DEVELOPMENT OF A SERIES PHEV “FORMULA STYLE” RACE CAR

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ABSTRACT
In early May 2007, a hybrid race car designed and built at McGill University won the SAE Formula Hybrid competition held at the New Hampshire International Speedway.

The vehicle used a continuously variable transmission (CVT) driven independent rear wheel drive system powered by two compact permanent magnet DC motors. It operated as a series hybrid via the use of a custom made single cylinder 4-stroke DC generator.

This paper looks at the power train design of McGill's winning entry. Models of components and sub-systems developed by McGill in Matlab/Simulink are discussed. These models were used to try to predict the vehicle’s performances and optimize them. Results obtained from the computer simulations are compared to the results obtained from vehicle testing.

INTRODUCTION
McGill University has in the past developed very successful electric vehicles. Design of these vehicles was based mostly on manufacturer component data and the experience gained through trial and error. Recently, McGill has started to apply its electric vehicle experience to plug-in hybrid vehicles. In doing so, one of the first realizations made was that, given the much higher complexity of interactions between components in hybrid vehicles, the simple trial and error methodology which was successful in the past would be extremely inefficient in designing hybrid vehicles. To make the design and optimization of its hybrid vehicles a much more efficient process, McGill University has incorporated a virtual modelling and simulation aspect to its traditional design process. This paper looks at a recent example of that in the case of McGill's Formula Hybrid race car.

VEHICLE
Goal
The goal with the first McGill Formula Hybrid vehicle was to design, model, test, and validate two original plug-in vehicle drive train subsystems:

1. A self balancing independent rear wheel drive system
2. A self regulated direct DC generator hybrid power pack

This paper presents the modelling results to date on the second subsystem: the self regulated DC generator hybrid power pack.

Concept
The idea behind the self regulated DC generator hybrid power pack is to have a simple, reliable, low cost & efficient hybrid system which can easily be integrated into an existing electric vehicle platform thus transforming this vehicle into a plug-in series hybrid vehicle.

The main “off the shelf” components used in the system are an internal combustion engine with mechanical governor, a permanent magnet motor/generator and a battery pack capable of high amperage charging. By selecting properly sized components, and connecting the engine/generator (genset) in parallel with the load and the battery, the team theorised that the
genset’s output would be automatically shared between the load and the battery based on the battery’s state of charge and the load’s power demand.

History
The team first implemented this concept in McGill’s Hybrid Snowmobile prototype which was in demonstration at the 2007 SAE Clean Snowmobile Challenge. This first iteration of the concept showed promising results. It was then decided that with minor modifications, the same system would outfit the McGill’s Formula Hybrid race car. In May 2007 the inaugural SAE Formula Hybrid competition was held at the New Hampshire International Speedway. McGill’s Formula Hybrid race car was the only car to complete all of the events. It won the overall title, the endurance event, the handling event, the marketing presentation event, and finished in the top three in all other events. The reliability, efficiency and low cost of the team’s unique hybrid system were all major factors in the team’s success.

Components
The vehicle’s main drive components’ power flow block diagram is presented below in Figure 1.

![Power flow block diagram](image)

The components under consideration in this paper are contained within the orange dotted line. Details about these components are presented below.

Battery Pack
Batteries are a critical component for all hybrid and electric vehicles because their performance must match the requirements of the vehicle. For this projects’ particular application, the batteries must be able to accept large charge and discharge currents, be able to handle indefinite constant charge voltage, and be safe to use in a dynamic environment (i.e. vibrations, lateral forces, changing temperatures, etc).

The batteries chosen to make the battery pack for this project are Hawker Genesis rechargeable sealed lead acid batteries. These batteries have a nominal voltage of twelve volts and their capacity is rated at 26 amp-hours at a C/10 discharge rate. They are capable of outputting approximately 300 amps for up to two minutes. The only limitation for cyclic charging requires that charge voltage may not exceed 14.7 - 15.0 volts. Finally, sealed lead acid batteries are a very common, cost effective and robust technology that is often used for applications with requirements similar to those of this project.
**Genset**

The main criteria for the genset aspect of the power system is that it be a direct current (DC) genset that can be coupled with the battery pack without any governing electronics in the circuit. The secondary criteria is that it be self-governing when incorporated into the system, and that it be power limited such that it would be very difficult for the genset to overcharge the pack; both current and voltage wise. These criteria were satisfied by developing a custom DC genset by coupling an internal combustion engine with a brushed permanent magnet DC motor.

The components selected to make the genset are a Robin-Subaru EX-21 engine and a Perm PMG-132 motor. The EX-21 is a single cylinder four-stroke engine rated at 5.1 kW\(^1\). It is equipped with a mechanical governor. The PMG-132 is a compact permanent magnet motor rated at 72 volts, 110 amps continuous and 200 amps peak\(^2\).

When the genset is coupled to the battery pack and there is no external load, there are three possible scenarios: 1) current flows from the genset to the battery pack (charging), 2) no current flows at all, 3) current flows from the battery pack to the genset making the PMG motor crank the engine. Of the three, only the first scenario is desirable (unless starting the genset). To avoid the latter two, the mechanical governor is used to set the speed of the genset which fixes the no-load voltage at the terminals of the PMG-132 (open genset voltage or OGV). If this voltage is set higher than the open circuit voltage of the battery pack, then current will not flow from the pack to the genset under normal operation. When a load is incorporated into this system, current is diverted from the genset to the load until the load reaches the maximum capacity of the genset. At this point, current flowing from the genset to the pack has reached zero. If the load is again increased, current begins to flow from the pack to the load supplementing the genset current to the load.

In this way, when the battery pack, genset and load are all coupled together, they all see the same voltage. This voltage is called the system voltage, and is governed by the dynamic interaction of the three components. The genset attempts to push this system voltage towards its no-load voltage by adjusting its power output: For example if the voltage of the battery pack sags, the genset will increase its output to the battery in an attempt to counter that sag to reach its no-load voltage. However, when outputting a current, the genset never quite attains its no-load voltage and rather the system settles at a voltage slightly lower than the genset's no-load voltage. How much lower depends on the current being produced by the genset. The genset voltage drop from the no-load set point can be accounted for by the internal resistance of the PMG motor/generator as well as the actual deceleration of the EX-21 allowed by the mechanical governor for a given load.

**SIMULATION**

**Goal**

The main goal of this project is to develop a working MATLABSimulink\textsuperscript{®} model of the interaction between the battery pack, genset, and load. This was done using Kirchhoff’s Current Law and Ohm’s Law as the underlying principles of interaction.
Components
In order to focus on the interaction between the hybrid power pack’s components, the vehicle’s drive system was simplified to a system with one power source (genset), one power sink (load), and a unit which, depending on the conditions, can act as a power source or a power sink (battery pack). This interaction is illustrated in Figure 2.

Figure 2: Components under consideration.

Battery pack
The battery model developed for this application is a resistive model (Johnson, 2002)\(^3\). Battery models typically aim to estimate the voltage at the battery terminals over time given a specified current load (source or sink). For the chosen batteries, if temperature effects are not taken into account, the terminal voltage was found to be governed mainly by two variables: first the state of charge of the batteries, and second the magnitude of the charge or discharge current at any given time.

On their website, Hawker provides a wealth of information about safe charge and discharge currents and cycle life\(^4\). They also provide minimum safe voltage and capacity, both as a function of discharge current. Using this information, initially a simple model capable of determining state of charge over time given a specified current load (source or sink) was constructed. This was accomplished by calculating the percentage of battery capacity removed or added to the model in each time step, and integrating this over time starting from some initial state of charge. For any given time step, the state of charge can then be used to estimate what the battery’s open circuit voltage (OCV) would be, if the battery was left to settle. This relationship was assumed to be linear from fully charged state to fully discharged state.

To complete the model, the battery's dynamic response to current must be added to the OCV state of the unloaded battery. For a given state of charge, this dynamic response is for the large part governed by the charge/discharge current. It is seen as voltage sag on discharge, or as applied voltage at the battery terminals when charging. One way to achieve this dynamic aspect of the response is to calculate a value in volts that can be subtracted (discharging) or added (charging) to the open circuit voltage based on current and state of charge. This value will be termed the closed circuit response (CCR). In this way, the output of the model can be seen to have three states which represent: 1) the open circuit voltage at the terminals if current demand for the given, time step is zero, 2) the terminal voltage (OCV - voltage sag) if the model is being discharged and, 3) the applied voltage at the terminals that would be needed to charge the battery at a specified current. The value of the CCR is calculated by multiplying the current by an
estimate for internal resistance ($R_{int}$) of the battery. The $R_{int}$ values are based on sign and magnitude of the current, and the battery's state of charge. The data used for this aspect of the response was obtained experimentally mainly through constant current charging and discharging.

Figure 3 shows a complete discharge cycle of a battery at a constant current of 70amps. It illustrates the two aspects of the model’s response. Note that at approximately 1080 seconds the current demand drops to zero, at this point the battery rebounds to its open circuit voltage over a period of about 300 seconds where the model instantaneously jumps up to the open circuit voltage predicted by the capacity aspect of the model. This difference is simply due to the fact that the team chose to keep the model simple and ignore the short period of battery voltage rebound observed under open circuit conditions after the battery has been loaded.

The main sources of error for the model can be categorized into two groups. First, error originating from the instruments used to collect data for the model. These have inherent inaccuracies and noise which can only be remedied to a certain extent. Second, error that originates from assumptions made when analyzing and compiling the data into the model. An example of this second group would be the method by which the value of $R_{int}$ is calculated using current and state of charge. From the raw data, values of $R_{int}$ are calculated using the following equation: 

$$OCV = CCV + I \times R_{int}$$

In this equation both CCV and I have been measured by instruments but OCV cannot. The assumption was made that OCV decreases linearly along with the state of charge. A more accurate means of estimating OCV from state of charge could potentially reduce the total error of the model and will require further testing and validation before any other conclusions can be made on how well this can diminish the error in the model.

**Genset**

The genset modeling went through two stages of iteration. The initial model was made using manufacturer data from both Robin-Subaru\(^5\) and Perm\(^6\). This model was then modified using data acquired in house with the genset coupled first with the battery pack only, and then, coupled with both the pack and the load.

The model simulates how the genset attempts to output the no-load voltage specified by the governor, while remaining within the power limitation of the EX-21. This simulation uses the in house data to calculate the maximum available current from the genset for a given system performance.
voltage, and employs proportional control to determine what fraction of that maximum current the model should output. The proportional control compares the system voltage to the no-load voltage set point of the genset and adjusts the genset output until these two values are as close as possible, taking into account the voltage drop due to the PMG’s internal resistance and the deceleration of the EX-21 allowed by the governor. A linear function was used to approximate the relation between genset voltage drop and output current.

**Complete Model (Battery + Genset)**
The model is essentially composed of the battery pack and the genset. The model has three inputs: 1) load current as function of time, 2) initial voltage of each battery in the pack, and 3) genset no-load voltage which is constant with time. The main outputs from the model are: 1) system voltage, 2) battery pack current, and 3) genset current. Some secondary outputs include: all data for the individual batteries (i.e. OCV if load was removed, state of charge, Rint, etc), as well as speed and torque of the genset. Therefore, with an input of load current over time, the model evaluates the system voltage and then the genset operating point which in turn provides both the genset and battery currents. Given a proper fuel map, the model can also use torque and speed data for the engine to determine instantaneous fuel consumption. Unfortunately the engine manufacturer was unable to supply a complete fuel map. The team is currently gathering its own data to generate a fuel map.

**RESULTS**
Figure 4 depicts the data acquired from testing of the race car. All three main outputs are shown, plus the genset’s no-load voltage (OGV) and load current are included. Negative values for battery current mean that the battery pack is being charged while positive values mean that the pack is being discharged. These tests were performed using a series string of five batteries to make up the pack. The system was loaded by applying “throttle” and brakes. The flat orange line gives the genset no-load voltage (OGV) setting for each segment of the test. This value was varied between the pack OCV and the genset’s maximum voltage so as cover the entire range of possible operating points. Note that the load current shown here is not an output of the model, but rather the input into the model.

![Figure 4: Data from vehicle testing.](image-url)
In the tests presented in Figure 4, the genset is always connected to the pack. From time 0, the throttle is increase steadily until approximately 130 seconds. At this point, the brakes are applied. This drastically increases the load current. This cycle is repeated two more times until approximately 400 seconds into the test sequence where the genset is allowed to charge the pack to approximately 550 seconds into the test sequence. Following this charging section five more throttle and brake loading cycles are performed.

The following Figures 5 and 6 show the same test sequence as in Figure 4 but with the three main model outputs superimposed over the test data.
DISCUSSION

The above section presents results obtained from a model assembled from a genset model and a battery model which were each developed independently. It must be noted that the genset model was created using data provided by component manufacturers without any in house validation of the data. On the other hand, the battery model used was a final iteration of a model that had been originally created using manufacturer data but was then remapped using in house test data as described in the battery modeling section.

This first iteration of the complete model followed the general trends of the system behaviour as seen from the test data. However, some discrepancies in this simulation were significant enough to justify further iterations of the model in the anticipation that the model would more closely match the system behaviour.

First of all it can be seen in Figure 5 that the simulation system voltage sags well below that of the actual measured voltage under heavy loads. This can be partially explained by the very low state of charge of battery pack for this test. As seen in Figure 3, the battery model shows a relatively large error a low state of charge. Battery testing has shown that the Rint value steeply increases as a battery nears the end of its charge. This already drastic change in Rint profile vs. state of charge worsens as current demand is increased. The resultant is a sharply increasing error when a high current is demanded from the battery as the battery nears an empty state of charge.

Secondly, during the section between 400 and 600 seconds, the genset was left to charge the batteries while no external load was applied. This section brings out a significant offset between real and simulated data both in Figures 5 and 6. Upon examination, one can see that while the simulation predicted too high a battery charging current, it also predicted too low a system voltage. If the battery model were operating correctly in this zone, a simulation predicting too high a current would also predict too high a voltage, and if this was the case, the problem would lie within the genset section of the model. However the observed contradiction implies an error in the dynamic response section of the battery model; specifically, the model has too low of an internal resistance (Rint) when charging. The team speculated that by increasing values of the model’s Rint data for the range of operation in question, the model’s output would more closely match the system behaviour. The exact reason for this difference between the Rint data acquired from battery testing and the perceived Rint in these tests is unknown. However it must be noted that this behaviour has been observed in all the tests performed with the race car. Further testing and data gathering is required to pin point the reason for the discrepancy.

Lastly, while not shown in the data presented Figures 5 and 6, other tests showed sections in which both current and system voltage were too high simultaneously. Such a result points to the fact that another problem lies within the genset model. These situations show the system settling down to a system voltage that is higher than the actual measured data. This settling point is determined in the genset model by the voltage drop associated with current output from the genset. In constructing this model a simple linear relationship between genset voltage drop (difference between no-load voltage and settling point) and current was employed based on data obtained from the system. However, it is believed that this relationship could be more complicated than it was originally assumed to be and that the simple linear relationship used in
the model is likely the cause of this error. Further investigation is required in order to establish concrete knowledge on this aspect of the genset behaviour.

Figure 7 and 8 shown below are duplicates of the comparison graphs above but with modifications made to the model. As can be seen in Figure 7, the discharging error previously mentioned does not improve because no changes were made to the discharge Rint data of the model in this test. However, when one looks at the section between 400 and 600 seconds in both Figures 7 and 8, the difference between the measured values and the model output has decreased. This was accomplished by, as suspected, increasing the value of the charge Rint data of the model.

![Figure 7: Actual and Re-worked Model Voltage vs. Time](image)

![Figure 8: Actual and Re-worked Model Current vs. Time](image)
Conclusion
The development of this model has enabled the McGill team to get a better understanding of the behaviour of the hybrid powertrain. The model is still being improved, but already, results from this simulation have been used to optimize the existing system. They are also being used to develop McGill's next generation compact hybrid powertrain. The McGill team believes that the knowledge gained through this modelling/simulation/validation exercise is such that the team will be able to optimize future hybrid drivetrain of similar nature even before assembly. While the time, resources, and funds invested in this modelling/simulation/validation exercise is non negligible, it is believe that this investment will be more than completely recovered on all three counts right away in the development of the second generation compact hybrid powertrain.

So far, McGill University has assembled all the infrastructure, the hardware and software capability to develop these models in house. The McGill team believes that if a common basis for modelling and simulation is established between different organisations, then models could be exchanged between organisations with a common interest. This would avoid the costly and time consuming task of each organisation having to assemble its own complete infrastructure, hardware and software capability. Furthermore, it would speed up product development time while decreasing product development cost through cost sharing between organisations with common interests.

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2 http://www.perm-motor.de/pm_e_htm/products/pmg/daten_pmg_132.htm [Aug 07]
4 http://www.enersysreservepower.com/catalogInfo.asp?id=100&brandID=3 [Aug 07]
6 http://www.perm-motor.de/pm_e_htm/products/pmg/daten_pmg_132.htm [Aug 07]