Development of Sustainable Electric Conversion for Snowmobiles in Wintry Regions

2010 SAE Clean Snowmobile Challenge

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ABSTRACT

The South Dakota School of Mines and Technology (SDSM&T) Alternative Fuel Vehicle (AFV) team has designed and manufactured an electric drive conversion. Using a 2008 Polaris IQ FS Touring chassis, a synchronous belt drive developed with Mark Hoffman of Crazy Mountain Xtreme (CMX) couples the NetGain Impulse 9 series wound DC electric motor to the track drive shaft. The energy storage uses 30 Tenergy 3.2-V, 100-Ah lithium iron phosphate battery cells to store 9.6 kW-hr of energy at the nominal voltage of 96-V. To transmit the power to the electric motor a Curtis 1231c motor controller has been implemented. The appearance of the snowmobile will remain stock with the exception of the seat. With the AFV team's design the seat will incorporate the battery box; essentially, the rider will be riding on the battery box. The initial goal for the SDSM&T AFV team was to design the highest performing sled to compete with at the SAE CSC, in Houghton, Michigan,

INTRODUCTION

The existence of environmentally sensitive regions such as the National Science Foundation research facility at Summit Station, Greenland, facilitates the need for transportation drive systems which limit or eliminate the production of environmentally harmful emissions. Transportation drive systems which emit chemical substances that alter the state of the environment produce the potential risk of long term damage to key research regions. Advancements in electric vehicle technology make possible the development of purpose-built vehicles or conversion systems for existing vehicles, which allow mobility in wintry regions.

Development of the South Dakota School of Mines and Technology (SDSM&T) Alternative Fuel Vehicle (AFV) team's Ramblin' Wreck IV focuses on the application of an electric drive system to a 2008 Polaris Touring FS. Emphasis is placed on the development of a modular electric drive conversion which can be adapted to multiple snowmobile makes and models. Evolution of the Ramblin' Wreck IV electric snowmobile conversion design is detailed with emphasis on overall design methodology.

DESIGN METHODOLOGY

Entering into the SDSM&T AFV Team's fourth (4th) year of participation in the SAE CSC, the team set in motion the development of the 2010 electric snowmobile by assembling a design methodology. Comprised of a set of concepts or principles, the design methodology provided the framework for the design of the 2010 electric snowmobile. Throughout the design process, the design was analyzed according to the ordering of the design methodology in Figure 1.

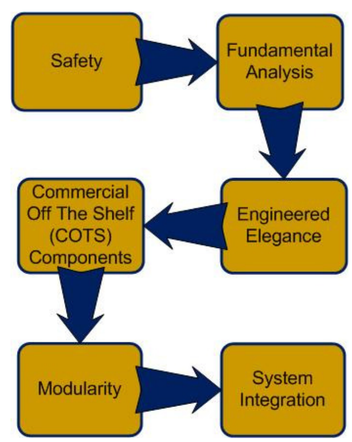

Figure 1: Design Methodology flow chart

SAFETY

Within the design methodology, safety was of paramount importance. The design of the 2010 electric snowmobile was contingent on safety. Located at the top of the design flowchart, designs must comply with the AFV Team's safety standards prior to continuing down the design flowchart. The AFV Team's safety standards were based upon pre-existing SAE CSC Rules and safety stands which exceeded competition rules.

FUNDAMENTAL ANALYSIS

Fundamental analysis focuses on the AFV Team's understanding of the fundamentals of the installation of an electric drive system into a snowmobile, and is concentrated on understanding the fundamental vehicle dynamics of an electrically driven snowmobile and the impact which the addition or deletion of components had on the overall system. Through the analysis of the fundamental vehicle dynamics, the adverse impact of the electric drive system conversion was minimized.

ENGINEERED ELEGANCE

Engineered elegance refers to the AFV Team's concept of developing the Ramblin' Wreck IV as an electric snowmobile conversion which is simplistic in design and aesthetically pleasing. A simple designed system makes for easy troubleshooting in the event of a failure. Keeping component numbers to a minimum makes for effortless system inspection, while maintaining the desired performance.

COMMERCIAL-OFF-THE-SHELF (COTS) COMPONENTS

Due to the primary use of an electrically driven snowmobile in wintry regions breakdowns could become devastating events. Using commercial-off-the-shelf (COTS) parts, make minimal turnaround time for repairs. Remote locations, such as Summit Station, Greenland can have replacement components available, so in the event of component failure the possibility of quick on-location repair is made possible and relatively simple.

MODULARITY

Modularity pertains to the configuration of components and the ability to separate components for servicing or repair without disassembly of non-related system. The design concept of modularity centers around the development of discrete modules which are self contained. Modules were developed to minimize the impact on adjacent systems during servicing or replacement.

SYSTEM INTEGRATION

The design concept of system integration concerns the integration of discrete modules into a system which functions according to the design specifications. Development of system integration integrated discrete modules into the overall system.

DESIGN PROCEDURE

The SDSM&T AFV design team used a simple yet effective procedure in their design. The procedure is as follows:

- Team atmosphere design brain storming
- Design evaluation according to design methodology
- Finalize Design Analysis
- Final Design Development
- Final Design Implementation

ELECTRICAL SYSTEM

After experiencing an unexpected complete electrical system failure at the 2009 SAE CSC the AFV team performed a complete redesign of the electrical system for the Ramblin' Wreck IV. The design of the electrical system of the Ramblin' Wreck IV kept safety as top priority. In combination with safety, the electrical design kept the idea of Engineered Elegance in mind.

HIGH VOLTAGE

SDSM&T's inaugural electric snowmobile, Ramblin' Wreck I, used a 72-V, 38-Ah Sealed Lead Acid (SLA) battery pack, while Ramblin' Wrecks II and III utilized a 72- V, 100-Ah lithium-ion (Li) battery pack; as part of the Ramblin' Wreck IV's redesigned

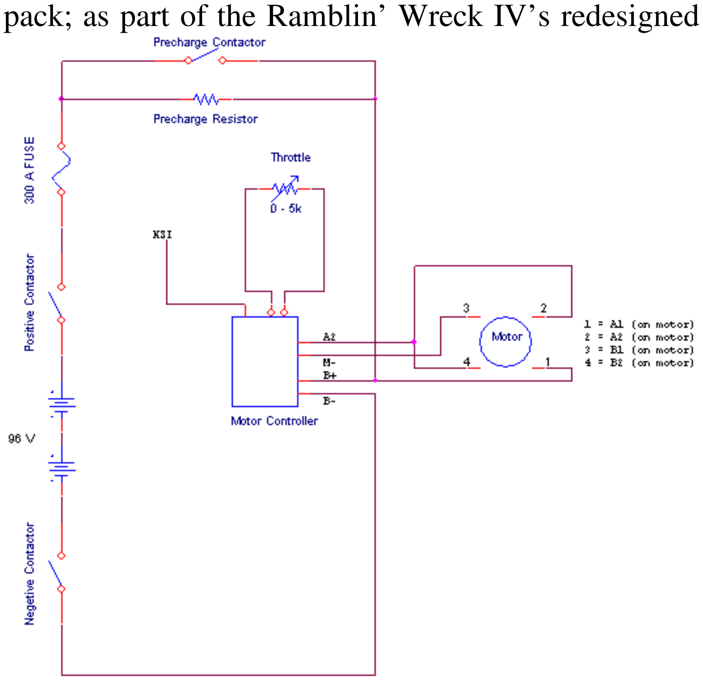

Figure 2: Ramblin' Wreck IV's High Voltage Wiring

electrical system the battery pack voltage has been increased to 96-V but maintains 100-Ah and the battery cell chemistry has changed to lithium iron phosphate (LiFePO4). To insure safety during operation and charging of the snowmobile three (3) contactors have been implemented into the design. Figure 2 depicts the wiring schematic for the high voltage system of the Ramblin' Wreck IV.

In the design of the high voltage system of the Ramblin' Wreck IV, maintaining battery pack isolation while the snowmobile is not excited was a large focus of the design team. To maintain the desired isolation of the battery pack two (2) Tyco Kilovac 500-A, 320-V, LEV200 Contactors are used. By implementing a contactor on both the positive and negative sides of the battery pack, desired isolation is obtained. When all kill switches are open (snowmobile in an unexcited state), the 96-V battery pack is completely isolated. Isolation of the battery pack allows for charging without risk of excitation to circuitry external of the battery pack module. The Tyco contactors have 12-V control terminals which are connected to the kill switches implemented into the low voltage system of the Ramblin' Wreck IV. The cardinal idea behind including the contactors with the low voltage system is in the event that one of the snowmobile's kill switches becomes open, the battery pack will become completely isolated, keeping both the rider and the snowmobile safe.

The pre-charge circuitry of the HV system includes one (1) Tyco Kilovac 500-A, 320-V, LEV200 contactor. The pre-charge contactor is controlled by a NTE Electronics, Inc. R61 Series timed relay which is intertwined into the low voltage (LV) system. More of the operation of this pre-charge will be discussed in further detail in the Low Voltage section of this design paper.

In compliance per SAE CSC rules all HV system wiring is completely enclosed in orange flexible conduit. The goal of the HV system was to enclose the wiring in a water-tight conduit system, to minimize the possibility of water exposure.

ENERGY STORAGE

As safety has been continually reiterated, the electrical design team used safety along with weight as the major deciding factors for the choice of the battery cell used for the Ramblin' Wreck IV. The battery cells chosen use a Lithium Iron Phosphate (LiFePO4) cathode material. This type of battery cell has a non-toxic, Earth-friendly design. The elements iron and phosphate are an extremely abundant material. The low cost of theses raw materials help drive down the price of these battery cells which makes them much less expensive than the average lithium-ion battery cell.

The LiFePO4 chemical bond is very strong and this makes the battery cells extremely invulnerable to thermal runaway or breakdown. Figure 3 shows the robust stability of the LIFePO4 bond compared to other types of Li-ion battery cell chemistries.

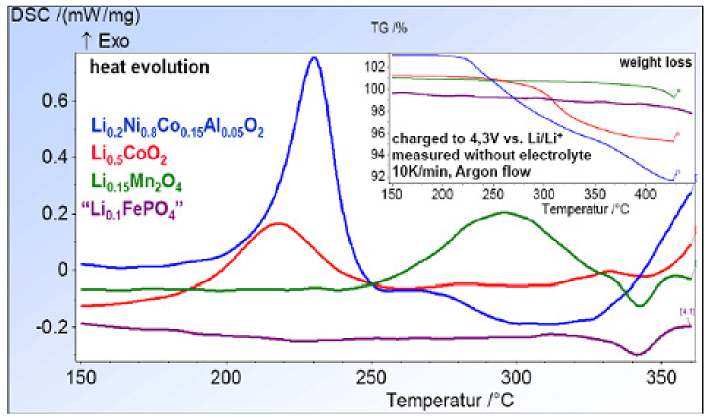

Figure 3: Measured by ZSW: J. Power Sources 1 (Argonne National Laboratory, USA)

From Figure 3 it is evident that these battery cells have little to no exothermic reaction when heat is applied to the bond. Not only is this bond very stable but it is also evident that hardly any chemical weight loss is caused due to heat directly presented.

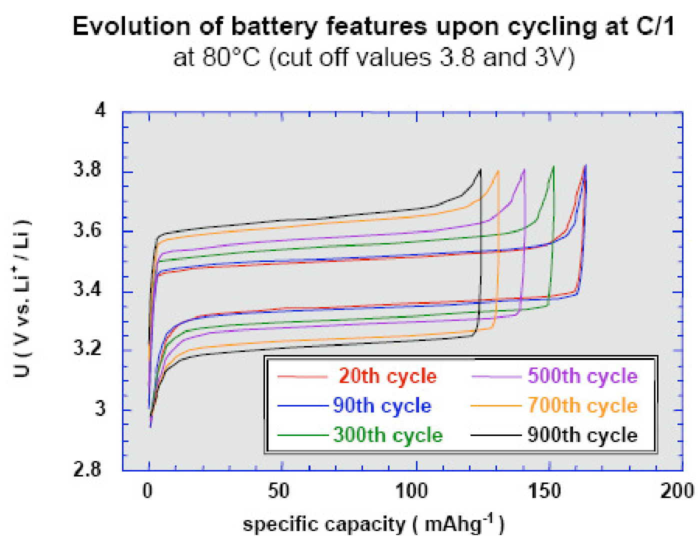

Figure 4: Measured by University of Montreal (2001)

When using the proper discharge and charge characteristics, it has been publicized that the cycle life of LiFePO4 battery cells is substantially long. A study was conducted at the University of Montreal to reveal how well the specific capacity is held in this ionic bond after multiple charging and discharging cycles. Figure 4 conveys graphically the experiment which was demonstrated.

Even after 900 cycles the specific capacity of these battery cells is still almost 70% than that of the first. Tenergy, which is the manufacturer of the batteries used in the Ramblin' Wreck IV, states that their $LiFePO_4$ battery design has a life span of roughly 2000 cycles. This proves that the life duration of $LiFePO_4$ technology is incredibly long; almost 8 times that of lead-acid battery cells and 3 to 4 times that than most other Lithium-ion battery cells. If properly used, these battery cells can last between 5 and 6 years in electric vehicle applications.

A major deciding factor as mentioned before was the light weight design of the LiFePO4 battery cells. Compared to the battery cells that were implemented in Ramblin' Wrecks I – III, the Tenergy LiFePO4 battery cells were considerably lighter. Each individual battery cell weighs 3.54-kg, which makes the overall weight of the Ramblin' Wreck IV's 96-V battery pack 106-kg. This amounts to roughly a seventy pound weight reduction of the Ramblin' Wreck IV's battery pack from those of Ramblin' Wrecks I-III.

CHARGER

To safely and efficiently charge the Ramblin' Wreck IV's LiFePO4 battery pack, a special charger is required to meet the proper charging algorithms specific to this battery cell type. Because a rapid charge could potentially damage and even shorten the life span of these battery cells, a high frequency charger is needed. After much research was completed to determine which charger was best for the Ramblin' Wreck IV, the AFV team decided that the Zivan NG1 best met the criteria.

The Zivan NG1 is a light-weight, compact design that uses a "trickle charge" charging method to maximize the charging safety and life span of each battery. This charger is factory programmed with the correct encoding to specifically meet the battery pack's specifications. It is controlled by a microprocessor to ensure internal protection from an overload, transient voltages, and circuit shorts and improper charger connection. The Zivan NG1 is highly efficient, operating up to almost 90% efficiency. All the safety features and efficient qualities of the Zivan NG1 is main reason for choosing this charging system for the Ramblin' Wreck IV.

MOTOR CONTROLLER

To administer proper control of the power from the energy storage to the motor, the Ramblin' Wreck IV uses a Curtis 1231c motor controller. The Curtis 1231c motor controller operates at voltages between 96-V and 144-V and up to 550-A instantaneously and down to 225-A hourly. This motor controller is MOSFET design. The MOSFETs used are a majority carrier device and don't utilize carrier storage; therefore, eliminating any lag time due to storage. This technology allows the Curtis 1231c motor controller to utilize fast frequency shifting. Fast frequency shifting creates a very small voltage drop which minimizes battery and motor losses. The 1231c shifts from frequencies between 15 hertz (Hz) and 1.5 kilohertz (kHz). This low throttle input helps to limit current to help eliminate motor stall or failure. This controller also has a few other safety features including a completely sealed design. It is equipped with a couple safety circuitries; one that trips the motor power when a throttle shortage or other wiring failure is sensed and a thermal circuitry that allows power flow under all temperature conditions.

LOW VOLTAGE

The Ramblin' Wreck IV continued the use of Engineered Elegance in the design of the low voltage system. The low voltage system design incorporated all the kill switches to completely remove all excitation of the electrical system. In accordance with the SAE CSC, the low voltage includes all the required kill switches. Figure 5 depicts the overall low voltage system schematic.

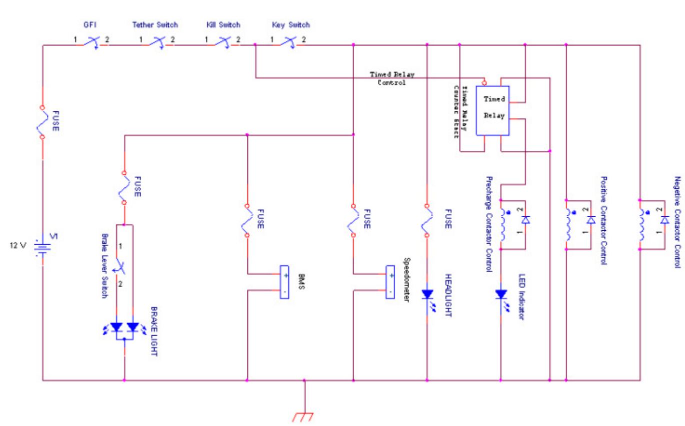

Figure 5: Ramblin' Wreck IV's Low Voltage Wiring Schematic

By inspection of the wiring schematic it is noticed that the headlight, tail light, and brake light are also included into the low voltage system. The lights that are required per SAE CSC regulations are wired into the LV system to become excited once all kill switches are closed.

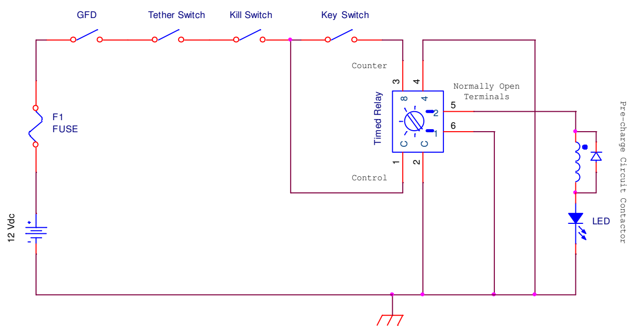

Figure 6: Ramblin' Wreck IV's pre-charge circuitry

Another aspect of the LV system is the pre-charge circuit control (see Figure 6). The pre-charge circuitry of the Ramblin' Wrecks I – III all included rider interaction. The Ramblin' Wreck IV's pre-charge circuitry has been designed to be automated. The circuit has incorporated a NTE Electronics, Inc. R61 Series timed relay to control the pre-charge circuitry contactor. Once the ground fault detector, tether switch, and kill switch are closed the control voltage will be supplied to the timed relay. Closing the key switch the counter/delay time begins. After 2 second (s) time delay the pre-charge contactor will close allowing the motor controller to become fully excited. Upon excitation of the motor controller a LED indicator illuminates on the dash of the snowmobile. The LED indicator would inform the snowmobile operator that the snowmobile is ready to operate.

To provide a user interface to control speed is the implementation of a Curry Thumb Throttle. The thumb throttle is connected to spade terminals two and three of the Curtis 1231c motor controller.

The electrical system design retained safety and Engineered Elegance in mind throughout the design. During the design process it became evident that the LV system had to be intertwined into the HV system slightly for control purposes, while also maintaining as much LV system and HV system isolation as possible.

MECHANICAL SYSTEM

The mechanical system of the Ramblin' Wreck IV focused on simplification of the Polaris snowmobile mechanical system. Overall system design focused on the retention of components essential to the incorporation of an electric drive system.

TRACTION MOTOR

The traction motor selected for the Ramblin' Wreck IV electric drive system conversion is the NetGain Motors, Impulse 9 series wound, direct current electric motor. The Impulse 9, which is manufactured by the Warfield Electric Motor Company, has a maximum rated voltage of 170-V and maximum rated amperage of 2000-A. (NetGain Motors, Inc.) Figure 7 displays the NetGain Motors supplied specifications for the Impulse 9 excited at 72-V.

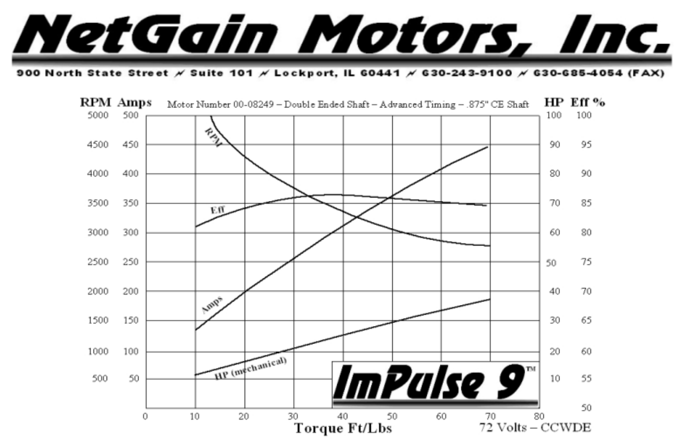

Figure 7: NetGain Motors Impulse 9 supplied specifications depicting, RPM, Efficiency, Amperage and Mechanical Horsepower for constant torque. (NetGain Motors)

At a maximum current of 300-A (the maximum current of the Ramblin' Wreck IV battery module) the Impulse 9 motor is capable of producing a maximum

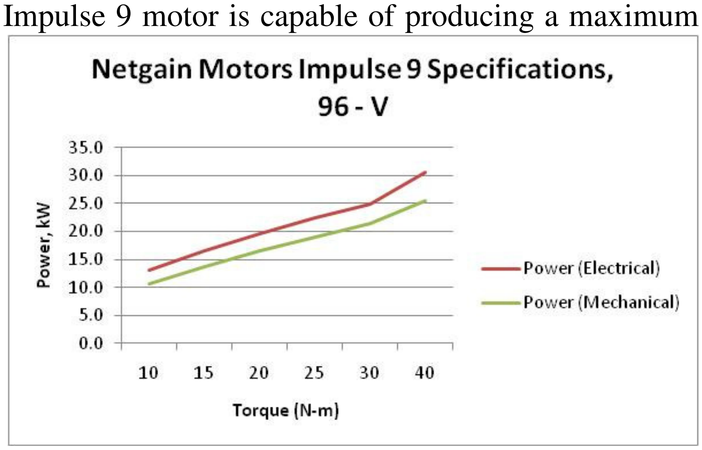

Figure 8: NetGain Motors Impulse 9 specifications for an excitation voltage of 96-V depicting electrical and mechanical power for constant torque.

torque of 50 N-m. The dynamic relationship between the excitation voltage and the power produced by the Impulse 9 is that as the excitation voltage is increased, the mechanical power produced increases. The increase in power is the result of an increase in the angular velocity of the output shaft with an increase in excitation voltage. Figure 8 displays the Impulse 9 specifications for an excitation voltage of 96-V.

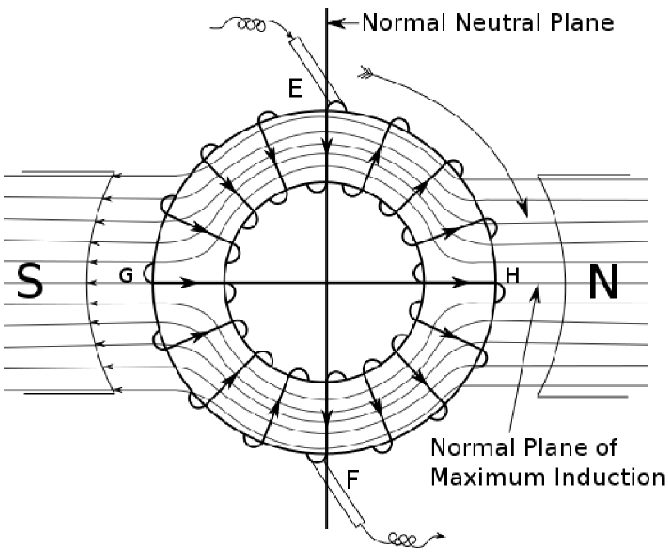

Figure 9: Neutral commutator timing for low excitation voltages. Depiction of uniform, undistorted magnetic field and commutator timing introducing current perpendicular to magnetic field. (Hawkins Electrical Guide, Volume 1)

The design of the Impulse 9 permits the usage of differing battery module designs to be used with the Ramblin' Wreck electric drive system conversion. The design of the Impulse 9 incorporates commutator timing to allow the Impulse 9 to optimize efficiency at increased excitation voltages. The effect of commutator timing is illustrated in Figure 9. In Figure 9, the conversion process by which electrical energy is converted to mechanical energy through the deflection of electrons moving through a closed loop in a magnetic field is displayed (Commutation and Commutator). The conversion of electrical energy to mechanical energy is quantified using Equation 1 where N, i, A, B and θ are the number of windings in the electric motor, current, area enclosed by the winding, magnitude of the magnetic field and the angle at which the current passes through the magnetic field at, respectively (Torque on a Current Loop).

Equation 1

From Equation 1, the optimization of the produced torque occurs as the current is passed through the magnetic field at an angle of 90° when the sine of θ is equivalent to unity. At high angular velocities caused by increased excitation voltages, distortion of the magnetic field occurs causing the current to pass through the magnetic field at a non-optimized angle of 90°. Commutator timing which is demonstrated in Figure 9 and Figure 10 compensates for the distortion of the magnetic field by realigning the current to pass through the magnetic field at an optimized angle of 90°.

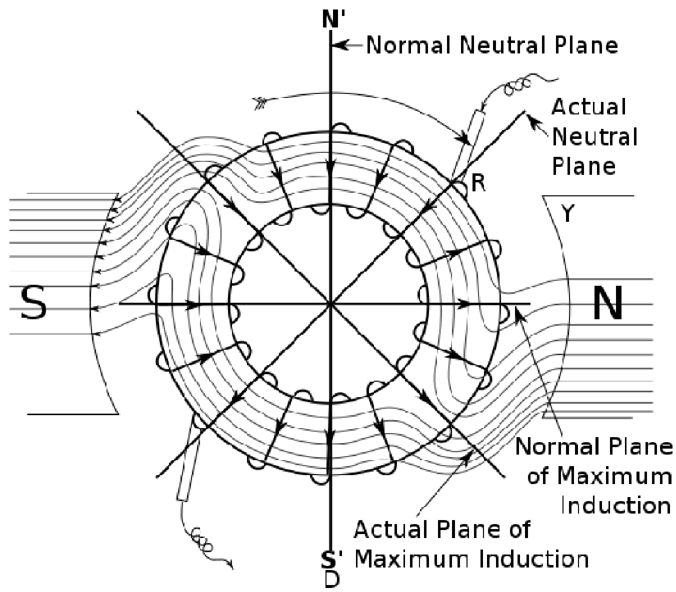

Figure 10: Advanced commutator timing for high excitation voltages. Depiction of uniform, distorted magnetic field and commutator timing advanced to introduce current perpendicular to distorted magnetic field. (Hawkins Electrical Guide, Volume 1)

DRIVETRAIN

The drive train for the Ramblin' Wreck IV makes use of a synchronous belt drive to transfer power from the Impulse 9 electric motor directly to the track shaft. The synchronous belt drive was developed with Mark Hoffman of Crazy Mountain Extreme located in Clyde Park, Montana. The synchronous belt drive utilizes commercial off the shelf components sourced from Crazy Mountain Xtreme's CMXDS to decrease the overall drive train weight, rotating mass and rotating inertia.

During preliminary design of the drive train three (3) options were considered for the design of the drive train. The options considered for the drive train were the Fallbrook Technologies Nuvinci® CVAD, a synchronous drive belt and the Polaris continuously variable transmission (CVT). The three drive train options were evaluated according to criteria developed from the design methodologies previously explained.

Remaining true to the design methodologies the drive train focuses on the concepts of engineered elegance, modularity and system integration. The drive train design of the Ramblin' Wreck IV eliminates the Polaris drive train consisting of the primary CVT, secondary CVT, jackshaft, brake rotor, brake caliper, chain and sprocket set as well as the chain case and stock track shaft. The Polaris drive train is replaced with a modular drive system which is developed for the Polaris Touring FS chassis but is easily adaptable to other snowmobile brands. The drive system design centers around a primary drive plate which positively locates the Impulse 9 electric motor output shaft in reference to the track shaft. The primary drive plate is necessary to decrease deflection of the driving synchronous drive pulley relative to the driven pulley which is attached to the track shaft. Incorporated into the primary drive plate is the track shaft bearing housing, the brake caliper, belt idler pulley mount and electric motor mount.

The drive ratio of 2:1 for the synchronous belt drive system is established through the use of a 30 tooth driving pulley and 60 tooth driven pulley. The pulley center distance is 363 mm which is established by locating the Impulse 9 electric motor output shaft 305 mm forward and 152 mm up from the center of the track shaft. Locating the 59 kg (130 lbs) Impulse 9 electric motor low in the chassis at the aforementioned location and near the stock snowmobile center of gravity, decreases the adverse effects towards the overall handling and performance characteristics of the snowmobile.

SUSPENSION SYSTEM

The Ramblin' Wreck IV suspension system utilizes the 2008 Polaris Touring FS unequal length A-arm front suspension and the 3.45m (136 in) Comfort, fully coupled rear suspension. The foundation for the development of the Ramblin' Wreck suspension system is the design methodology concepts of fundamental analysis and system integration. System integration of the electric drive system is achieved through the fundamental analysis of the suspension system in response to design constraints of the electric drive system.

The use of SolidWorks 2009 SP3.0 Simulation is a key aspect of the suspension system development. Development of the rear suspension was facilitated by creating a dimensionally correct model within the SolidWorks 2009 SP3.0 environment (See Figure 11). Following the development of the model, SolidWorks 2009 SP3.0 Simulation was utilized to simulate a drop of the suspension from a height of 305mm. Simulating the drop required the establishment of the drop constraints. The drop constraints applied to the interaction between the drop surface (ground) and the suspension skid frame as well as the interaction between the coupling components of the suspension. The SolidWorks 2009 SP3.0 Simulation environment contains built controls for the addition of adjustable spring and damper systems into models. Applying spring and damper systems to the front and rear torque arms the rear suspension system was tuned to a slightly underdamped system which minimized the force applied to the snowmobile chassis and thus maximized rider comfort.

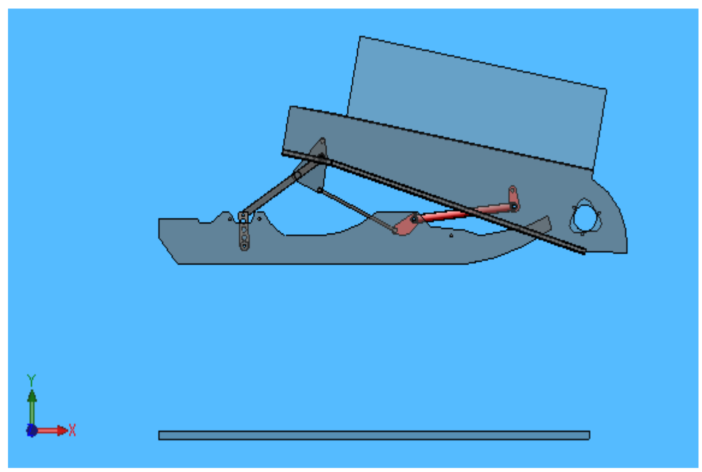

Figure 11: SolidWorks Motion modeling of Polaris Comfort track suspension subjected to forces generated by mass of energy storage module.

Addition of the mass of the energy storage module to the SolidWorks 2009 SP3.0 Simulation environment provided key information regarding the response of the rear suspension system to variance of the centroid of the snowmobile. Figure 12 displays the acceleration experienced by the rider as the centroid of the energy storage module is shifted from the front of the track tunnel to the rear of the track tunnel. Analysis of Figure 12 reveals that as the centroid of the energy storage module is transitioned from the front of the track tunnel to the rear, acceleration is minimized near the center of the track tunnel and that at the front and rear extremes of the rear suspension system the system becomes unstable. The instability of the system is a result of the isolation of the front and rear spring damper systems which occurs as the line of action of the inertial force of the energy storage container is moved over the front or rear torque arm. Movement of the line of action for the inertial force of the energy storage module over the front or rear torque arm decreases the effectiveness of the coupling mechanisms which allow the loading of the rear suspension system to be carried both the front and rear spring-damper systems.

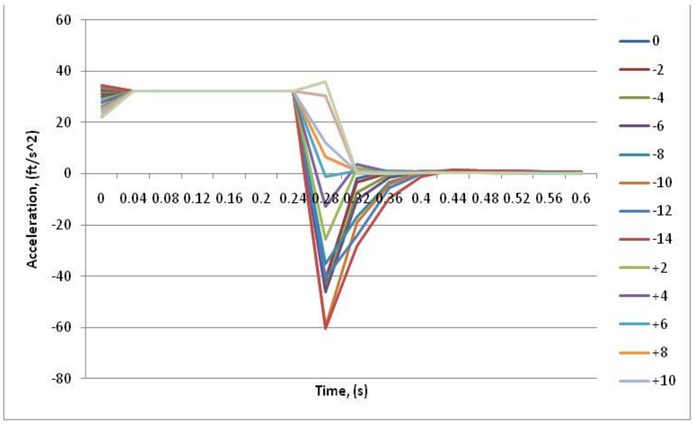

Figure 12: Acceleration of track suspension tunnel with varying positions of energy storage module centroid.

ENERGY STORAGE MODULE

The energy storage module of the Ramblin' Wreck IV focused primarily on the design concept of safety. The design concept of safety eliminated many designs during the preliminary design phase and produced many refinements to the finalized design. With an energy capacity of 9.6-kW stored in close proximity to the snowmobile operator, safety was a key attribute of the energy storage module but integration of the energy storage module into the system required observance of the remaining design concepts.

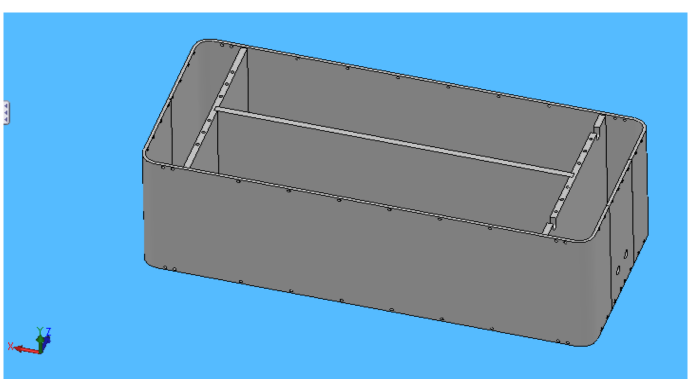

Figure 13: SolidWorks modeling of energy storage module depicting 4 compartment configuration.

The basic configuration of the energy storage module was determined through fundamental analysis. Making use of the analysis conducted on the track suspension system the centroid of the energy storage module was positioned at the midsection of the track tunnel. Figure 13 displays the finalized design of the energy storage module. Locating the centroid of the energy storage module was accomplished by incorporating a four compartment design. The four compartment design also allows for component isolation. In Figure 13, the 30 series connected battery cells are oriented in two parallel rows which are insulated by a dividing wall. Located in the forward compartment, the contactors, fusing and pre-charge circuitry is insulated from the adjacent batteries through the use of an insulated dividing wall. Stored in the rear compartment of the energy storage module, is the battery management system.

The material selection for the energy storage module is ultra-high-molecular-weight polyethylene (UHMW PE). UHMW PE was selected due to the materials combined mechanical, electrical and thermal properties. Mechanically, UHMW PE is carries a high impact resistance in comparison to other non-conductive materials. UHMW PE also carries a brittleness temperature of -103°C. Electrically, UHMW PE is non-conductive within the limits to the Ramblin' Wreck IV's high and low voltage electrical system, which allows the energy storage module to insulate the contained systems from the environment as well as insulating the components contained within the energy storage module. Thermally, UHMW PE carries a UL V-0 certification which requires that the material self extinguish in less than 10 seconds.

CONCLUSION

The need for zero emission transportation has driven the SDSM&T AFV design team to design an electric drive system that may be used in different snowmobile makes and models. From the content of this paper it is evident that all components used are able to be utilized in different snowmobiles. As previously stated, the use of COTS allows for rapid repair in the event of a break down. The design team feels that the system designs implemented for the electric drive conversion are safe for the use in other snowmobiles. Having isolation of the battery pack allows for safe charging.

With the use of SolidWorks the mechanical design team was able to redesign the suspension to withstand the abuse, which is endured with the excess weight, from the electric drive, that must be carried. During the redesign of a stock snowmobile one must always compensate for the difference in weight the snowmobile is expected to handle when converting to an electric drive.

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