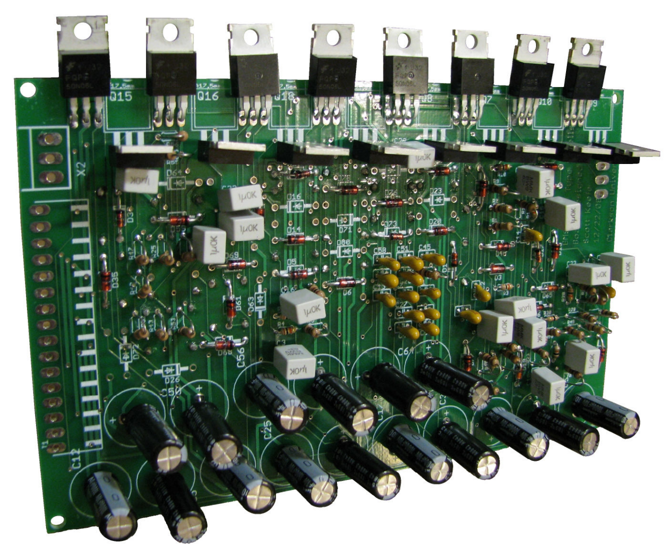

Figure 6: Battery Management System Board

The timer circuit is what makes the whole BMS work. The advantage of this timer circuit is that it uses very small amount of power. The design called for the clock signal to be created using an optocoupler. After testing the circuit with the optocoupler, many problems arose and it was found to be far simpler to just use a 555 timer circuit. Once the 555 timer creates the clock signal, it is wired to the P1 portion of the circuit and to the P2 portion. Before it goes to P2, the signal is inverted 180 degrees. In the P1 section, a voltage three times that of the voltage given to the 555 timer is inputted. The P2 section receives a voltage two times that of the 555 timer's inputted voltage. As shown in Figure 5, each board is connected by CEU and CED. These connections allow the boards to "communicate" with each other.

---

[1] "Switched Capacitor System for Automatic Series Battery Equalization". César Pascual, Philip T. Krein. Department of Electrical and Computer Engineering University of Illinois, Urbana, Illinois 61801. © 1997, IEEE.

CHARGING

There are three prominent considerations in designing a battery charger, efficiency, charge time, and battery integrity. In an effort to increase efficiency of the charger, non-resistive control techniques were implemented. Transformers and reactors were used to regulate voltage and current, performing a function similar to switched power supplies, but using a standard 60Hz voltage source to reduce complexity.

There is a trade-off between charge time and battery health, pushing more current into the battery pack charges it faster, which is convenient, but may compromise the integrity of the battery pack. Lithium polymer cells require two charge stages, a constant current stage that persists until the cell reaches maximum voltage, followed by a constant voltage stage that persists until current flow drops below a certain value recommended by the cell manufacturer. Lithium batteries are readily damaged by over charging, so it is important to accurately terminate charge current. A safe charge current of 10A was chosen for the snowmobile, which provides reasonable charge time without potentially degrading the batteries. Current limiting is performed by a saturable reactor connected in series between the AC input and a bridge rectifier that provides a DC voltage directly to the batteries. A low voltage DC control circuit provides saturating current that is inversely proportional to a feedback signal from a current transducer that measures the DC current flowing into the battery pack, thereby regulating the current. The constant voltage stage is achieved by setting the open circuit voltage of the charger to the maximum battery voltage before connecting the battery pack and commencing charge. The signal from the current transducer is also used since terminating current will open a relay to terminate the charge cycle.

DRIVE SYSTEM

The drive system is powered by the main 37kW power system that enters a DMOC445 motor controller from Azure Dynamics and is passed onto the Solectria AC21-A motor. The motor translates the power from the motor controller into rotational movement that turns the sprockets that make up the belt driven, direct drive system.

MOTOR - The motor is a brushless, 3-phase AC motor from Solectria, seen in Figure 7, that is capable of a peak efficiency of 92%. This motor has a continuous power rating of 16kW and a peak power of 37kW. Translated into horsepower, this particular AC motor provides continuous power of 21.45hp and peak power of 49.60hp.

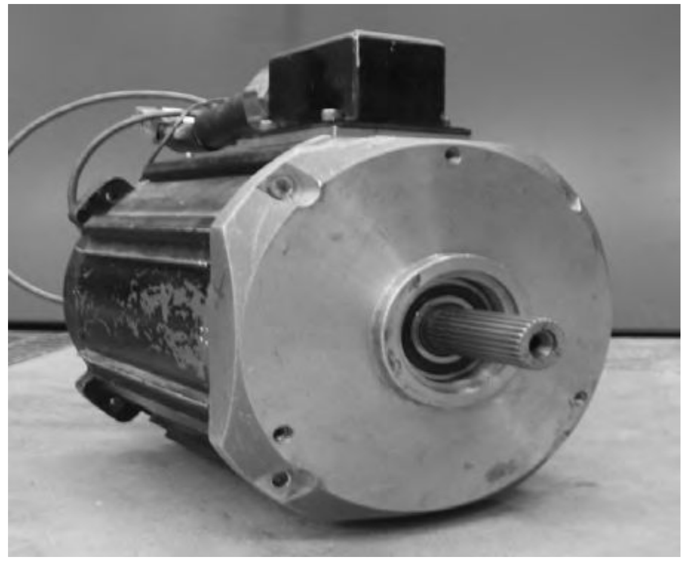

Figure 7: Photo of Solectria AC21-A Motor

MOTOR CONTROLLER - Azure Dynamics DMOC445 was selected and programmed to control Solectria's AC21-A motor. The DMOC, as seen in Figure 8, weighs in at 14.7kg and operates at a nominal voltage of 144. It produces a peak power of 78kW, continuous power of 38kW and is between 96%-98% efficient. This controller was chosen to provide the motor with more power due to the output limitations of the UMOC425T used in the 2007 and 2008 designs. In choosing the DMOC445, the snowmobile shed 3.5kg due to its lighter composition when compared with the previous controller, the UMOC425T.

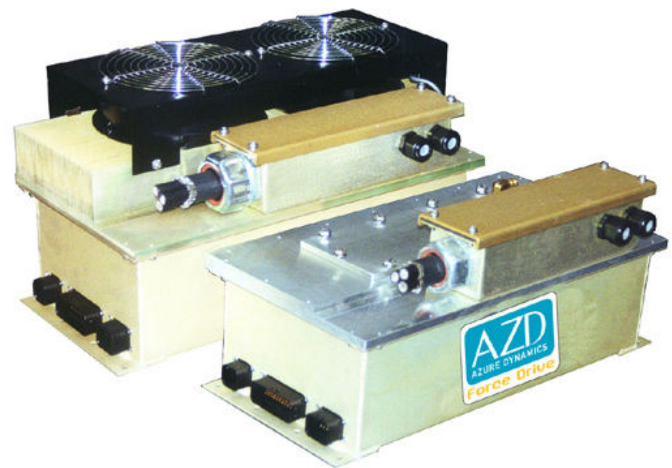

Figure 8: Azure Dynamics DMOC 445

DRIVE TRAIN SELECTION - When exploring drive train options, three different types were examined as seen in Table 2. Since one of the design goals involves minimizing noise emissions, this immediately eliminated the chain drive which was 20dB louder than the options of the belt drive and CVT.

Drive Type	Life Span (miles)	Noise (dB)	Lubrication	Cost ($US)	Gear Ratios
Belt	60,000	60	None Required	633	One (fixed)
Chain	60,000	80	Oil Bath	400	One (fixed)
CVT	3,000	60	None Required	650	Infinite

Table 2: Drive train Comparison Chart

CVTs are used in a lot of vehicle drive systems to provide more torque at lower speeds. It does this by changing the ratios according to speed to provide an adequate amount of torque to keep the vehicle moving. The problem is that electric motors provide instant torque at lows speeds so a CVT would need to be modified to incorporate the torque of the motor.

The drive train that was chosen involved a belt driven direct drive because of its ease of implementation, cost, life span, and noise emissions. The specifications of the system were easily designed to be able to take advantage of the speed, torque, and efficiencies that the motor had to offer, as determined from Figures 9 & 10. Since torque is a function of speed, by manipulating the gear ratio to increase or decrease speed allows the torque output to be modified. The 2008 snowmobile design sported an overall gear ratio of 5:1 outputting 80Nm of torque at 4000RPM. During the draw bar pull, the snowmobile lost traction very early showing that there was too much instant torque that the track was overcoming the maximum static friction between the track and snow. With last year's design flaw in mind, the drive system was designed with a 2.5:1 overall ratio which will output approximately 40Nm of torque at 6000rpm. This design will offer increased speed while filtering out unnecessary torque. The sprockets are connected with a Gates Polychain belt that can withstand the speed range of the snowmobile while limiting noise emissions. By reducing the gear ratio, the snowmobile weight was reduced by approximately 5kg.

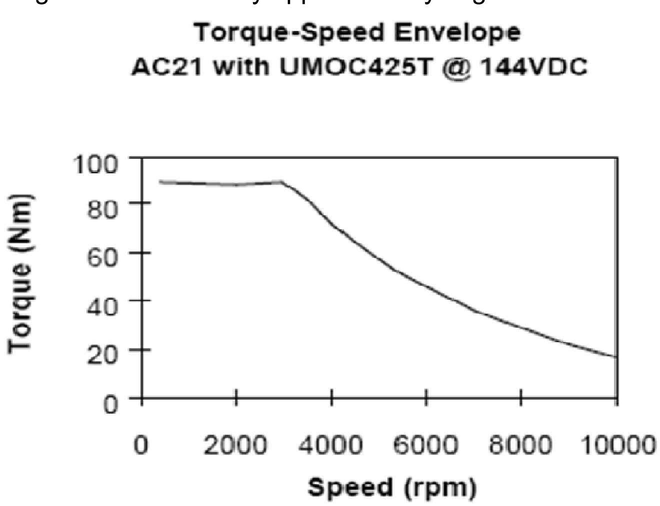

Figure 9: Motor Torque-Speed Envelope

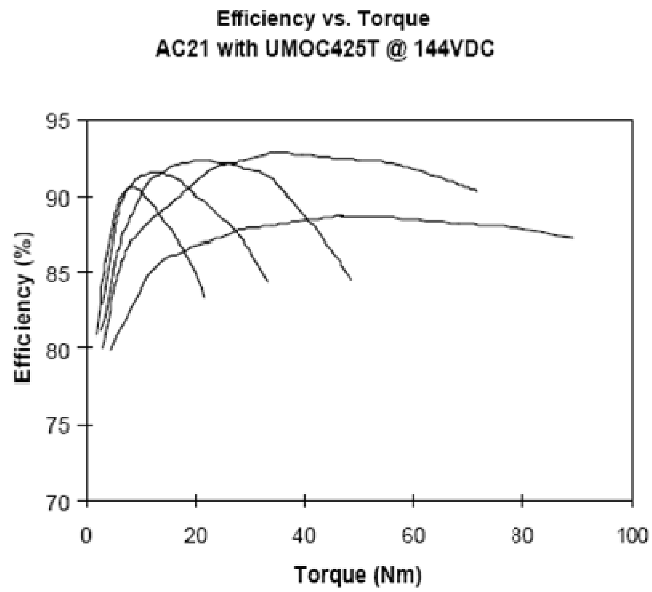

Figure 10: Motor Efficiency Graph

TRACTION

In accordance with the design goal of a light weight snowmobile and less sound emission, the team looked for ways to improve the traction components while attempting to meet design goals.

SKIS - Since the stock Polaris skis are not one piece and are bolted at the toe of the ski, it was assumed the flexion of the ski created noise at the bolted connection. In order to reduce possible noise caused by the design of the ski, the team replaced the stock ski with a touring ski from Camoplast. Camoplast's touring ski is blow-molded creating a single piece ski that is comparable in dimensions to the stock Polaris ski and offers a reduced weight of 2.05kg.

SUSPENSION - The 2008 Polaris 600RR is fitted with Walker Evans race shocks that help cushion the added weight of batteries as well as absorb trail shock during riding. Since electric motors are relatively quiet when compared to internal combustion engines, most of the noise emitted can be attributed to the track. In order to make the rear suspension as efficient and quiet as possible, a new rear shock was attached to the skid frame as well as new block wheel mounts to reduce side to side movement of the bogey wheels. These changes will help negate unnecessary movement by component parts and help reduce noise emissions.

TRACK - Camoplast's Ripsaw track comes standard on the 2008 Polaris 600RR. In order to reduce the opportunity for slippage in the draw bar pull, the team switched to Camoplast's Cobra track which offers a slightly longer lug length at an additional weight of one kilogram. The track came with a pre-drilled stud pattern to help offset any additional weight increase.

HANDLING

In order to maintain a center of gravity close to that of a stock snowmobile, the team has organized the bulk of their battery system inside the old gas tank over the front portion of the track as seen in Figure 11. This keeps the overall weight situated over the skis and over the front of the track while keeping the center of gravity low to avoid snowmobile roll-overs.

Figure 11: Battery Box Placement

The suspension involves Walker Evans racing shocks that help cushion rough trails. The rear suspension was recently replaced with a stock Walker Evans shock to help improve impact absorption and prevent the rider from getting the brunt of the shock.

A Camoplast Cobra track replaces the stock Camoplast Ripsaw and offers a slightly longer lug length to help grip the snow during travel. This change was made with less than a one kg increase in weight. The addition of a pre-drilled stud pattern in the Cobra has made the track weight the same, if not slightly lighter than the stock Ripsaw.

NOISE EMISSIONS

Due to the natural low noise emissions of electric motors, it is generally difficult to distinguish one electric snowmobile as much quieter than another. Being able to make slight, inexpensive changes to snowmobile will be important in trying to reduce noise emissions.

There are two main sources that contribute to noise emissions. One source is the motor and the second source is the track. The motor is noticeably quieter when compared to the track, but since the direct drive system must be covered to prevent injury in the case of drive failure or catastrophe, this offers an opportunity to reduce noise emitted from the motor. On the inside of the drive system cover is a spray-on insulating foam to help reduce any noise or vibrations that may otherwise pass through the metal cover. The track noise can be reduced through the use of a track skirt, but this option is not aesthetically pleasing. Rather than adding a track skirt, the team decided to make the track as efficient as possible by replacing old worn parts such as the slide rails and block wheel mounts to prevent undesired movement and noise. Also, rubber mounts were used to isolate the track from the tunnel to prevent chassis rattling due to vibrations from the track. The team is also exploring different materials to insulate the inside of the tunnel, but no current data is available.

RANGE

In order to maximize range, discharge of the main battery system, moving components, and snowmobile weight has to be as efficient as possible.

The Battery Management System equalizes the main battery system to ensure the most efficient discharge. This equalization prevents any one battery cell from dropping below the minimum operating voltage thus preventing poor performance by the entire battery system.

Replacement of chain case bearings, slide rails, skis, scags, and rear suspension seek to reduce friction of moving parts. Reduction of friction within moving parts requires less energy consumption to overcome internal frictional forces making it easier to propel the snowmobile.

Lighter weight vehicles require less energy to move. By incorporating lighter parts such as skis, sprockets, motor controller and track, the snowmobile requires less energy to move it. Energy consumption is inversely related to range, so lower energy consumption means further range.

Preliminary testing is inconclusive at this point, but more on range will be discussed during the oral presentation.

TOWING CAPACITY

Towing capacity features a many challenges such as finding the right balance between torque and speed along with determining the right amount of traction needed. A possible solution to traction would be to add studs to the track, but this requires the tradeoff of sound and weight. Last year’s design only pulled a maximum of 382.1 pounds before the snowmobile lost traction. This year’s design features a slightly longer lug length on the track and unnecessary torque has been exchanged for speed with a different gear ratio. These changes should improve towing capacity, but currently there is incomplete data and this topic will be further covered in the oral presentation.

CONCLUSION

This year’s design has addressed each and every one of our design goals. The Battery Management System took a lot of time and testing to create and ensure its reliability, but provided the team with a huge sense of accomplishment. Other goals such as reducing the gear ratio to increase speed and reduce torque, and making the snowmobile lighter have also been completed in an effort to correct shortcomings in the snowmobile’s previous designs. This project has at times required patience and extreme creativity along with an immense amount of research and teamwork, but all of this has led to a working electric snowmobile that wouldn't appear electric at a glance. Inside is a bunch of creativity that has met and exceeded the team's expectations for the year. However, creativity usually comes at a price. Batteries with high energy densities, better motors and controllers, and systems to ensure the safety of the batteries have proven to be a large investment. Overall the team has met challenges and expectations head on and has created a remarkable machine.

ACKNOWLEDGMENTS

The Clarkson University Electric Knights would like to extend a great deal of thanks to Babcock Power Inc, Gates Corporation, Cadsoft Corporation, Advanced Circuits, Camoplast Corporation, and Woody's International for their generous donations. Without the help of these companies, many of our goals could not have been met.

REFERENCES

1. "Switched Capacitor System for Automatic Series Battery Equalization". César Pascual, Philip T. Krein. Department of Electrical and Computer Engineering University of Illinois, Urbana, Illinois 61801. © 1997, IEEE.Type references over these paragraphs.

2. BatterySpace.com/ AA Portable Power Corp. (2008). High Power Polymer Li-Ion Cell. http://www.batteryspace.com/index.asp?PageAction=VIEWPROD&ProdID=3819.

3. "Electrical Motor Efficiency." (2005). The Engineering Toolbox.http://www.engineeringtoolbox.com/electrical-motor-efficiency-d_655.html

4. "Cobra." Camoplast Hi-Performance Trail Tracks. (2009). Camoplast Corporation. http://www.camoplast.com/tracks/tracks/cobra.html

5. "Ripsaw." Camoplast Hi-Performance Trail Tracks. (2009). Camoplast Corporation. http://www.camoplast.com/tracks/tracks/ripsaw.html

6. "Poly Chain GT." Drive Design Manual. (2007). Gates Corporation. http://www.gates.com/drivedesign

7. Solectria Corporation. (2000). Solectria Motors. *Solectria.* http://www.solren.com/downloads/ac21a.pdf.

8. Society of Automotive Engineers, Inc. (2009). The SAE Clean Snowmobile Challenge 2009 Rules. SAE Collegiate Design Series: Clean Snowmobile Challenge: Rules and Important Documents. http://students.sae.org/competitions/snowmobile/rules/rules.pdf.

9. Society of Automotive Engineers, Inc. (2009). 2008 Results - Zero Emissions Class. SAE Collegiate Design Series: Clean Snowmobile Challenge: Competition Results. http://students.sae.org/competitions/snowmobile/results/