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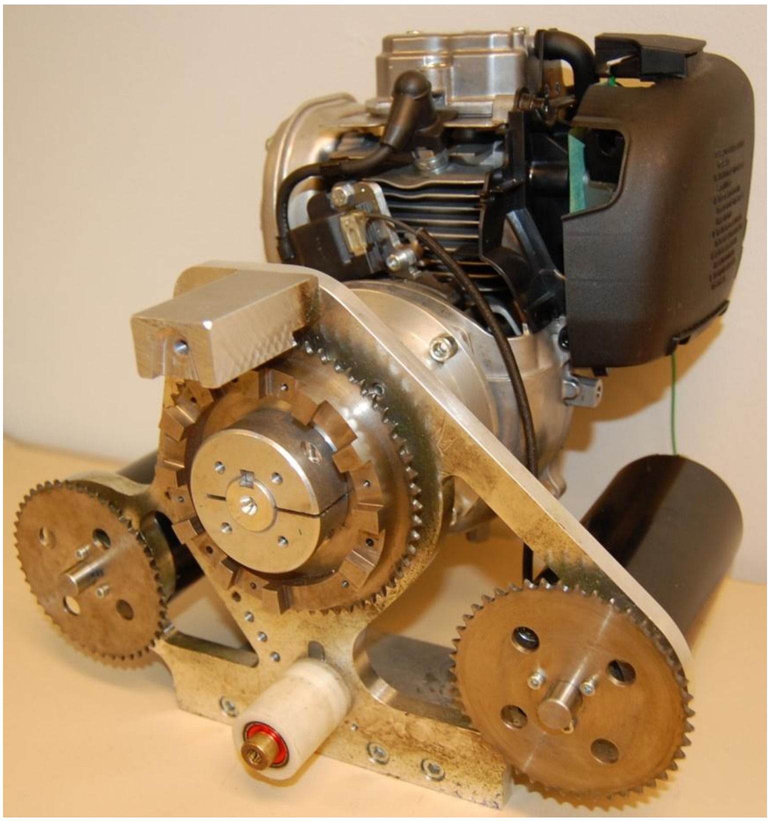

Design and construction of a hybrid vehicle driveline

Developed for an ECO-marathon car

Master of Science Thesis

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Göteborg, Sweden, 2009

Abstract

In this work a test bench for a small hybrid electrical vehicle was designed and built. In particular it was designed since Chalmers is building a car to be able to compete in Shell ECO-marathon. This car is going to be a hybrid car using petrol as primary energy and electricity as secondary source. The resulting drive train system which was first tested in the rig was a series hybrid using a 35 cc 4-stroke engine with two brushed DC-motors attached to it via a chain. These are directly connected to a super capacitor with a soft start in between to be able to connect them in a smooth way. By doing this, the generators are also used as a start engine. The drive motor is also a brushed DC-motor connected to the super capacitor via a converter. All parts of the test bench are controlled by a PLC-system. Interesting quantities are measured and logged to be able to analyze the data to calculate efficiency etc.

The strategy was implemented in Chalmers car Smarter and was competing in the Shell ECO-marathon 2009. Unfortunately the car suffered from mechanical problems and weren't able to achieve a complete race but the whole power train operated as planned.

The test bench is complete and working for a series hybrid with an ICE of about 1 kW. The test bench can be modified to a parallel electrical hybrid set-up with reasonable efforts and be used to optimize Smarter for future years.

Acknowledgements

First of all we would like give a big thanks to our supervisor Anders Lindskog at the division of electric power engineering at Chalmers for all his help, support and a lot of interesting discussions throughout this project.

We would also like to thank our examiner professor Torbjörn Thiringer for his help with structuring our report writing.

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1 Introduction

1.1 Background, Eco-marathon

The Shell Eco-marathon is a competition where the goal is to reach as far as possible on one liter of petrol. The competition consists of two classes, the Prototype class and the UrbanConcept class. There are different rules for these classes. In the Prototype class the restrictions on the vehicle isn't that hard. In the UrbanConcept the vehicle should look more like a standard car and should have four wheels.

The competition is arranged by Shell and is in its current form run since 1985. There is also an American version since 2007. In 2008 the record in the Prototype class was 3382 km and in the UrbanConcept it was 848 km.

Previous years Chalmers has competed with the prototype car Vera. They hold the Swedish record in this class of 772 km. This year Chalmers is going to compete with a newly built hybrid car Smarter to compete with in the urban class. This car will be built by students in the last part of their education.

1.2 Purpose of work

The purpose of this master thesis is to acquire knowledge and understanding about how drive system in hybrid cars works. Moreover, an important objective is to design and build a test rig for testing different drive cycles where key quantities shall be available so that the test of the driveline can be as close to real circumstances as possible. Furthermore, the aim is that when the test rig is complete it should be able to read in a data file with data of a track and desired speed. Finally the goal is that the set-up shall be constructed in such a way that it can easily be converted between a parallel and a series drive line to be able to determine which solutions is the best for various drive cycles and vehicles.

Every component of the rig needs to be chosen and analyzed in order to get the most performance out of every part. The control parameters needs to be determined and the complete drive line must be tested so that no errors can occur when put in a car. In the end, an optimal complete solution for the test rig will be determined in order to get the most distance out of one liter of fuel. This optimal solution will be implemented in this year version of Chalmers race car Smarter for competing in the Shell ECO-marathon in Germany. The test rig will also be used for experimentation and simulations for future work at Chalmers Technical University.

2 Theory

2.1 Overview of the test rig

Figure 1 shows the test rig using a series hybrid configuration. The generators are connected to the super capacitor via a soft start card making it possible to disconnect and connect in a smooth way without any high currents. The drive motor is connected to the super capacitor via a converter making it possible to current control the motor in a suitable way. Voltages and currents are measured at the generators and the drive motor making efficiency easy to calculate. The speed of the ICE is measured by the ignition signal and the speed of the drive motor is measured by the torque bench. This makes it possible to calculate the mechanical power knowing that the torque is proportional to the current in a DC-motor. Temperature is measured as well in order to shut down the system if something gets too hot. The ICE can be shut down via a relay and another relay is connected in parallel to assure that the PLC program is running to be able to start the ICE.

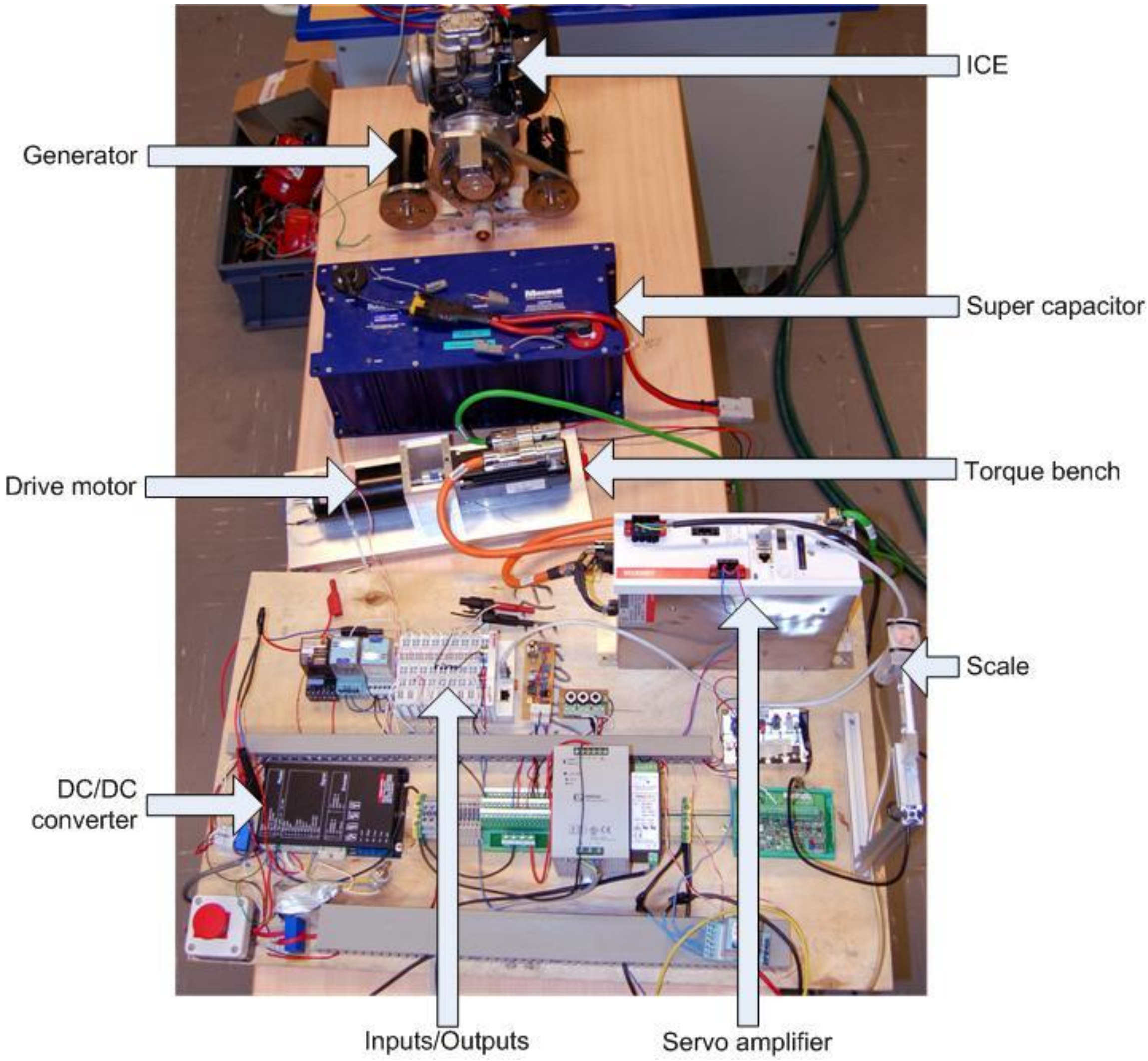

Figure 1, Overview of a series hybrid concept test rig

2.2 Series and parallel hybrid concept

Figure 2 shows an overview of both the series concept. As can be observed the series concept has no direct connection between the ICE and the wheels. Because of this all the energy from the generator charges the super capacitor and all the energy to the motor is taken directly from the super capacitor.

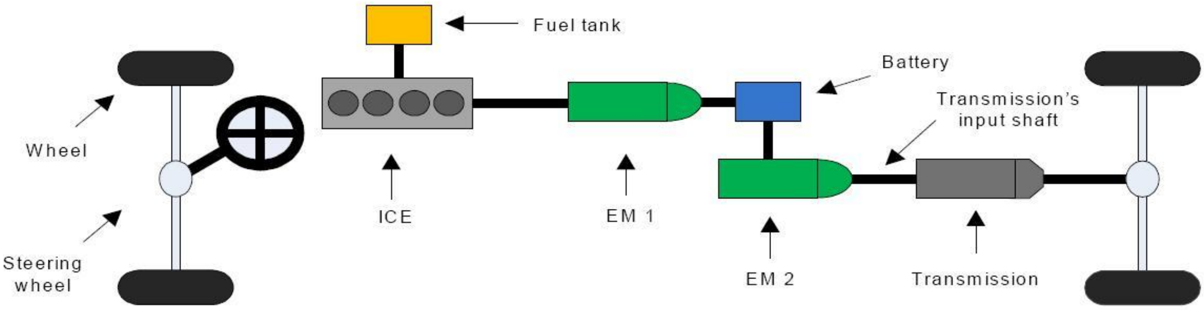

Figure 2, Overview of a series hybrid concept [1]

In the parallel concept shown in *Figure 3* the required energy goes to the wheels and the rest to the super capacitor. When the battery has enough charge the ICE is shut off and all the energy is taken from the battery. By using this motor the need for one of the electrical machines is taken away since the machine can work both as a generator and a driving motor.

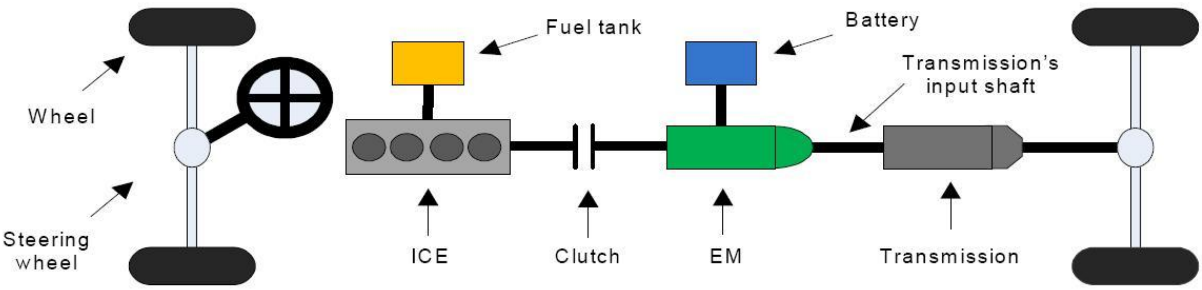

Figure 3, Overview of a parallel hybrid concept [2]

To be able to see the differences between a series and a parallel configuration of the car two basic Matlab Simulink models are created. The models assume no friction losses, and the converter efficiencies are set to 80%. The output power is set to 100W and the ICE is set to deliver 200W. The duty cycle of the ICE is then set so that the energy in the battery is the same when ending the cycle as it was when starting it. The Matlab Simulink models can be studied in Appendix A.

For the parallel configuration the duty cycle for the ICE cycle becomes 61% and the total efficiency becomes 82%. The efficiency of the ICE is not covered in this model but it is assumed to have the same efficiency for all speeds and therefore there are no difference between series and parallel configuration. The power produced or used for the different components can be seen in *Figure* 4.

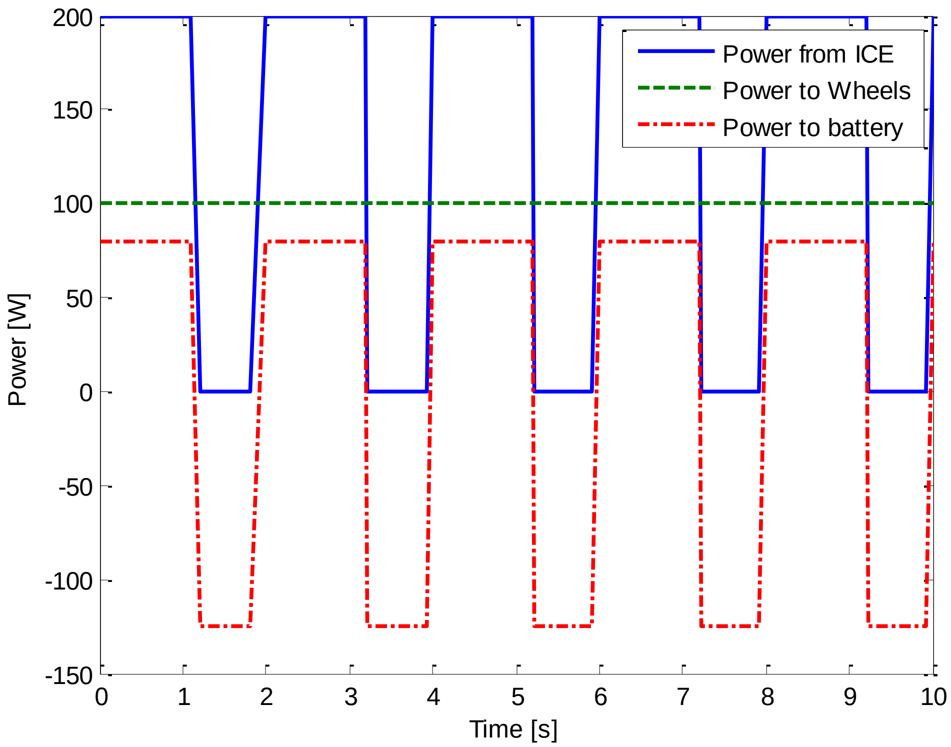

Figure 4, Power produced/used by different components in a simulation of a parallel driveline

For the series case the duty cycle becomes 78% instead and the efficiency becomes just 64%. This is because all the power produced by the ICE must go through both converters. In the parallel case some of the power can be transferred directly to the shaft without any electrical losses. The power produced or used by the different components can be seen in *Figure 5.*

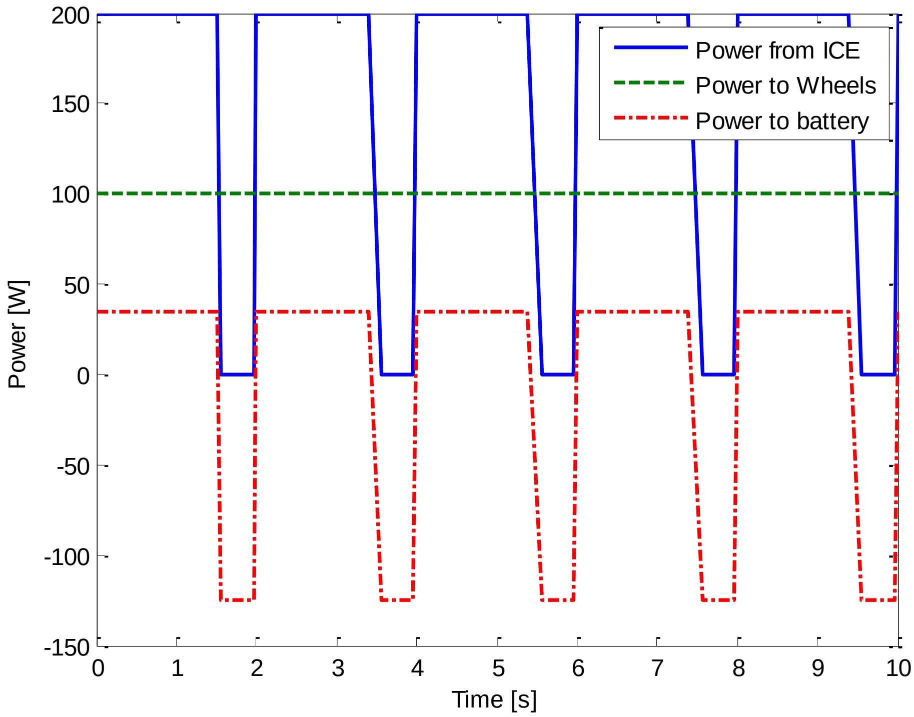

Figure 5, Power produced/used by different components in a simulation on a series driveline

With models like these the most optimal solution would have been to have an ICE without any hybrid modification. The problem is that to be able to have maximum efficiency the ICE must go with full throttle at low speed. To be able to achieve that the engine should then be much smaller than the ones in the simulations and smaller engines have lower efficiency. Another problem is that when acceleration occurs more power is needed and the period where constant speed takes place must be at a lower throttle level with less efficiency.

2.3 Test rig bottom plate

2.3.1 Aluminum bottom plate

The initial idea was to design and order a bottom plate for the test rig. It should be about one and a half meter long and about 70 cm wide. It would need some holes for attaching the different components of the test rig. The benefits with this are that it can be ordered in the exact size needed with holes in the exact right places. The disadvantage is that such a test rig cannot be modified without ordering a new bottom plate or by machines modifying the existing one.

2.3.2 T-track table

In one of the laboratories at Chalmers there is a T-track table. The second proposal was to move this table to the location of the test rig and build the test rig directly on this table. In order to do this help is needed from a moving and an elevator company. The pros of doing this are that a lot of time is saved and it could also be cheaper than other options. It will also be very easy to build everything on the table since it has a lot of tracks for attaching brackets. Since the table is made of metal it is very easy to ground it and at all times have easy access to zero potential. By doing this it is less probable that there are faults due to bad grounding. The only disadvantages are that once the T-track table is in place it is very hard to move. It may also unnecessary big with a lot of empty space on it.

2.4 Start Engine

2.4.1 Sliding DC motor with coil

One approach when constructing the start motor for the ICE is to have a sliding mechanism for a dc-motor. When a start is requested the whole DC motor is slided towards the ICE to create a mechanical connection. Applying a voltage to the dc-motor starts the ICE and by having a freewheeling mechanism the dc-motor will be disconnected from the ICE. By measuring the current to the dc-motor it is easy to know when this happens since no torque is applied at this point. The sliding mechanism is then released to avoid losses in the freewheeling mechanism.

The DC-motor needs to be fairly large since the simplest construction doesn't use a gearbox. The ICE requires approximately 2 Nm to spin in the starting region and the speed required to start it is very low. Since a gearbox was not used the DC-motor selection therefore needs to be able to produce about 2 Nm from start. Choosing a motor of this size means that it will have a fairly large radius which will make it heavy but the speed will be sufficient without a gearbox. It may also be possible to have a smaller motor and somewhat overload it. Since it will not take long time for the ICE to start this would probably not be a problem.

For the sliding mechanism a linear step motor can be used. Another way is to use pneumatics or a solenoid to make the slider go back and forth. The problems with pneumatics is that it would not be realistic to put this in the car since it will require a compressor which is too heavy and takes up a lot of space. It also requires some extra controls and valves in order to control the pneumatics.

The brackets to hold these parts will need some work and is not very basic to construct. The control for these requires two signals, one for the linear actuator and one for the dc-motor. The current also has to be measured to know when the motor is started. Once the current of the DC-motor goes down to almost zero or if it has a lower speed than the ICE it will go down to a negative value. Alternatively the speed of the outgoing shaft can be measured to know when the engine is started. When the speed of the ICE exceeds a certain preset value the ICE has started. The start motor will then be shut off and the linear actuator will go back to its starting position. This solution may be too advanced to put in the eco-marathon cars since it requires some extra space and it has some moving parts that needs to work when things are in motion and may be vibrating a lot. It is probably also the most expensive and most heavy solutions of the ones proposed.

2.4.2 Piaggio Start Engine construction

One proposal is to use a start engine from a small scooter. In this case it is taken from a Piaggio. One part needed with this construction is a bendix gear-wheel so that the starter won´t be connected to the shaft all the time. This drive works by having a twisted track to push gear-wheel "2" in *Figure 6* forward due to the acceleration and speed. As long as the speed of wheel "2" is higher or equal to the speed of wheel "1" it stays in this condition. As soon as wheel "1" gets a higher speed than wheel "2" the coil inside the construction pulls wheel "2" back again so that it is not connected to the drive shaft.

This bendix drive is directly connected to the start engine at all times. The bendix drive and start engine must then be mounted into some kind of construction that keeps everything into place. This needs to be designed and ordered for construction before it can be mounted on the T-track table.

One proposal can be seen in *Figure 7* where the ICE shaft will run through the construction and have a large sprocket on the shaft.

Figure 6, Piaggio bendix gear used to connect start motor to the ICE [6]

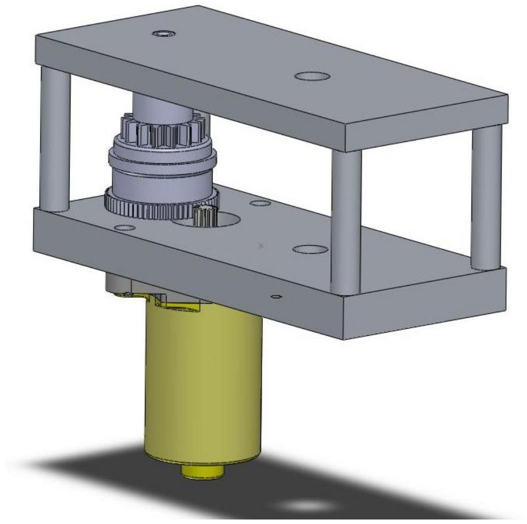

Figure 7, Proposal for start engine mechanism using a scooter start engine

The benefits with using this solution are that a lot of time is saved; it's lighter than some other solutions and it´s really cheap.

2.4.3 Using generator as a start motor

Since the generator is an ordinary DC-motor it should also be able to work as a start motor. Since it is at all times connected directly to the ICE this would probably be a very easy solution. It will force the ICE to fast go up to the speed of the generator which is directly proportional to the voltage level in the super capacitor. Since the only time that a start is performed is when the voltage level in the super capacitor is rather low the ICE will drive the generator once it has started. One problem with this approach is that it makes it much more difficult to use the external battery for starting the ICE. Therefore it is important to know how much energy that is needed for a start of the ICE, compare this with the energy required to carry the extra weight of another start motor to be able to know which solution is the most optimal.

By connecting the DC motor to the ICE, performing a start and measure the voltage over the DC motor and the current through it and multiply this with each other the instantaneous power is achieved. If this is integrated over the time it takes to start the ICE the total energy of one start is achieved. The calculation becomes

$$W_{start} = \int_0^T u(t)i(t)\,dt \qquad (1)$$

This method is the absolute cheapest and simplest since it requires no additional parts at all. The only thing that may be needed is a soft start circuit which makes the generator ramp up in speed much slower than just putting the super cap voltage straight to the generator. This is done to prolong the lifetime of the generator since the brushes will take less damage in each start. It will also be better for all shaft connections, the chain and the ICE.

2.5 Electric Motor

The choice of the electric motor to power the ECO-marathon car is dependent of the choice of hybrid strategy. In the parallel case the maximum power of the electric motor will be equal to the power needed on the wheels when the ICE is turned off if efficiency is assumed to be 100%. One way to limit the maximum power is to use the ICE to provide power the wheels for the heaviest scenarios. This may limit the maximum power required by the electric motor but the knowledge of the track must then be known in advance and the control for the hybrid car will be much more advanced. In a series hybrid the power delivered by the electric motor will be equal to the power of the wheels at all time. The maximum value of the power will be equal to the case in the parallel configuration when running without the ICE. The difference between parallel and serial configuration is the average power consumption. The serial motor will have the same average output as the wheels needs but in the parallel case the ICE will take up a lot of the energy required to the wheels and therefore lower the average power consumption for the DC-motor.

2.6 ICE

The first proposal is to use a small four stroke combustion engine with a cylinder volume of 25ccm. The first tests with this engine show that the internal ignition doesn't work when a torque is applied below 4000rpm. An external ignition would probably solve this problem. It could also be the carburetor that doesn't work properly when the air flow is very low.

Since this application requires that the engine runs at its optimal operation point the data of the engine needs to be analyzed. This data is obtained both for the 25ccm and the 35ccm Honda GX engines. *Figure 8* and *Figure 9* below shows power together with speed and the specific fuel consumption together with speed. With a configuration consisting of two generators with a chain gear in between the generators are together able to convert about 650 Watt mechanical power into electric power. *Figure 8* shows that in order to not exceed the maximum power limit of the generator the speed needs to be kept lower than approximately 4000 rpm when using a 35ccm engine. With a gear ratio of 4:5 the speed of the generator will then be 5000 rpm and this is where the generators can handle the most power. The 25ccm engine on the other hand cannot deliver much more than 650 Watts. *Figure 9* shows the specific fuel consumption at different speed. In this chart the important difference between the two engines is shown. Specific fuel consumption is a measurement that shows how much fuel the engine consumes per kWh. Since it is much more difficult to construct a small engine with good enough efficiency the GX35 have significantly lower specific fuel consumption at all motor speeds. Therefore the GX35 is a much better choice than the GX25.

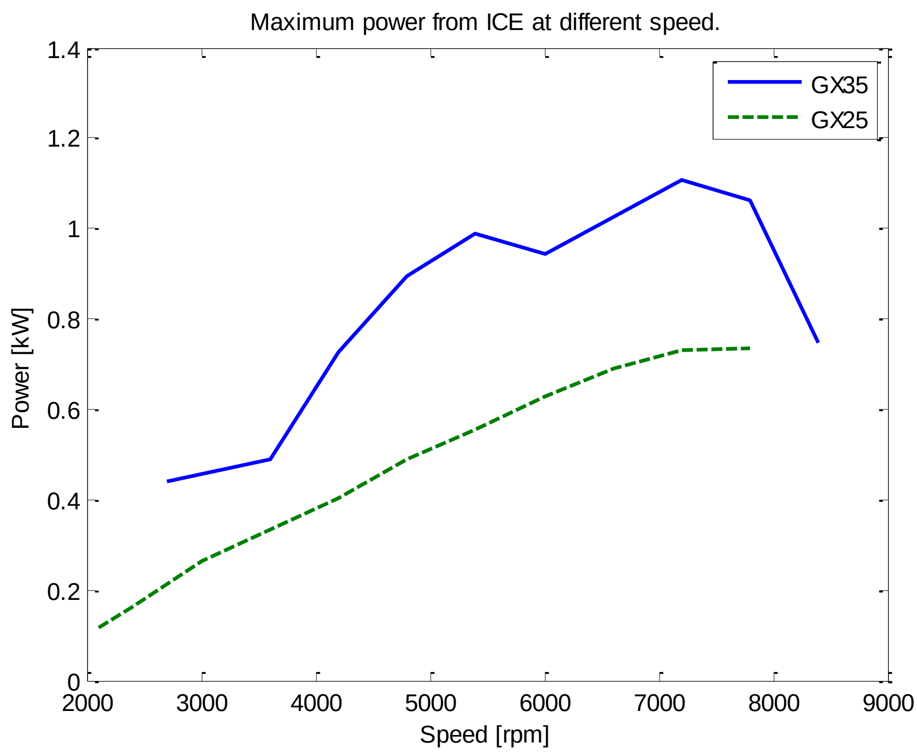

Figure 8, Maximum power from the ICE for different speeds [7]

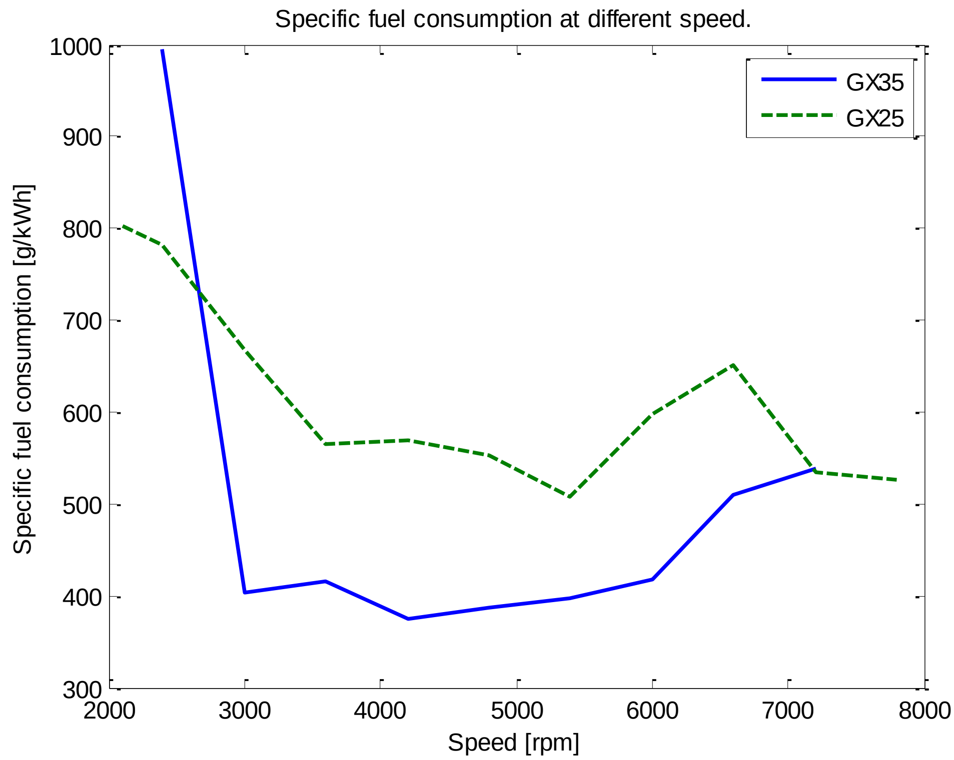

Figure 9, Specific fuel consumption for different speeds [8]

2.6.1 Speed measuring

One method to measure the speed of the ICE is to utilize the ignition signal. One problem with this is that the output signal needs to be modified before it can be measured to get a correct rpm measurement. This shaping is done with a simple voltage comparator. It works by comparing the voltage level from the ICE with a fixed voltage level at the negative input of the comparator. If the voltage is higher than this voltage the output voltage from the comparator will be the same as the drive voltage for the comparator. In this case the drive voltage is 24V and the voltage to compare with is about 3V. This voltage to compare with can be adjusted by turning the potentiometer connected to the input of the comparator. This is necessary to calibrate it for different ICEs and pickup distances for the ignition system. Another reason why this is important is that the voltage peak is different at different rpm. *Figure 10* shows the signals at low speed and *Figure 11* shows the signals at high speed. The different plots are signals at different parts of the circuit.

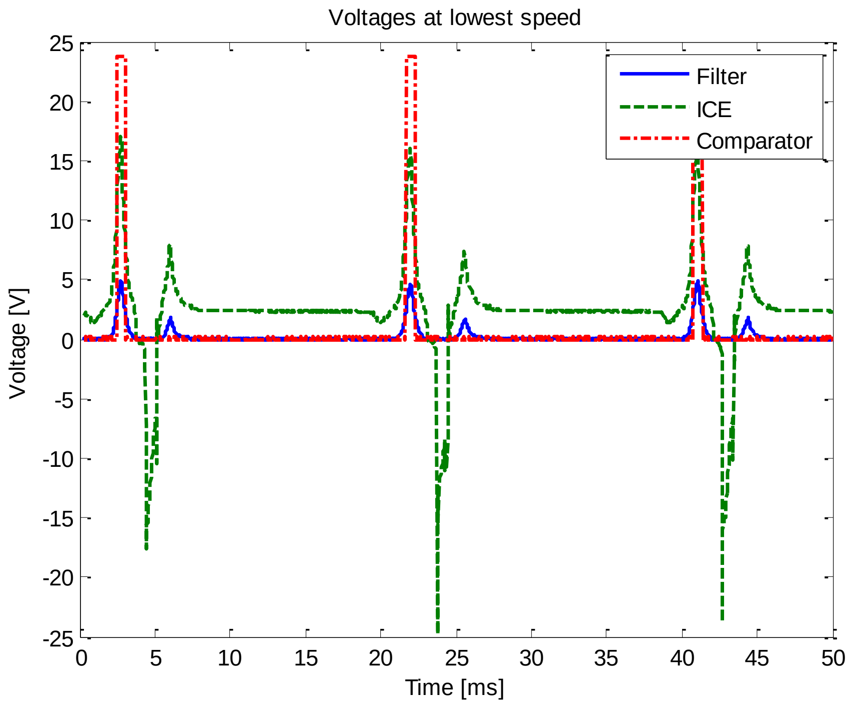

Figure 10, Voltages at different places in the RPM measurement circuit at low speed.

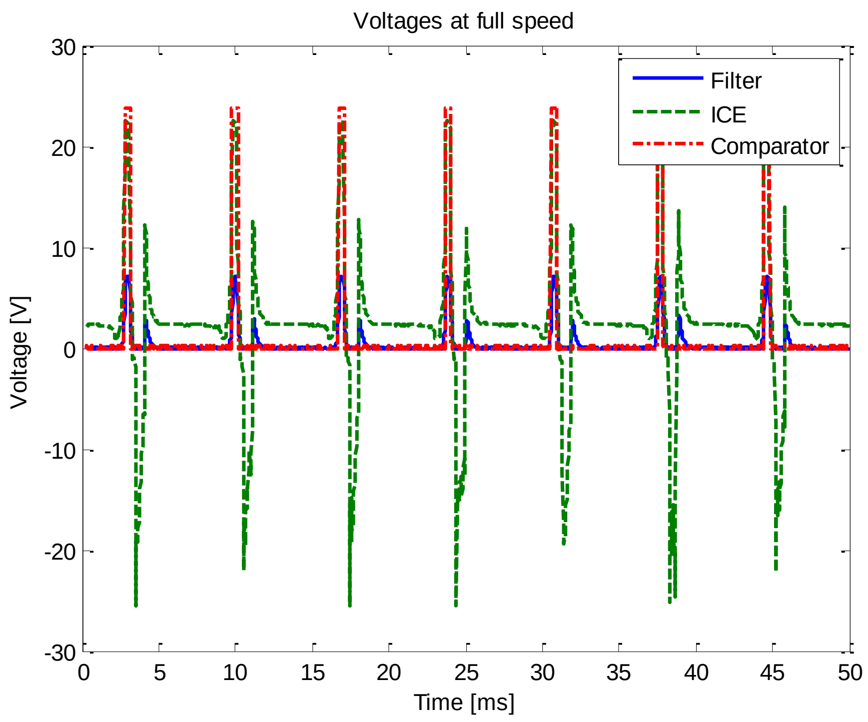

Figure 11, Voltages at different places in the RPM measurement circuit at high speed.

When measuring the output signal from the ICE it´s seen that it is peaking about 60 volts. This voltage is too high to put directly into the comparator. Therefore a voltage divider needs to be used to get a lower voltage into the comparator. This divider makes the voltage three times lower than before.

When testing this method there are still some unwanted peaks due to the high voltage drop when there is a flashover in the sparkplug. The first attempt to get rid of these peaks was to add a low pass filter in order to lower the rise time of the system and get some longer square pulses out from the comparator. With this method there are still some unwanted peaks so that wrong measurements are obtained. The second attempt to get rid of these peaks was to double the resistance in the filter so that even smoother signals are obtained as inputs to the comparator. This is still not enough because the amplitudes of the negative peaks are too high. The third attempt to fix this was to add a diode at the input to get rid of the negative part of the signal completely. When doing this a good positive square wave between 0V and 24 is obtained. The final circuit is shown in *Figure 12* below. The output signal from this circuit can then be sent to a counter in order to get the speed of the ICE. In parallel with the output signal there is a protective zener diode. If the output voltage is higher than the specific zener diode voltage drop the diode starts to conduct and by this protect the plc system from over voltages. The same kind of protection is also used on the input to the circuit in order to protect the circuit itself from over voltages.

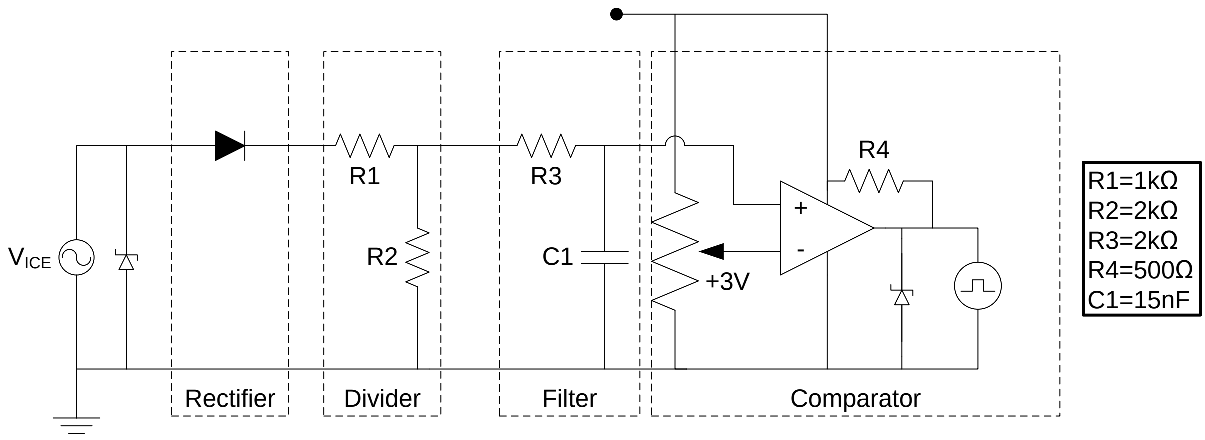

Figure 12, Schematics of RPM measurement circuit

2.7 DC/DC Converter

A converter is used to change the voltage level from one level to another. This is needed because the dc motor shouldn't have the same voltage applied to it all the time. If the super capacitor would have been connected directly to the DC-motor the current would be extremely high until the DC-motor would be up to speed corresponding to the voltage in the super capacitor. If this was done in the car this time would be very long and the motor would be thermally damaged. The rest of the power train would break as well because of this high torque. To achieve a smooth acceleration the voltage applied on the motor needs to slowly increase. This is handled by the converter. The voltage can be set to any level needed, giving any speed needed, and some converters can apply the voltage in the opposite polarity making the motor spin backwards.

If the converter would operate without any losses the power in should be equal to the power out and

$$U_{in}I_{in} = U_{ut}I_{ut} \quad (2)$$

This is however not possible and a converters efficiency is normally around 90 % depending on the operating case and the power dimension of the converter.

3 Test rig

3.1 Driveline Concepts

In order to know which solution that is the most optimal the test rig will eventually be designed so that it can be easily converted from a parallel drive line to a series drive line. When converting it to a series drive line some extra components need to be added. The DC-motor used in the parallel version for both driving the car forward and charge the batteries needs to be split up into a separate generator and a separate motor. Since there can be different speeds on the generator and motor in a series drive line some extra sensors needs to be added to measure this. Also the voltage, current and temperature needs to be measured on the extra motor. The overview of the parallel and series construction is shown in *Figure 13 and Figure 14.*

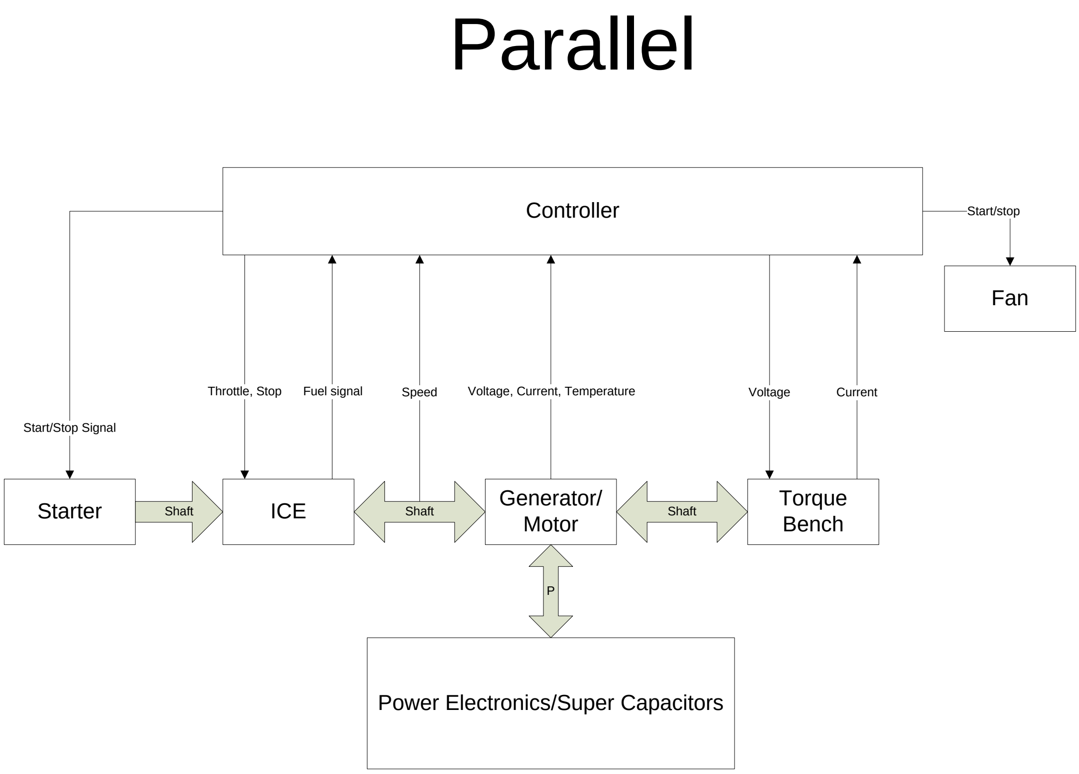

Figure 13, Overview of a parallel drive line

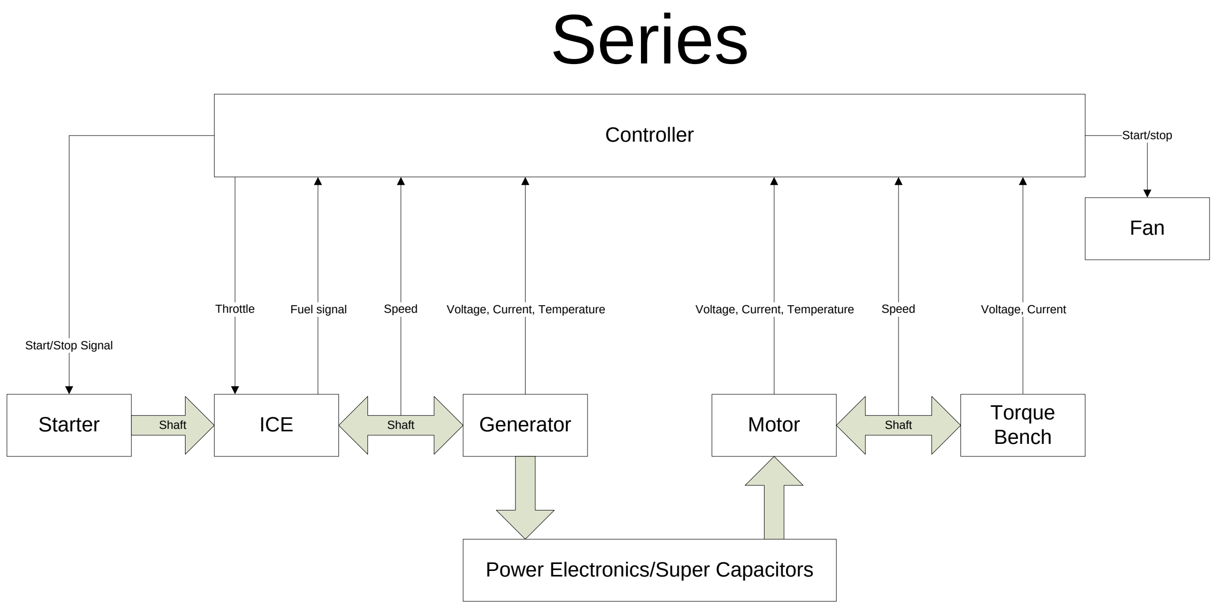

Figure 14, Overview of series drive line

3.2 Driveline Overview

The test bench built up can be seen in *Figure 15*. The main parts are the generators, the super capacitor, the converter, the dc-motor and the torque bench. The generators can be connected to the super capacitor if a control signal is given from the PLC to the soft start. The dc-motor can be connected if an enable signal is given from the PLC as well as a desired speed or torque depending on the mode the converter is operated in. The torque bench automatically applies a counter torque according to the formulas in the PLC software. To be able to start the ICE the software needs to be running because a signal is needed on the protection signal so that the short circuit of the ignition signal isn't enabled. The engine can then be set to run or stop by the killer signal.

The measuring signals can be seen to the right in *Figure 15*. The voltage measurement needs to be scaled down to be able to match the voltage region of the input card. The measurement of the voltage of the DC-motor is done with a differential probe which gives a matching voltage to the input card. Current is measured with a LEM module which doesn't interfere with the object measured. The module produces a current proportional to the current measured and this current is sent through a resistor where the voltage is measured.

The speed of the ICE is measured with help of a filtered signal from the ignition coil. This is then measured with the software to determine the speed. The speed of the generators is calculated with the knowledge of gear ratio of the sprockets.

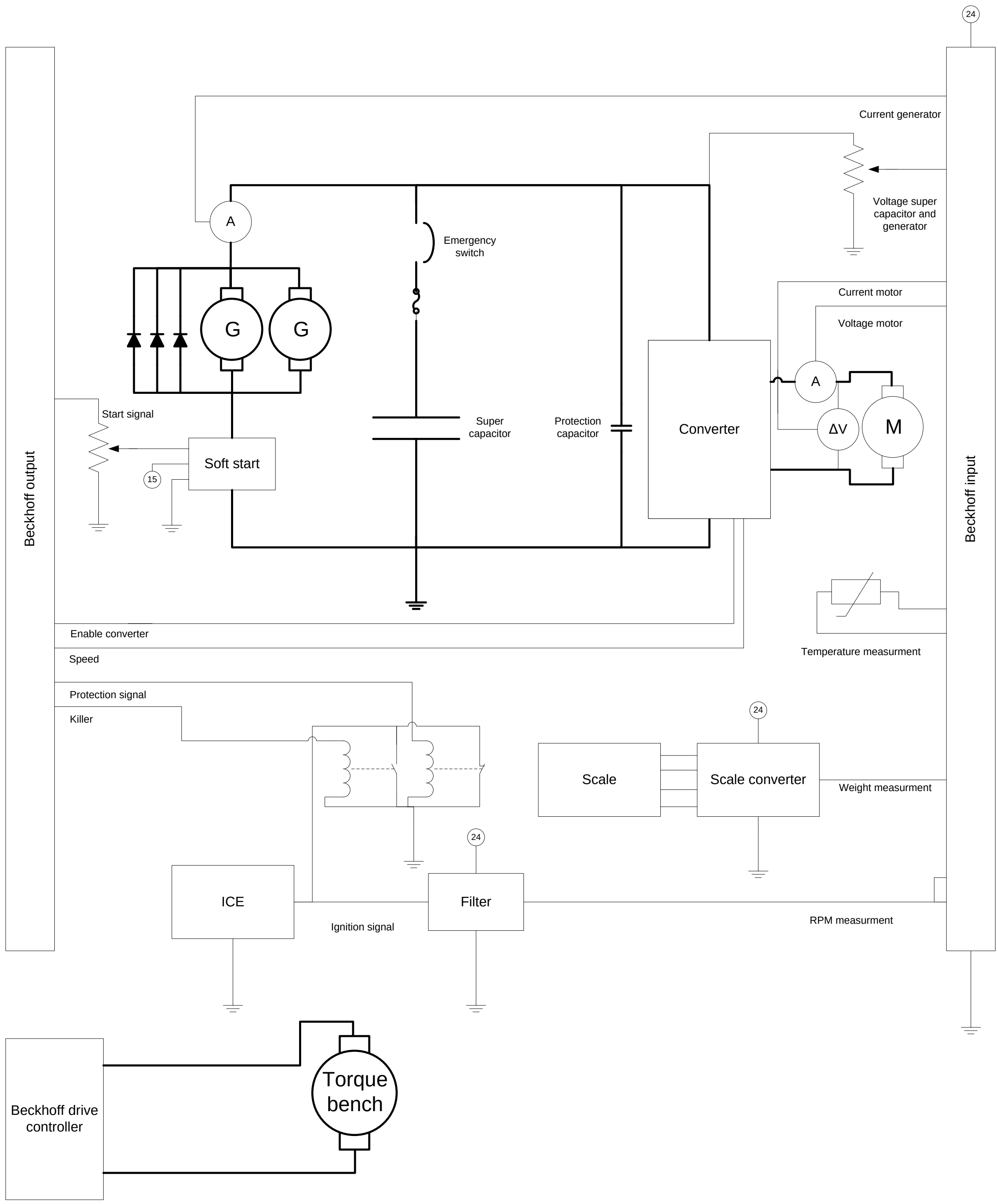

Figure 15, Overview of test bench with measurement signals and control signals

3.3 ICE

3.3.1 Start engine

Since after calculations it has shown that the most energy efficient start method to use in the driveline is to start the ICE by using the generators connected to it. This is because it will put almost no extra weight at all onto the driveline and it is the absolutely easiest way to start the ICE.

3.4 Electric Motor

The electric motor chosen to drive the car forward is the Maxon RE65 36V is a brushed DC-motor. The efficiency of this motor is very high and it is possible to over speed it to get even better efficiency. The rotor is completely ironless minimizing the inertia. The rotor only consists of the winding so the stator is placed both inside and outside the rotor. The rotor can be seen in *Figure 16* as part 5. If operated at too high speeds the winding will be forced out to the stator and it will break due to friction.

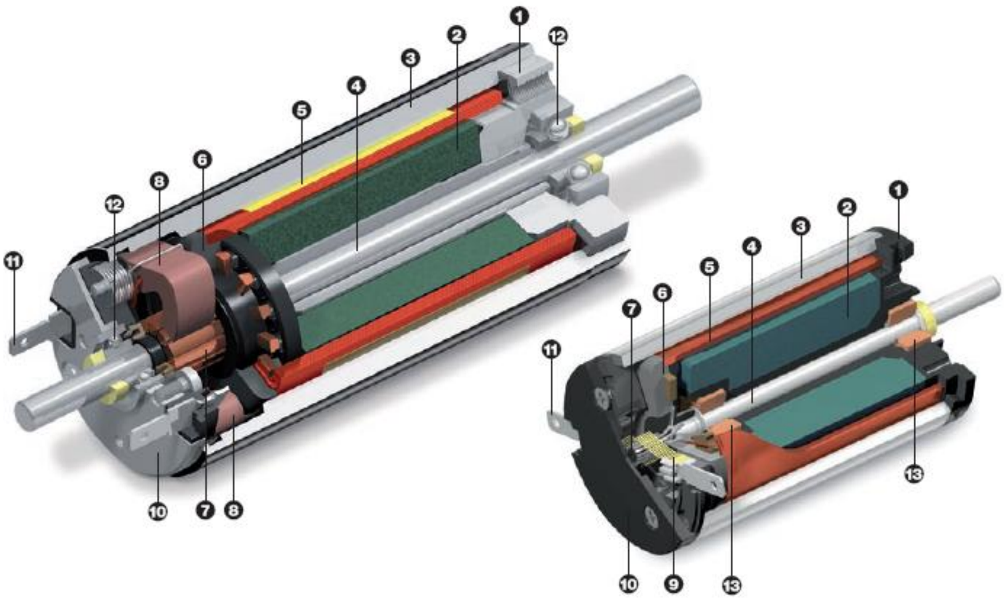

Figure 16, Maxon RE65 series brushed DC-motor [3]

The motor uses permanent magnets so no power is needed to create the magnetic field. The permanent magnets used are Neodymium magnets which are very powerful in prospect to the weight.

A lot of accessories are available to the motor such as tachometers and gearboxes. Since the speed is measured in the torque bench there is no need for a tachometer and a gearbox is unnecessary because the parameters that the torque bench uses can be modified to simulate a gearbox.

The power needed to be produced by the motor is both losses in the mechanical system as well as friction and air resistance. The car will use about 130 W when travelling at 25 km/h according to simulations which responds to about 4000 rpm at the motor axis. This gives a torque of

$$T = \frac{P}{\omega} = \frac{130*60}{2\pi*4000} = 0{,}3\ Nm \tag{3}$$

Assuming that the friction force is constant it can also be assumed that this rolling resistance gives a constant torque. The 36V version of the Maxon RE65 can deliver 0.645Nm [4] giving 0.345Nm available for acceleration. The acceleration this gives to the car becomes

$$A = \frac{F}{m} = \frac{T\frac{\omega_{nom}}{v_{nom}}}{m} = \frac{0{,}345*\frac{418{,}9}{6{,}94}}{75} = 0{,}277\,\frac{m}{s^2} \tag{4}$$

This acceleration will be constant since the motor produces a constant torque and the rolling resistance is assumed to be constant. The air resistance is usually acting as the square of the speed but is much smaller than the friction losses since the car is operated a low speeds. With an acceleration of 0,227 m/s^2 the car will be up to speed in

$$T = \frac{v}{a} = \frac{6,94}{0,277} = 25\ s \tag{5}$$

This is a little too long time but the motor can be used at twice its rated torque at a time longer than the acceleration time without being damaged.

3.5 Generator

To be able to charge the super capacitors, a generator s needed. A brushed DC- motor is used since they have high efficiency. The DC-motor is the same as the generators and handle a current of 7 amperes continuously and has a nominal speed of 3550 rpm but the manufacturer states that it will hold for 5000 rpm. If running at this high speeds the power produced will be about 350 watts which is a little too low since the ICE produces around 600 watts. Two generators are therefore connected to the ICE through a chain to be able to select different speeds for the ICE and the generators. The benefit of having different speeds is that the generators have higher efficiencies at higher speeds and the ICE has it optimal speed of around 3500-4000rpm according to *Figure 9*. The generators will also induce a voltage proportional to the speed and by running them at 5000 rpm the voltage will match the super capacitor voltage.

When these two DC-motors are connected in parallel with each other it is very important that they have the same characteristics. If this is not the case, one generator will take care of all the current produced or even run the other engine around.

When the super capacitor is connected to the generators they will spin up to a speed proportional to the voltage level in the super capacitor. When the voltage level of the super capacitor is low the ICE will revolve at low speed and then as charging is in progress the voltage level will go up and increase the speed of the ICE. This span of voltage will be fairly low and the ICE has good efficiency at this span. Because of this the generators can therefore act as a start motor as well.

3.6 Torque Bench

To be able to test the equipment as accurate as possible we need to connect the DC-motor to a torque bench. This torque bench then has to be configured to put some torque to the DC-motor in an accurate way depending on for example speed and acceleration. The Forces applied on the car is both aerodynamic, friction and the force from the motor. The acceleration of the car will then be

$$ma = -F_{friction} - F_{airresistance} + F_{motor} \tag{6}$$

The torque needed to be applied by the break will become

$$F_{break} = -F_{motor} = -ma - F_{friction} - F_{airresistance} \tag{7}$$

This force will act in the opposite direction to that of the dc motor. The acceleration of the vehicle is proportional to the acceleration of the DC-motor. The friction force can be assumed to be constant when the vehicle is moving, the air resistance force can be assumed to be proportional to the square of the speed. Knowing that the speed is proportional to the rotation speed of the DC-motor and that the force of the break is proportional to the torque the equation above can be written as

$$T_{break} = K_{friction} + K_{air}\omega^2 + k_{inertia}\frac{d\omega}{dt} \quad (8)$$

for speeds larger than zero. The friction force when starting the car is actually fairly large but is neglected here since it is under a very short time so it doesn't contribute much to the energy consumption.

The break motor selected for this purpose is a Beckhoff asynchronous motor with a control system which is easily implemented with the PLC. All feedback signals are easily obtained in the PLC and the desired torque is sent to the break control system without any additional gadgets. This torque without the acceleration force taken in consideration is shown in *Figure 17* below.

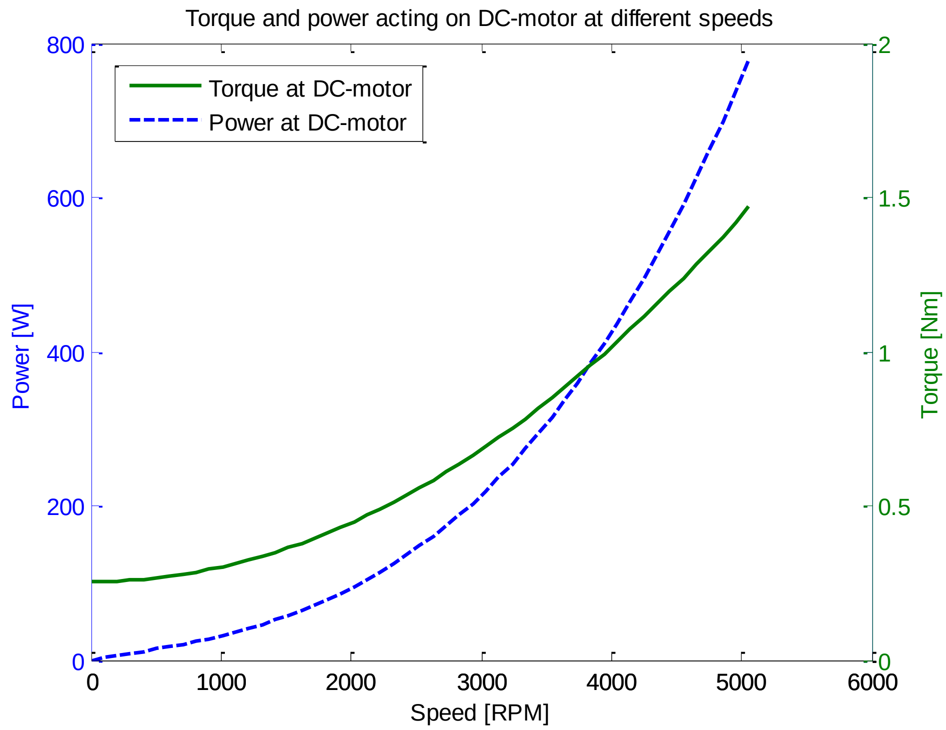

Figure 17, Torque applied for different speed of the drive motor. Acceleration torque not included.

3.7 Control System

3.7.1 Needs

The test bench should be able to measure and control different parts. The system should be easy to modify and the program in the controller should be able to log the operation.

The measurements are required for two reasons. One is that the control system needs data to be able to control. The other reason is for logging purposes and to be able to determine efficiencies for the different components. The parameters needed to be monitored are different depending on the hybrid strategy. In *Figure 13* and *14* the parameters for series and parallel hybrids can be seen.

The controller is required to actuate different systems depending on the variables measured. A control strategy is to be made and be easy to modify when something is changed in the system or when some parameters are to be changed.

The control system and the measurement system should be as compatible with each other as possible so that changes can occur with as little effort as possible making if simple and easy for people working with the test rig even if they don't have the knowledge about how it is build.

3.7.2 Sensors

3.7.2.1 Fuel Consumption

To be able to measure the energy consumed in a test cycle the fuel is weighted by a scale. The size of the scale can be calculated with the knowledge that the car uses about 130 W when driving in 25 km/h and this is the most common working point. The energy consumed in one test cycle can be calculated as

$$W_{wheels} = \int_0^t P\, dt \quad (9)$$

Assuming that P is constant at 130 W the energy consumed at the wheels becomes

$$W_{wheels} = P * t \quad (10)$$

The energy needed to be transformed with the ICE will be the energy consumed by the wheels divided by the total efficiency of the system which usually is around 0.3 for a petrol engine of this size. This number is just estimation and is only used to calculate the size of the scale. The energy consumed by the petrol engine then becomes around

$$W_{petrol} = \frac{W_{wheels}}{0.3} \quad (11)$$

To be able to achieve an accurate value of the fuel consumption in the test rig the scale must be able to measure the weight of the fuel in a good way. The force applied at the scale at the start of the run will be measured as well as the force at the end. The force in the start will be measured according to

$$F_{app,start} = F_{start} \pm error \quad (12)$$

The force at the end will be,

$$F_{app,end} = F_{end} \pm error \quad (13)$$

The error for most scales is proportional to the maximum force the scale can measure. The total mass difference will then become

$$M_{app} = \frac{F_{app,start} - F_{app,end}}{g} = \frac{F_{start} - F_{end} \pm 2 * e * F_{max}}{g} \quad (14)$$

The error in the worst case scenario will be equal to

$$\frac{M_{app} - M}{M} = \frac{\pm 2 * e * F_{max}}{F_{start} - F_{end}} \quad (15)$$

Make this equation as equal to 0 as possible F_{start} should be as big as possible and F_{end} should be as small as possible. This means using the whole range of the scale. The scales we have to choose from has an e=0.1% and a F_{max}=1 N. Applying this to equation above with a run of $F_{start}=F_{max}$ gives according to (15)

$$\frac{M_{app}-M}{M} = 0.2\% \tag{16}$$

which is approved. 1 N of petrol has the mass of 102g. The energy content of petrol is equal to 49.1MJ/kg which gives the energy of 102g of fuel equal to

$$W_{petrol} = 5\ MJ \tag{17}$$

(10) and (11) gives a running time of

$$t = 11538s\ =\ 3.2h \tag{18}$$

This is a sufficient maximum limit. The lowest run time will be about 15 minutes in our tests. The energy content in the petrol will according to (10) and (11) be equal to

$$W_{petrol} = 0.39MJ \tag{19}$$

The mass of that fuel becomes

$$M = \frac{0.39MJ}{49.1\frac{MJ}{kg}} = 7.9g \quad (20$$

The start force F_{start} then becomes

$$F_{start} = 0.0079g = 0.077N \tag{21}$$

With a F_{end} =0 the error will according to (15) become

$$\frac{M_{app}-M}{M} = 2.6\% \tag{22}$$

This value is a bit too high but this case is the extreme value. If the value is too high when measuring F_{start} the value will probably be too high when measuring F_{end} as well. This makes the error go to zero.

The chosen scale is therefore a good choice with an error of below 3% at a running time of 15 minutes and a maximum running time of around 3 hours. The accuracy increases with longer running times and the maximum error becomes 0.2%. The efficiency of the system is just estimation and can just as well be 10% depending on how good the carburetor or the injection system is calibrated. The accuracy for a 15 minutes run will then increase. The maximum running time will on the other hand decrease but an hour is good enough.

3.7.2.2 Temperature Measurements

The temperature of different components is measured to avoid the components to be damaged. PT100 thermistors are connected directly to a Beckhoff terminal EL3204 making readout simple. The values are then read into the PLC program where different safety precautions are made due to over temperature.

If the generators become too hot the PLC must short circuit the ignition signal making the ICE to stop. The super capacitors should also be disconnected.

If the DC-motor gets to hot a signal to the power electronics must be sent making the DC-motor disconnected from the super capacitances. The torque bench must be disconnected as well.

If the ICE gets to hot the same procedure as for the generator must be applied.

For all of these errors a message must be displayed on the GUI of the PLC.

3.7.2.3 Current Measuring

To measure the current from the generator a LEM module is used. This module needs to be supplied with both positive and negative voltage. To supply this module and possible other modules a special DIN mounted voltage source is used that supply the circuit with ±15V. To get the best accuracy possible the current carrying cable goes through the LEM module twice. A resistor is then connected to the LEM module and voltage is measured over this resistor. This voltage is taken into the computer and corresponds to a certain current through the module. This method is also used for measuring the current to the DC-motor.

3.7.2.4 Voltage measuring

Voltage is measured at different components to be able to calculate electric power and to monitor the super capacitor. The voltage measured is supplied to a voltage divider to be able to match the input on the A/D converter. The resistors in the voltage divider are set to a value about 10 times smaller than the input resistance of the A/D converter so the measurement becomes reliable. The accuracy of the resistors isn’t so important since a calibration in the software is very simple to do. The most important thing to handle is to see to that the maximum voltage measured corresponds to the maximum value of the A/D converter to achieve the best accuracy. But it may never exceed this level because then the A/D converter will give the wrong value and it may also break. Since the converters are working with high switching frequencies, the switched output voltage may be hard to measure right. To get accurate voltage readings the sampling frequency must be at least ten times higher than the switching frequencies. Since this is not the case with this measuring system a low pass filter with a cut of frequency of about 50Hz is used. Using this method, the voltage measured is only the DC component from the converter. Because of this, this measurement reading is no longer depending on the switching and sampling frequency.

3.7.3 Actuators

3.7.3.1 Start Relay

To start the electric motor some kind of relay must be used. There are some different choices available when choosing a relay. The problem in this application is that it must be able to handle high currents without too high losses. Another problem is that when just putting a voltage to the generator the torque required to make both the electric motor and the ICE to start rotating is very high. Therefore the currents in the first moments of the start get very high as shown in *Figure 18.*

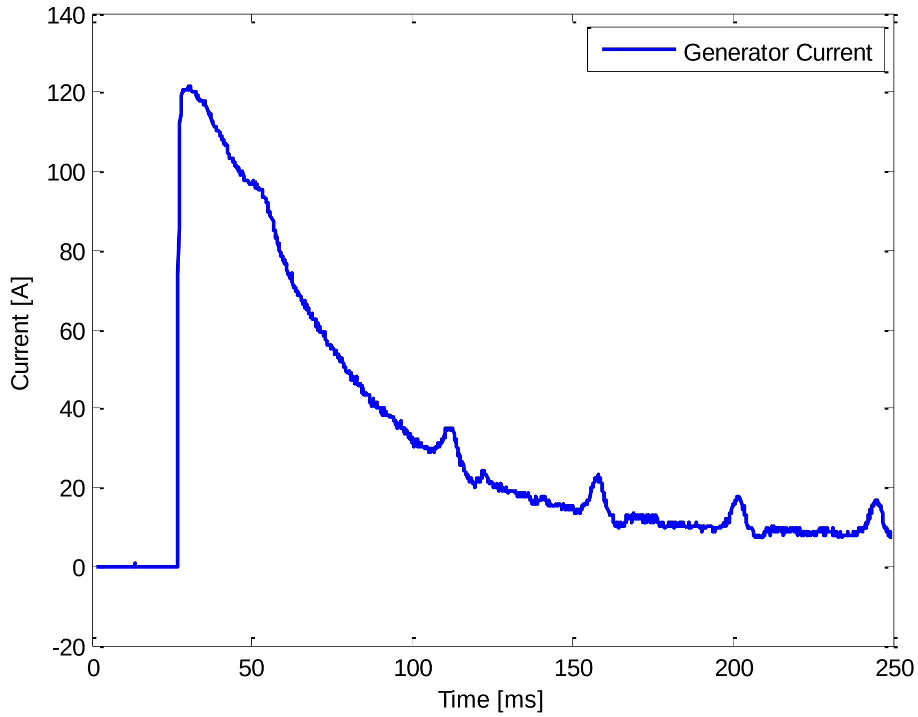

Figure 18, Generator current when directly connecting the capacitor to the generator

This will eventually damage the brushes in the DC-motor and shorten its lifetime. It will also contribute to higher losses due to that the losses are proportional to the rms value of the current. Therefore a soft start of the electric motor is required to prevent the current from having to high peak values and by this spare the brushes and get lower losses. There are some different ways to do this.

One design is to use an inductance to make the system current slow. The same inductance will also function as a low pass current filter. This solution would probably work as a soft start but will have all the disadvantages described in *Chapter 5.3.*A start with this configuration is shown in *Figure 19* below.

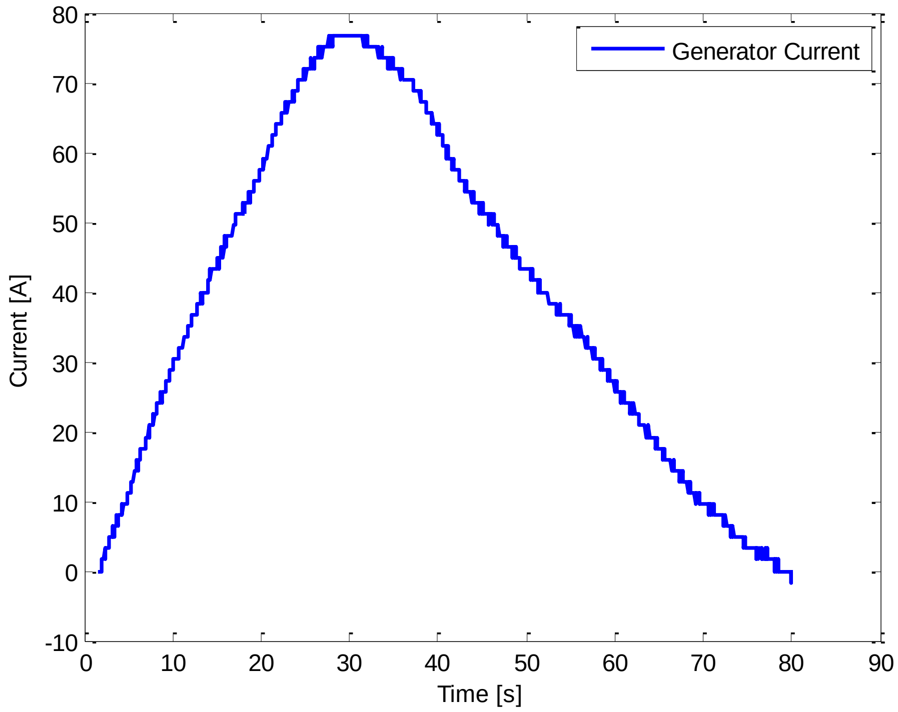

Figure 19, Generator current when connecting the super capacitor to the generator with a large inductor in series

Another simple way to do it is to use two different relays. This layout is shown in *Figure 20.* At start a starting signal is sent to relay one which is connected in series with a resistor. This resistor limits the current to the motor so that it will not exceed a certain limit. By doing this there are high losses in the resistor. Therefore another relay is needed. This relay is closed once the correct speed of the motor is reached. When this relay is connected the resistor is not connected anymore and therefore the losses are minimized.

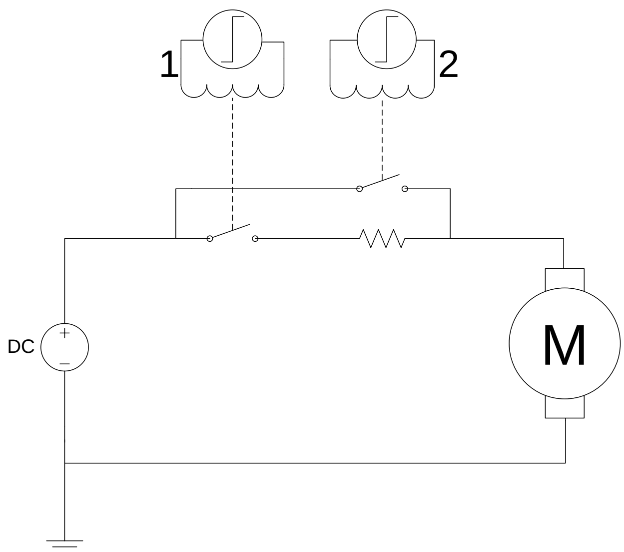

Figure 20, Soft start using mechanical relays to first start through a resistor and then directly

Another way to design a start relay is to use some MOSFETs and switching circuitry. This is a much cheaper solution and some weight is saved. The design is shown in *Figure 21.* One problem with this is that there will be some losses in the transistor since it has an on state resistance when it is conducting. If more transistors are connected in parallel the total on state resistance will be lowered. In the considered case there are four transistors in parallel. The transistors are controlled from a 24V output source that is controlled from the PLC-system. Since 24V is too high for the MOSFETs this voltage must be divided to a lower voltage. This lower voltage is applied to the gate of the MOSFET and the transistor starts to conduct. Because of internal inductance in the motor the current has to keep flowing a while when the engine is shut off. This will build up a voltage at the transistor source. Eventually this voltage gets to high and the transistor will break down. To prevent this some freewheeling diodes are used in parallel with the motor. Then the current keeps flowing through the diodes and eventually decay due to the internal resistance of the motor and the internal back-emf of the motor.

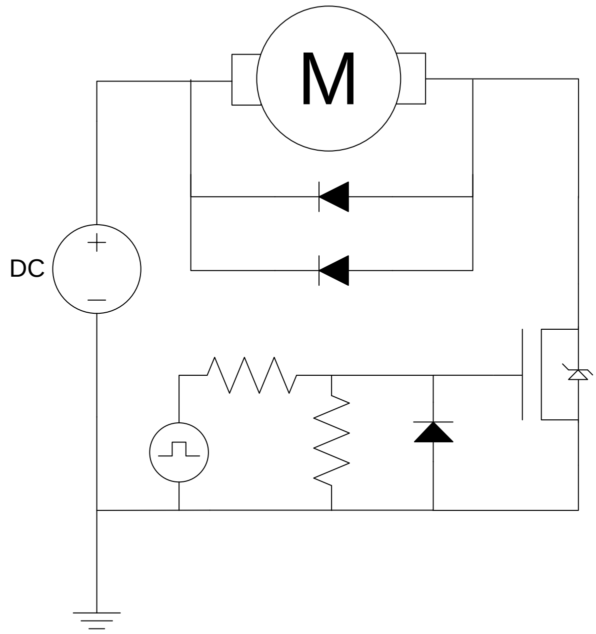

Figure 21, Soft start using a transistor to pulse the capacitor to the engine with an increasing duty cycle

Another possibility using the MOSFETs is to improve this construction even more and insert a soft start of the motor an RC-circuit can be inserted where the rise time is controlled by a capacitor which is charged through a resistor. The higher the resistance is the slower the capacitor will be charged. The same goes for the capacitor. If the capacitor has a higher capacitance it will store more energy and take a longer time to charge to a certain voltage level. When calculating the rise time the following equation is used:

$$t_r = 2.2\tau = 2.2RC \tag{23}$$

The problem with this solution is that when the MOSFET is partially on the resistance between source and drain is much higher than when it is fully on. Therefore with high current the power dissipated by the MOSFET gets very high. When trying this version of a soft start the power in the MOSFET got to high and the transistors broke down.

The next try with a soft start is to use a ramped up pwm signal to the gate of the transistor. The pwm signal is generated by an Atmel processor. By doing this the MOSFET is first on for a short time and then off for a longer time. Next cycle it is on for a little bit longer and the off. In the end the transistor is fully on. This solution is shown in *Figure 22* below.

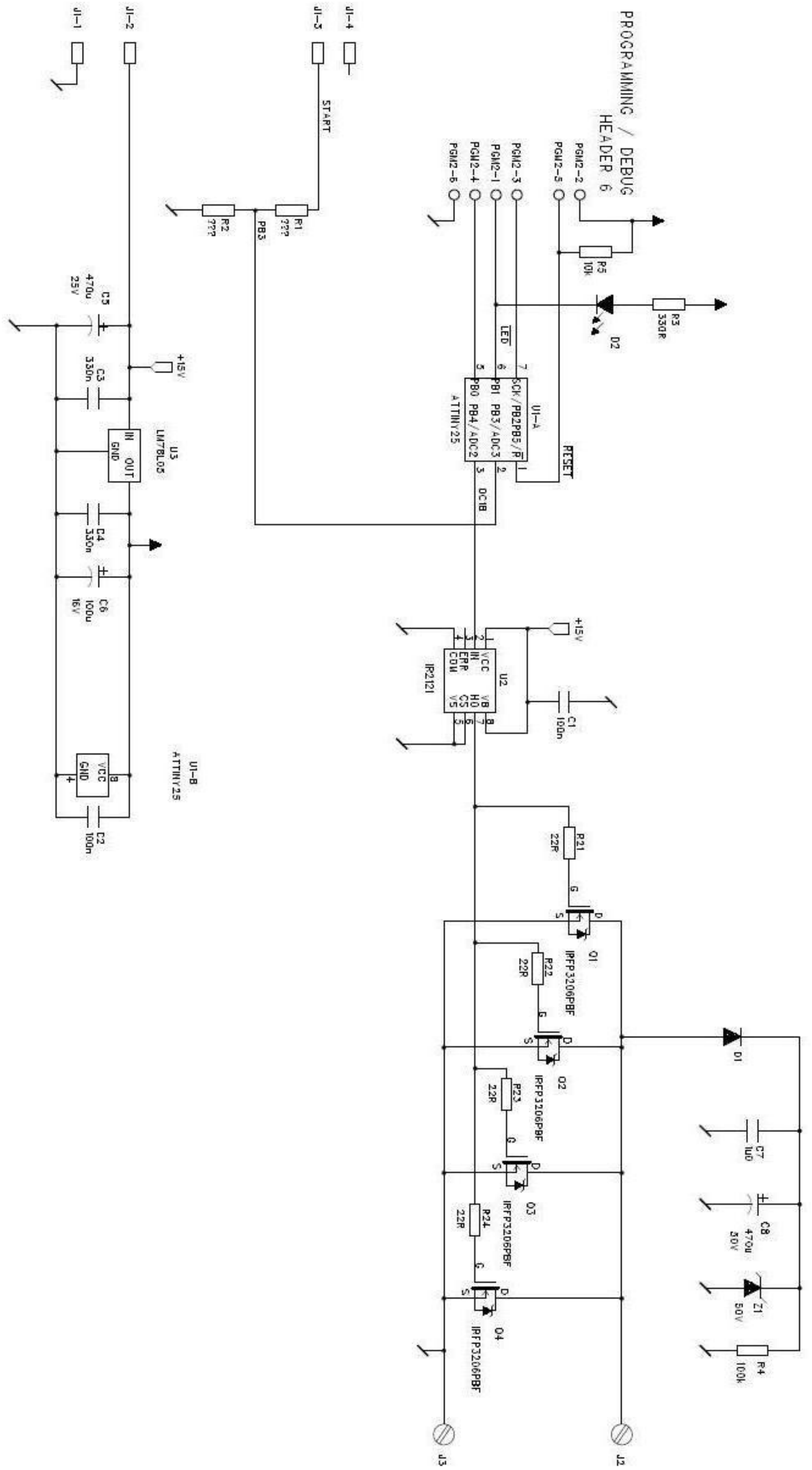

Figure 22, Schematics of soft start used to pulse the super capacitor to the generators [5]

When a start signal is applied to JK-3 the processor starts to ramp up the pwm signal with increasing duty cycle. After about a second the duty cycle reaches 100% and the MOSFET is fully conducting. According to the rules in eco-marathon a red light needs to be visible when the engine is starting. This processor is also used to light this lamp. The signal on PB1 on the processor is inverted so that it is high even though the diode in the schematic is lit. It then drives a transistor which lights the lamp. This lamp is lit for the same time as the ramping up of the pwm signal is active. Up to the right of the circuit scheme there is also a protective circuit with the function to take care of the energy from the inductance in the cables when the MOSFETs stops to conduct. This circuit consists of a diode, some capacitors, a zener diode and a bleeding resistance. The diode is there so that the protective components only take care of positive over voltages so that energy transfer back and forth will not occur. It will also make sure that the capacitors will not be short circuited every time the MOSFETs starts to conduct. If that were to be the case the capacitors would have been short circuited several thousand times during a start. The capacitors takes care of some fast peaks, one of the capacitors are really fast and the other one can store more energy. When the whole system is eventually shut down the bleeder resistance will slowly discharge the capacitors. The last part of the protective circuit is a 50V zener diode which will conduct and dissipate energy if the voltage exceeds 50V.

When this version of the soft start is tested it works fine when the super capacitor have a low voltage level. The result is shown in *Figure 23* below.

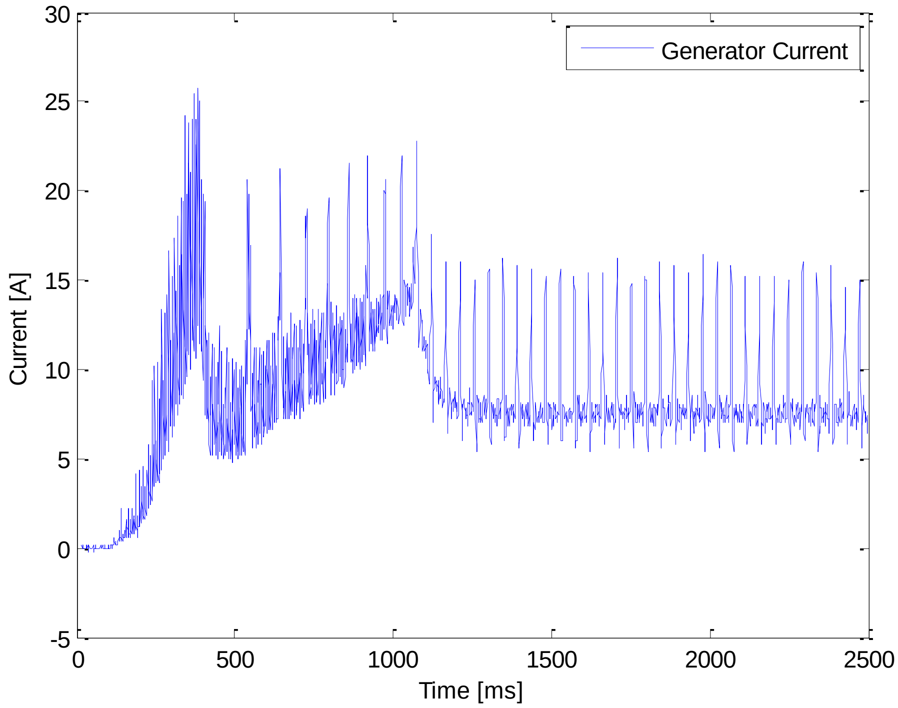

Figure 23, Generator current when connecting the super capacitor to the generators using soft start

Now the start current only peaks about 25A instead of 120A as it did without soft start circuit. This is a big improvement for prolonging the lifetime of the generators and shaft connections. The problem is that when trying the soft start circuit at high voltage the zener diode in the protective circuit broke down and exploded. This was probably because it didn’t have time to dissipate all the fast voltage peaks when the ramp up of the PWM-signal was occurring. Every time the MOSFETs is shut off there is a voltage peak due to the inductance in the cables. These voltage peaks charged the capacitors so that they could not store more energy. This causes so that the zener diode needs to dissipate all the energy from the voltage peaks. For every pulse it needs to take care of it gets warmer and warmer so that it eventually breaks down. The reason why it didn't break down at low voltage levels is that the zener diode, which is a 50V zener diode doesn't even begin to conduct before the voltage level has reached 50V. If the super capacitor has a voltage level of about 35V before the PWM forces it down to zero the stored energy in the cable inductance builds up a voltage that is just high enough to reach 50V. Therefore this is not a problem for the zener diode. When the super capacitor has a voltage level of about 45V the stored energy in the cable will still make the voltage over the protective circuit increase with 15V. The voltage now becomes 60V over the zener diode and it will eventually break down. This breakdown is shown in *Figure 24* below where the super capacitor voltage is the only voltage applied during the first 100ms. Then the energy stored in the cables contributes with a voltage raise up to over 60V which is too high for the zener diode and after 300ms it breaks down.

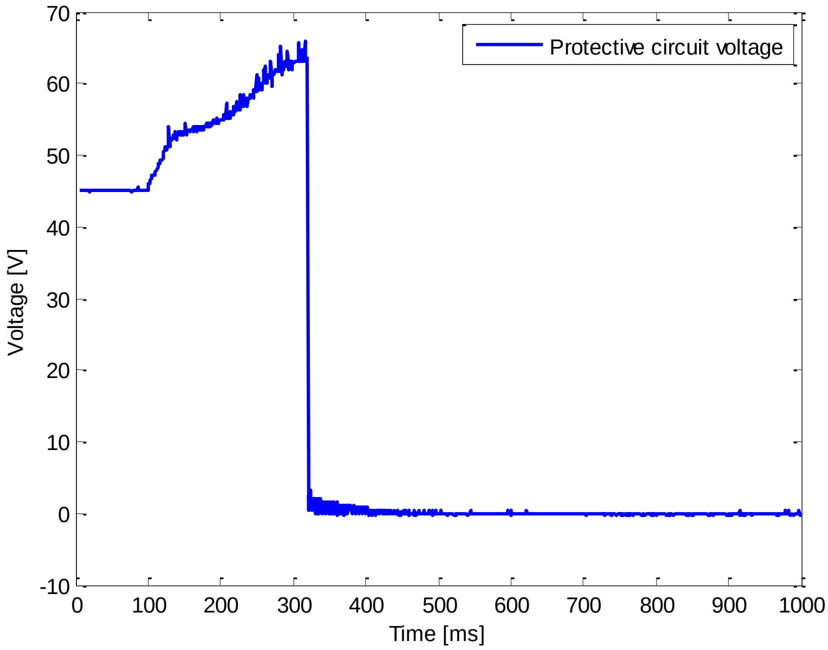

Figure 24, Voltage in protective circuit of soft start

3.7.4 Controller (PLC-system)

To be able to measure all parameters in the test bench a lot of sensors is used. A requirement is that every measurement should be saved on a computer for further analysis. There is also a need for control of all relays in order to start for example the ICE or the driving motor. All these functions are controlled by a PLC system.

There are a lot of different PLC-systems on the market but in this project a system called Beckhoff is used. This system has many benefits. For example it uses standard Ethernet cables to communicate between the computer and other modules in the system. Because of this, everyone with an Ethernet card is able to use it without buying extra interfaces for communication. It is also very easy to get an overview of the system since everything is controlled at high speed in real time on the computer. The whole PLC program actually runs on the computer. The programming language is much similar to "basic" and therefore most people can manage the programming. It is very easy to make graphical interfaces with different meters and histograms. This is shown in *Figure 25* below. As seen in this figure, most important inputs and outputs can be controlled by different buttons. The ignition for the ICE can be short circuited so that the ICE is impossible to start. The super capacitor can be connected and disconnected. If this button is pressed the generator will try to start the ICE. There is also a button which connects and disconnects the drive motor connected to the torque bench. The last button puts the whole system into run mode. In this mode the system is fully automatic. This means that it will enable the drive motor. It will also check the super capacitor voltage and if it is to low it will start the ICE automatically. When the super capacitor is charged to the right voltage level, the system again short circuits the ignition for the ICE and disconnects the super capacitor. The voltage level for the super capacitor to cycle between is preset in one of the subroutines for the programming. When pressing the run mode button it also starts a histogram window in the background which is logging every measurement into a data file which can later be analyzed with Matlab or any other computational program.

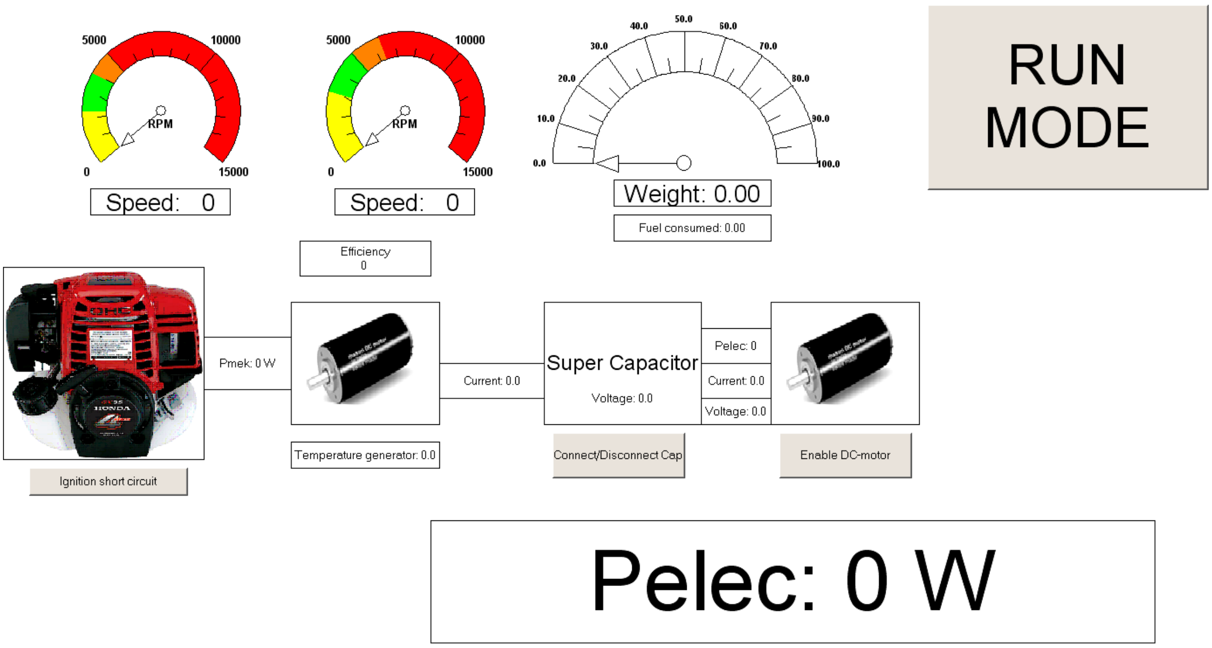

Figure 25, Overview of the GUI for the PLC controller

To control and measure different things in the circuit some different modules needs to be connected. For every application there is a separate module. Therefore it is important to consider the needs of the system before starting to build up the PLC-system. There are modules with analogue inputs and outputs, modules with digital inputs and outputs. These modules can be bought with different amount of inputs or outputs. There are also separate modules for more specific tasks like for example temperature measurements with PT-100 sensor, PWM outputs and modules with built in relays. All these modules need to be connected to a special terminal to be able to connect them to the computer. By connecting them they get there voltage supply automatically without connecting additional cables. The voltage needed for this system is 24V.

There are also a lot of other Beckhoff products that can easily be connected directly to the system using the same interface and system. One thing that is used in this project is a servo amplifier which controls a servo motor. This amplifier can be controlled directly from the PLC program on the computer and all parameters of the engine like for example: speed, temperature and torque can be read directly on the screen.

In the system of this project 6 modules are used. One two channel digital input module used for measuring the speed of the ICE. Four two channel analog input modules used for measuring fuel consumption, super capacitor voltage, drive motor voltage, generator current and the drive motor current. The last two modules are a four channel digital output for actuating relays and a PT-100 module for measuring generator temperature.

When measuring the rotational speed of the ICE both channels of the digital input are used. This is because the digital input can be used with oversampling. This means that the modules itself stores values in a vector and sends them over to the computer. To gain some extra speed and be able to measure as high frequencies as possible every other pulse is taken into channel 2. The reason why the analog input modules only have two inputs instead of four and by that don't need to use as many modules, is that the ones with two inputs can measure differential. This would probably not be necessary since the only place where this is used is to measure the drive motor voltage. If another converter would be used that can work with common ground, this would probably not be needed at all.

When programming the PLC-system it is important to start to make an overview of the program and to make a flowchart of it. This flowchart is shown in *Figure 26* below. The easiest way to program is to divide the program into smaller subroutines. One part which takes care of for example the voltage measurements and another that can take care of the current measurements. This is what is done in this project. This is also a good way to program since it makes it easy to get a good overview of the programming. It is also very easy to make changes in it since everything is divided into sub routines. If a change needs to be made in for example voltage measuring it is easy to find the right subroutine and change it without affecting anything else. This also makes it easier for people who have not been involved in the construction of the test rig to understand it, work on it and make changes or improvements on it.

Since every part is run once every cycle of the program it is important to use a lot of different variables that can either be "TRUE" or "FALSE" and then check these variables to know if a certain part of the program should be run at this moment. For example when starting the ICE the program checks once every cycle to see if the "run ICE" variable has been set to "True". As long as this variable is "FALSE" the ICE is off but when the start button is pressed this variable is changed to "TRUE" and the ICE starts. This procedure is repeated in almost every part of the program.

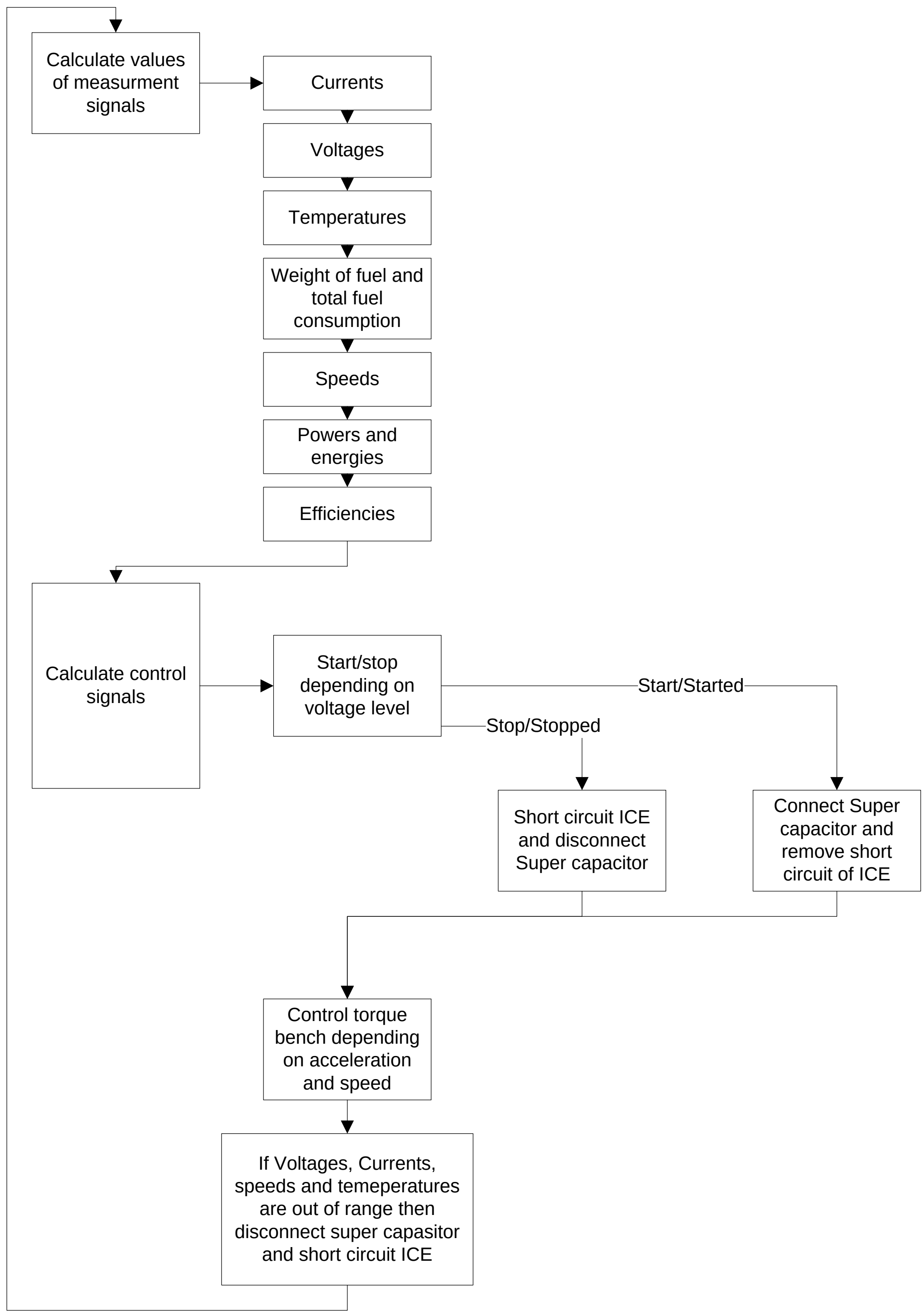

Figure 26, Flowchart of the system when in run mode

3.7.5 Safety precautions

To prevent the generator from rotating to fast or to get the voltage over the super capacitances to become too high a separate program is implemented in the PLC. If the generator rotates to fast the windings of the rotor will be thrown out towards the stator and eventually break down. The limit for the Maxon RE-65 is 5000 rpm according to technical support at Maxon. The voltage limit for the super capacitor is 48V. If the voltage gets to high it will store too much energy and eventually start to emit explosive gases with some risk of explosion. The program in the PLC checks these two values and if one of them is too high a relay short circuits the ignition signal to ground and in this way block the spark in the combustion chamber. It will also disconnect the super capacitor.

If the PLC is not running another safety precaution is implemented. Another relay is placed in parallel to the one mentioned before. This relay needs a voltage of 24 volts from the PLC to open making the ICE only to be allowed to operate if the PLC program is running.

3.8 DC/DC Converter

The converter chosen for the test bench is a Maxon 4-Q-DC servo amplifier ADS 50/10 shown in *Figure 27*. The advantage with this one is that it is 4 quadrants and it is in the perfect range of our dc-motor. Using a 4 quadrant converter gives the possibilities to run both forward and backward and to both generate and drive. The converter can be set in different modes. Running it in current mode it will control the voltage applied so that the current corresponds to the reference value applied on an input. Running it in speed mode it will control the voltage output so that the speed is obtained. The speed can be measured either by a tachometer or by calculating the speed using the knowledge of the parameters of the motor and using the measured voltage and current.

Figure 27, Maxon 4-Q-DC servo amplifier ADS 50/10 used to power the DC-motor in the test bench

One disadvantage with this converter is that it uses the energy in the super capacitor to power itself. This power is measured to about 2W which are lost but since this converter is going to be placed in the car it should also be tested on the test bench.

Another master thesis group is also working on constructing a new converter specially built for the Chalmers ECO-marathon car smarter. This converter is also designed to have as low losses as possible. Since there is no need to reverse the rotation of the motor an accordingly the car, it is a 2 quadrant converter. This converter has also been tested in the test rig and the result from this test is presented and compared later in this report.

4 Analysis

4.1 Weight optimizing

When choosing between different solutions for different applications weight must be considered. The air-resistance is neglected since it's much smaller than the friction losses. The energy saved for one solution must exceed the possible loss of energy for carrying some extra weight. Due to this it is important to know approximately how much extra energy/kg is needed. If it is assumed that the car needs continuously about 130W to keep 25km/h the rolling resistance coefficient can be calculated by using

$$\mu = \frac{P}{v\,m\,g} = \frac{130}{25*70*9.81} = 0.02726 \qquad (24)$$

When this is coefficient is known it is easy to calculate two different energy scenarios. One with a continuous power of 130W and one scenario using a car weight of 71kg. The calculations become

$$E_1 = P\,t = 130 * 52 * 60 = 405.6kJ \qquad (25)$$

$$E_2 = \mu\,m\,g\,v\,t = 0.2726 * 71 * 9.81 * \frac{25}{3.6} * 52 * 60 = 411.38kJ \qquad (26)$$

$$E_2 - E_1 = \Delta E = 411.38kJ - 405.6kJ = 5.78kJ \qquad (27)$$

The extra energy needed to carry one extra kilo around the track is about 5.78kJ. The extra energy per km and kg needed is

$$E_{km} = \frac{E_1}{D} = \frac{5.78kJ}{22.081km} = 0.26kJ/(km * kg) \qquad (28)$$

4.2 Energy required for a start with the generator

When using the generator as a start motor it is not possible with an easy method to take the energy for this start from the external battery. Therefore the energy needed to start the ICE must be measured. This is done by connecting a current probe to the generator cables. Then the product between current and voltage must be integrated to get the energy. The power required for a start of the 25ccm ICE is shown below in *Figure 28.*

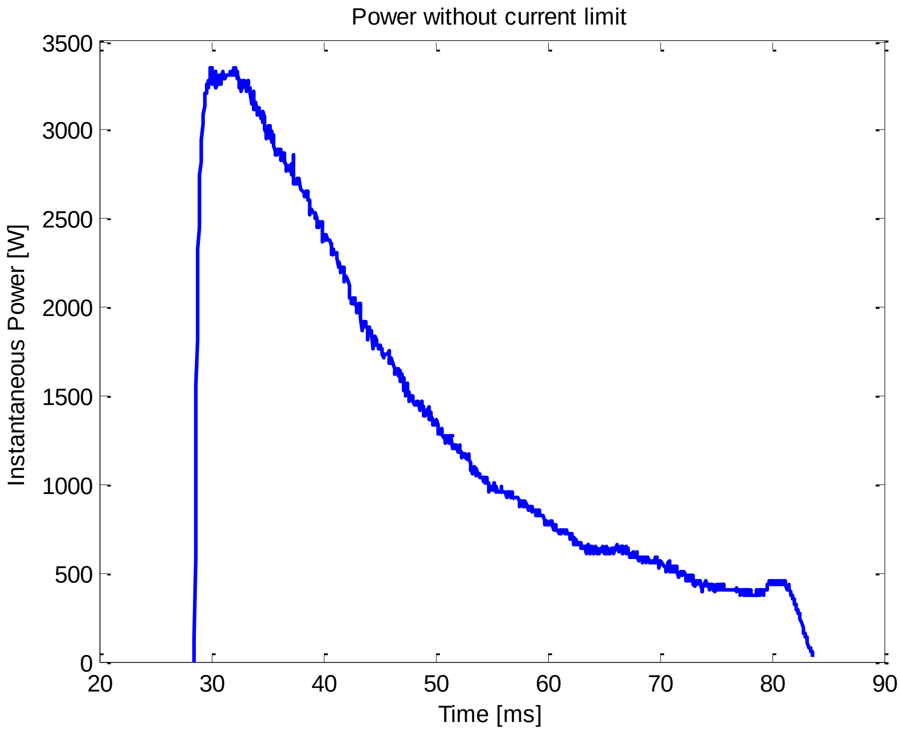

Figure 28, Power delivered to the generators when connecting the super capacitor directly the generators

When integrating the power over the time it takes for the ICE to start the energy required is about 75J. Since the motor needs to be started about 7 times in the race this energy becomes 525J. Since according to the weight calculations the extra energy needed per kilo is about 5.78 kJ this is probably the most proficient method to use. If another method is to be used it is only allowed to have a weight of maximum

$$m = \frac{525}{5780} = 0.091kg \tag{29}$$

This will most probably be impossible to find. By using this method the starting circuit can be made very simple and requires no additional parts except for a soft start circuit.

4.3 Energy from motor

The current from the DC- motor connected to the ICE must be analyzed in order to calculate losses and perform some cable dimensioning. When looking at the current below in *Figure 29* we can see that the current shifts a lot. It goes from negative to positive. Since the total charge to the battery depends on the mean value of the current and the losses in cables depends on the rms value of the current, this phenomena is undesirable since it lowers the mean value but keeps a high rms value.

Every cycle of the ICE can be identified in the figure. The highest peak of the current is achieved when the ICE is igniting. Then when it is going through its compression cycle it gets some torque from the DC-motor and therefore the current goes down to a negative value. It can also be seen when the valves of the ICE are opening. It is when the small peaks after the highest peak occur.

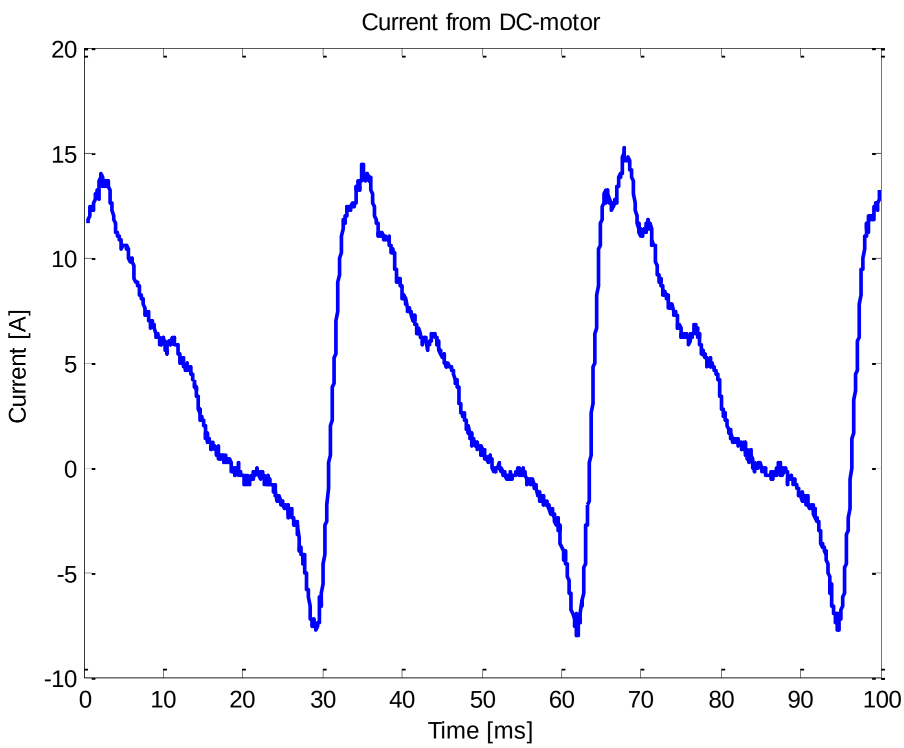

Figure 29, Current delivered to the super capacitor when running the ICE at full throttle

To get rid of this behavior an inductance can be added in series with the motor. This inductance makes the system current slow. If this inductance is high enough it will not have time to go down to zero and therefore the mean value and the rms value is almost the same. When this is done the losses are minimized.

A minimum inductance can be calculated by using *(30)* below where Δi is the maximum allowed current change and Δt is the time it takes for this change to happen.

$$L = \frac{U\Delta t}{\Delta i} \tag{30}$$

We allow a maximum current change of 0.5A and a voltage of with a change of 1.33V. One revolution of the ICE takes about 15ms at 4000 rpm. Since the engine only fires every second revolution this time is multiplied with 2. These values give us an inductance of 40mH. The current with a connected inductance of 40mH in series is shown in *Figure 30* below.

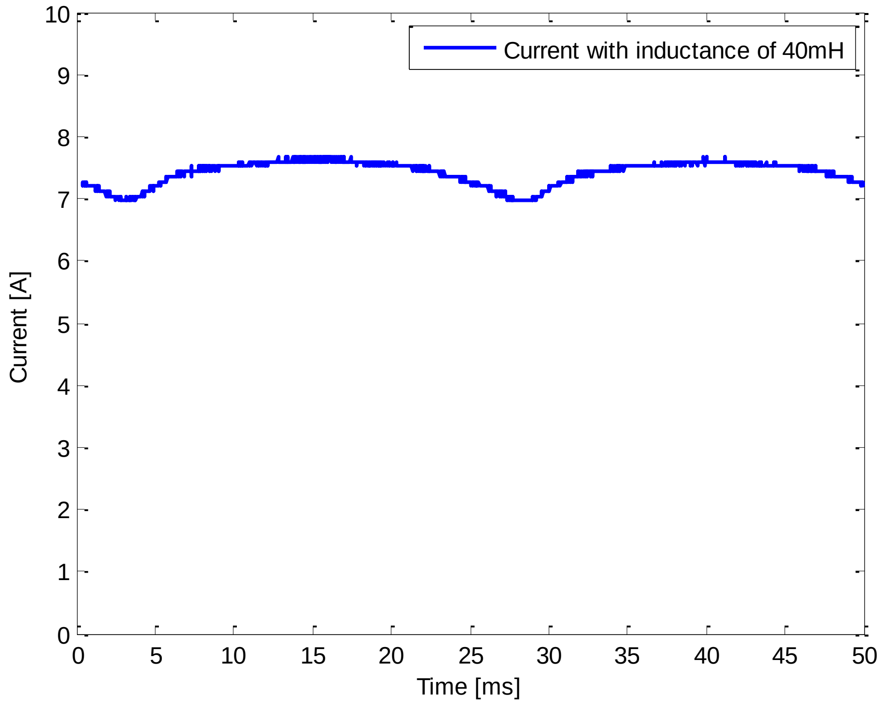

Figure 30, Current delivered to the super capacitor when running the ICE at full throttle using a large inductor in series

As seen this inductance takes care of almost all the current ripple. The problem with this connection is that an inductance of this size is very heavy, about 10 kg. It is probably too heavy to implement in the car. Since the largest problem is that the current goes to a negative value it could work with a smaller inductance as well.

Another problem with an inductance is that when the circuit is shut off instantaneously is that the energy stored in the inductance must have somewhere to go. If it doesn't have anywhere to go it will build up a very high voltage somewhere in the circuit. To protect the system from this a protection capacitor can be used. This capacitor is then placed in parallel with the components that needs to be protected from the overvoltage. This protective circuit is shown in *Figure 31* below. When putting the drive line into the eco-marathon car the switch must be directly in series with the super capacitor. Otherwise there are better places to put this so that protection from over voltages is not so important. When the switch suddenly is opened the energy from the inductance would without the protective capacitor theoretically go to infinity and there will be a breakthrough in the component. But with the capacitor this energy will go down into the capacitor and the overvoltage will not get high enough to cause a break through.

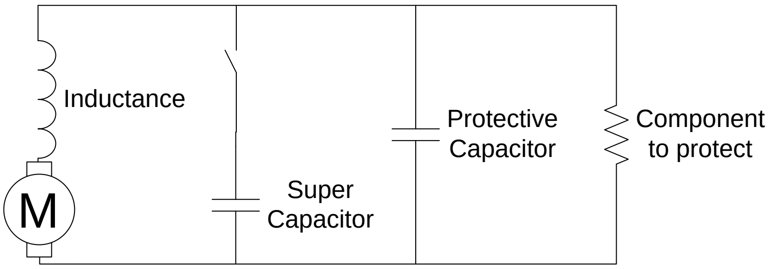

Figure 31, Schematics of the use of a protective capacitor

. To calculate the needed capacitance the equations used are

$$E_{cap,after} = E_{cap,sys} + E_{ind} = \frac{U_{sys}^2 C}{2} + \frac{I^2 L}{2} = \frac{(U_{sys}+U_{raise})^2 C}{2} \tag{31}$$

This means that the energy in the protective capacitor after shut off must be the same as the energy in the inductor before shut off. Since this energy will be extra energy the capacitor also must be able to handle the energy that is stored in it initially due to the system voltage.

How much the voltage rise that is allowed depends on which voltage level the capacitor used is built for. The super capacitor used in the test bench is rated 48V it may be good to use a 60V capacitor as a protection since this is a standard value for electrolytic capacitors. The maximum voltage raise allowed is then 12V. When choosing this it must be certain that the component to be protected can withstand this voltage raise. Otherwise a lower voltage must be chosen with a higher capacitance as a result. When combining the energy equations and solving it for the capacitor value the equation becomes

$$C = \frac{I^2 L}{(U_{sys}+U_{raise})^2 - U_{sys}^2} \tag{32}$$

If the system voltage is 48V, the maximum voltage raise is 12V, the inductance 40mH and the maximum continuous current is 13A when using a 35ccm ICE with two generators connected the capacitance needed becomes

$$C = \frac{10^2 * 40 * 10^{-3}}{(48+12)^2 - 48^2} = 3mF \tag{33}$$

If the component to protect cannot withstand a voltage level of 60V, a capacitor with a higher capacitance may be used. Another standard value for electrolytic capacitors is 50V. Since the system voltage is 48V this will only allow a voltage raise with 2V. If the calculations is once again performed with all the same parameters except the voltage raise it becomes

$$C = \frac{10^2 * 40 * 10^{-3}}{(48+2)^2 - 48^2} = 20mF \tag{34}$$

In both cases above there are some problems because none of these capacitors are easy to find. They are also very expensive and bulky. Therefore the solution to use big inductances as a current filter may not be a very good idea. They are very heavy by themselves and require big and expensive protective circuit.

There are other ways to take care of the negative torque obtained from the ICE. One way is to rectify the current from the generator. This will give some losses since all of the energy in the negative parts of the current will be dissipated in the diode and by this give an efficiency of zero at this moment. If this method where to be used the option to start the ICE with the generators wouldn't work since there can be no power flow in that direction due to the diode.

Since there are two generators connected to the ICE in order to take care of all the power there can be some balancing problems. If the DC-motors don't have approximately the same resistance and inductance parameters one of the generators may have to convert all of the kinetic energy to electric energy. If this happens the lifetime of one of the generators will be reduced and the other one will just spin along or even act as a motor if they are very different. In order to know if the motors need to be balanced, the current from both the generators must be measured and compared. If the currents differ too much some balancing must be done. This can be done by adding extra resistance or inductance to one of the motors. The measurements from the generators are shown in *Figure 32* below.

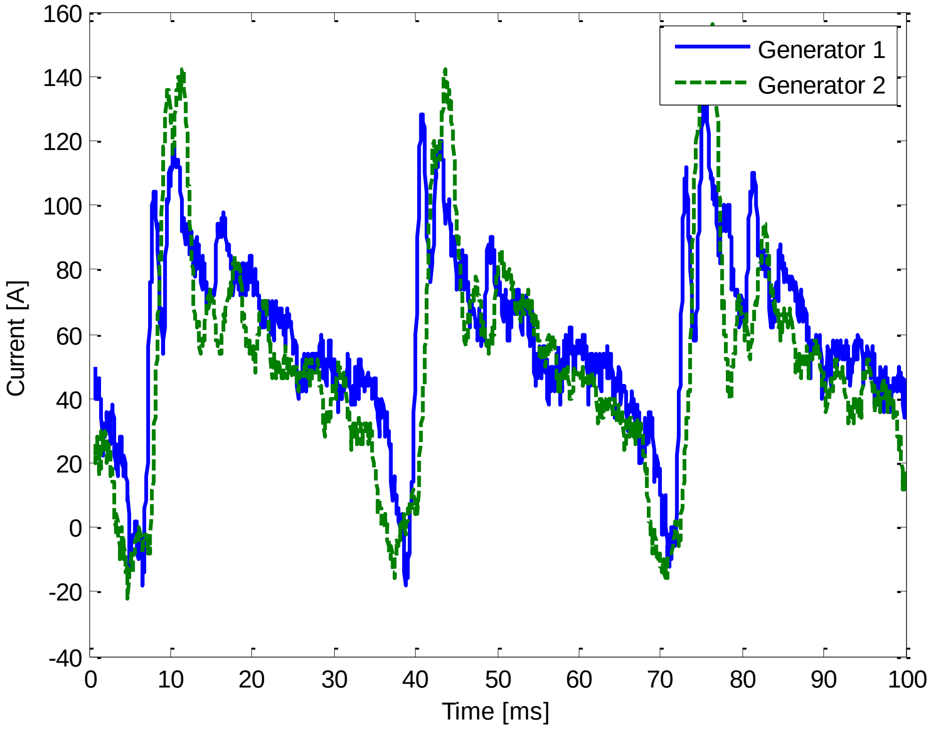

Figure 32, Currents from generators then running at full throttle

As can be seen the currents in this case are almost exactly the same. This means that the DC-motors have approximately the same parameters and that the load is divided equally between the two generators. Since the currents match this good, no balancing needs to be done.

4.4 Voltage measurement

When measuring the voltage from the converter with and without a low pass filter attached to get more accurate measurements due to limits in the measuring systems sampling frequency the plots in *Figure 33* and *34* are obtained. The first figure shows the voltage without a filter and the second figure shows the voltage with a filter attached. As can be observed, the voltage in the second figure is much smoother. This is because it only contains the DC component of the voltage. This is needed to be able to get the right efficiency calculations of the system. This procedure should also be done on all the currents.

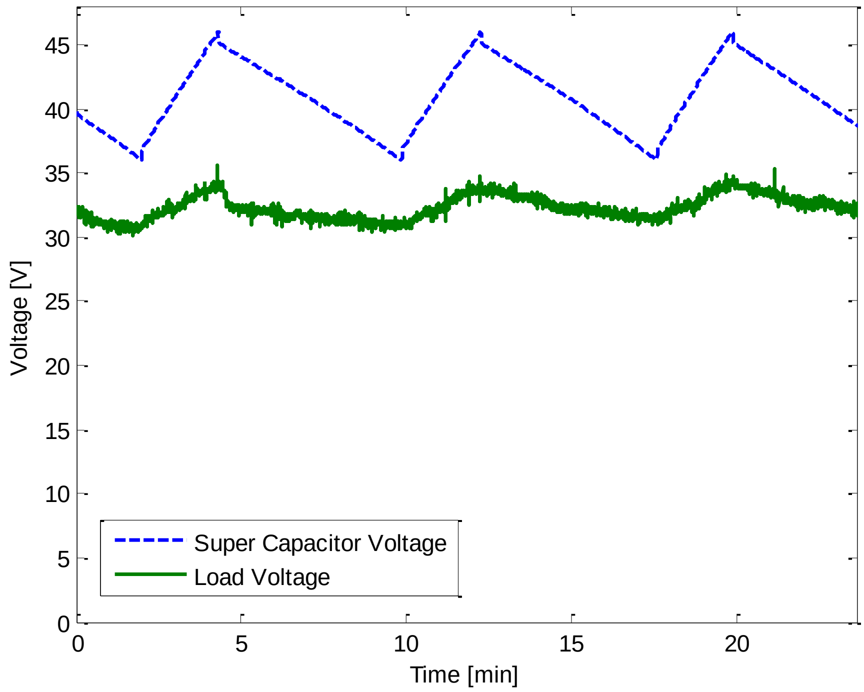

Figure 33, Voltages of super capacitor and DC-motor during a cycle without low passing the voltage signal

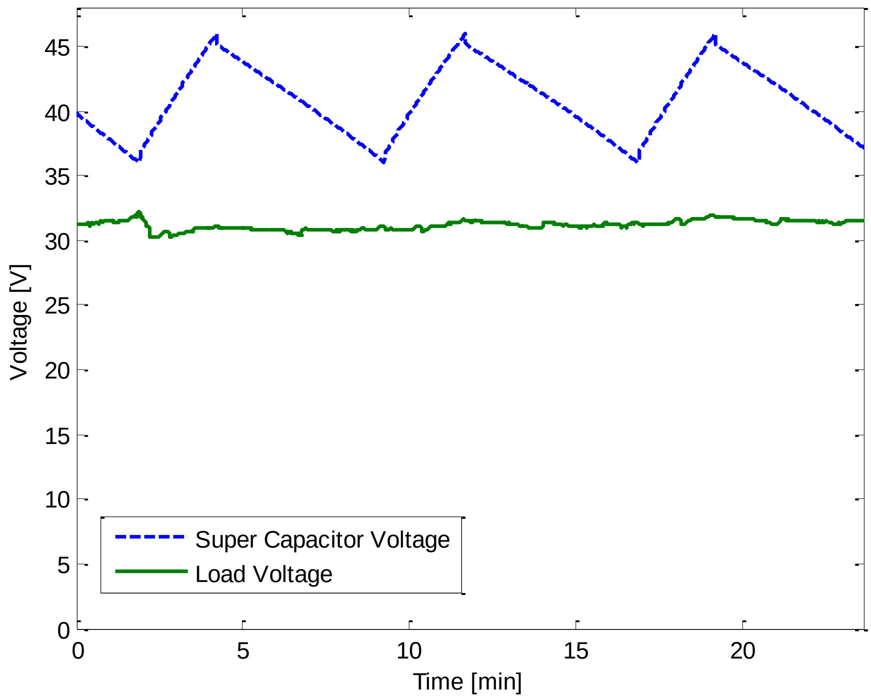

Figure 34, Voltages of super capacitor and DC-motor during a cycle when low passing the voltage signal

4.5 Testing the rig

When testing a real drive cycle in the bench some results were obtained. The voltage over the super capacitor and the drive motor is shown in *Figure 35,* the currents from the generators and to the drive motor is shown in *Figure 36* and the power which is the product of the voltage and the current is shown in *Figure 37.*

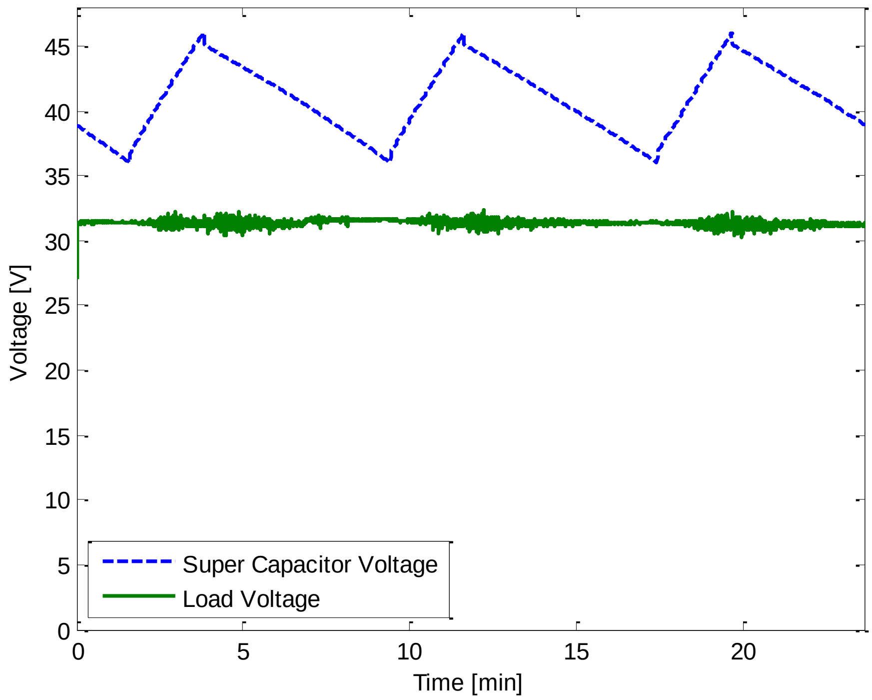

Figure 35, Voltages using Maxon converter during one cycle

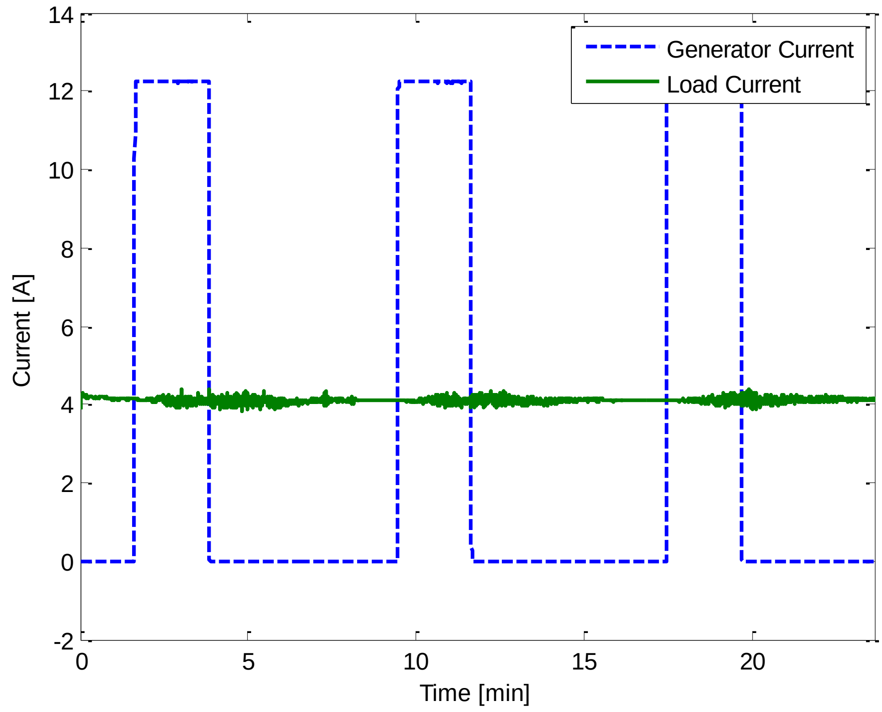

Figure 36, Currents using Maxon converter during one cycle

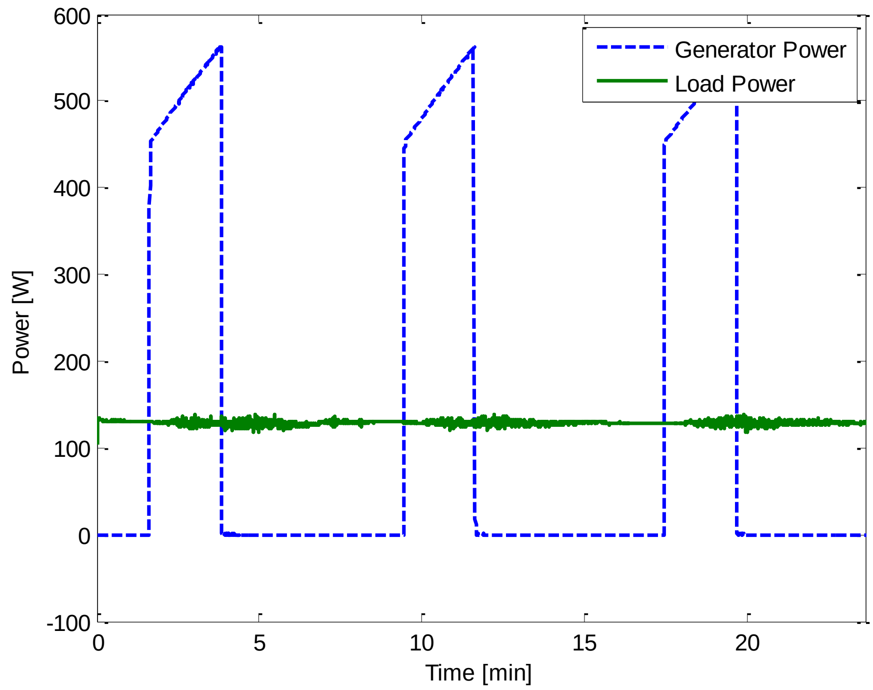

Figure 37, Power using Maxon converter during one cycle

With these results the total efficiency of the electrical system can be calculated by integrating the power taken out of the system and divide it with the power put into the system. When this is done the efficiency calculation with the Maxon converter becomes,

$$\eta = \frac{\int P_{ut} dt}{\int P_{in} dt} = 0.906 = 90.6\%. \quad (35)$$

It must be noted that this may not have very good accuracy since there are a lot of insecurities to take into account. But since the rig will be used only to measure if there is an efficiency improvement if something is changed in the drive line, the accuracy is not that important. When doing these calculations it is important that the energy stored in the super capacitor before start is the same as the voltage level after stop. Considering that this efficiency takes into account the full electric system of the car it is really good. One thing that can be done to improve the efficiency may be to change the converter to another one which is specially designed for this application and is designed to have as low losses as possible. This other converter especially built for his purpose is built by another master thesis group at Chalmers. The results when trying with this converter is shown below. The current is shown in *Figure 38* and the power in *Figure 39.*

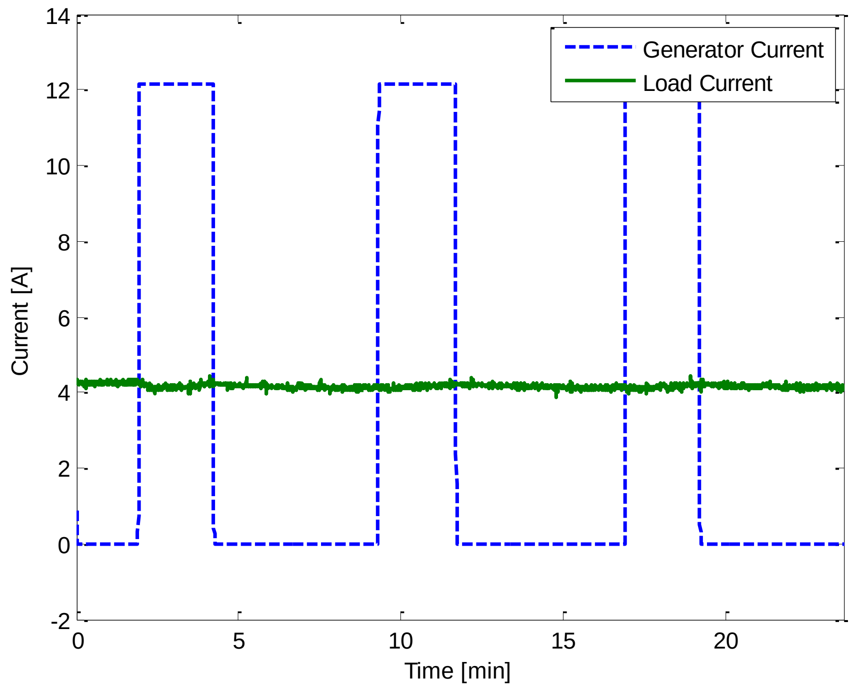

Figure 38, Current using specially built converter during one cycle

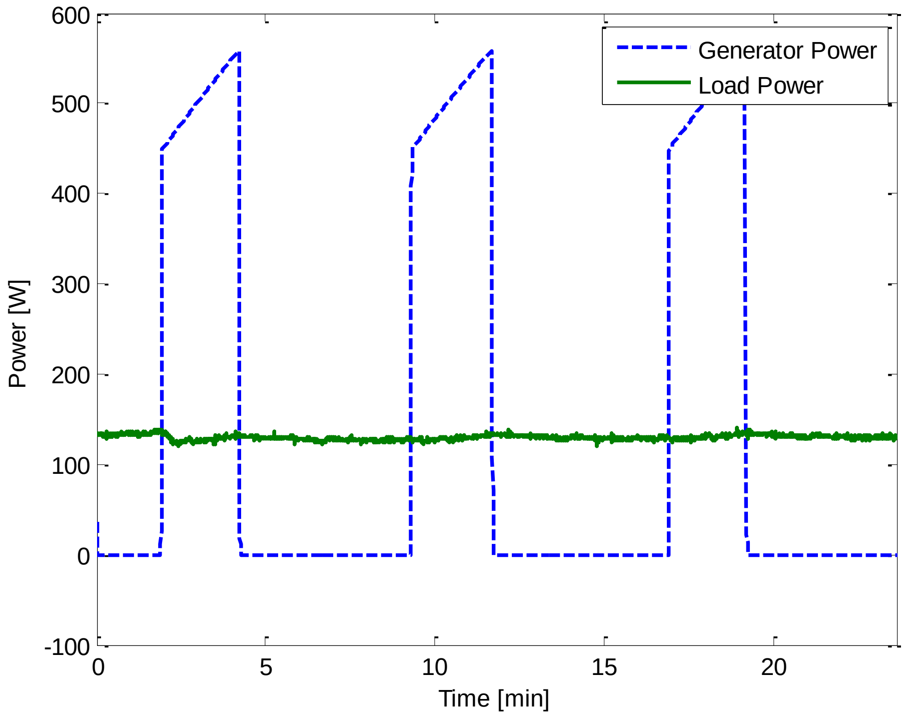

Figure 39, Power using specially built converter during one cycle

When calculating the efficiency in the electrical system with this converter it is only about 80%. This is not as expected since it should be especially built for this purpose. The problem is probably that it uses a method to switch out the current that makes the current go between a high value and zero. This makes the current have a low mean value but a high rms value and since the power loss in a resistance is proportional to the current squared, the losses in the motor winding get very high. Measurements on the converter itself on the other hand show that it has an efficiency of about 98%. This is probably true since it has a lot of MOSFETs connected in parallel to get as low losses as possible. The problem is that the way it switches does not fit the purpose in this case. This problem may be solved by increasing the switching frequency of the converter to get less current ripple. This will on the other hand contribute to more switching losses so an optimal solution for this must be found. It is also possible to use this converter with PWM-modulation instead to find out if this gives lower losses.

Because of problems with the scale for measuring the fuel which was suddenly broken the total efficiency of the system from fuel, through all the gear ratios and in the end to mechanical torque for the wheels cannot be calculated.

5 Implementation in ECO-marathon car Smarter competing in Shell ECO-marathon

Some of the solutions built up in the test bench were used in the ECO-marathon car. Mainly the ICE and generator pack was fitted right into the car making it a series hybrid. The DC-motor used to drive the torque bench was also used together with the converters as well as the super capacitor. This was a well-chosen strategy because we knew that all the parts were going to work together, and in this way the risk of failure was reduced.

The shell eco-marathon race 2009 was held in Lausitz in Germany. The car vas not fully assembled when we arrived three days before the competition. After a lot of work on the car we were able to attend in race number two after missing race number one. The safety inspection was completed in the last second and everyone was very excited.

The start worked fine as shown in *Figure 40* but after two laps the driver had to break the race due to that the voltage level in the super capacitor was too low. After a lot of discussions of what could have gone wrong the cause was found to be the brakes. The rear axis weren’t attached properly so the break disk was forced towards the break caliper and the power needed to travel forward was larger than the power that the ICE could produce so the voltage level got lower and lower.

Figure 40 Chalmers car Smarter in the second attempt at Shell ECO-marathon 2009

The next day it was time for the last attempt. Thirty minutes before the race the left front wheel hanging broke down as well as the chain between the generators and the ICE. Quick fixes for these problems were made but after just one lap the wheel hanging broke down again. Everyone was pretty sad but still satisfied with how much we had achieved in a very little time. A total of three laps were made with a car that was assembled in three days, and for the next year, a very good platform to work further on, had been created. The car should after some work to fix some weak mechanical constructions be able to compete again and achieve a decent distance of around 300 km/l according to simulations.

6 Conclusions

The result from this master thesis is a fully working test bench suitable to run engines of approximately 1 kW. All the measurement signals are optimized for the driveline for Chalmers ECO-marathon car Smarter so when a new driveline is fitted, some parameters need to be changed in the PLC system. A lot of work has been done to make Smarter run in the Shell ECO-marathon competition in Lausitz where a lot of the knowledge gained from the test bench was used.

The test bench is able to measure speed of the ICE, voltage and current of generators and drive motor, temperatures of different components and the fuel consumption. Many more things can then be calculated such as the torque of the motors, power at different stages and the efficiencies. This makes the system very flexible and suitable to use for many purposes and it may even act to bench mark an ICE up to about 1 kW.

The evaluation on starting the ICE with the generators was a success taking away the need of a separate start engine which adds weight and is a complicated construction that may fail. By using the generators to start the engine some energy is lost from the super capacitor but the loss in traveling distance is even smaller than what is lost by adding a separate starter engine due to its weight.

By using DC-motors as a generators and only changing the voltage in the super capacitor by some 10% makes it possible to connect the super capacitor directly to generators when running. This gives a very high efficiency and leaves out the need of a converter. The problem is then that when connecting the super capacitor to the generators the ICE will run up to speed in a very short time which may damage both the generators and the ICE. A soft start was developed for this purpose to apply an increasing voltage to the generators using PWM leaving the duty cycle on 100 %. This makes the ICE slowly accelerating so that no harm is done to the components.

7. Future work proposals

Now, a platform has been created, and the knowledge gained can easily be used for redesigning parts and software. The test bench is finished for a series hybrid and for a parallel there is just some work left. The parts connecting everything must be manufactured and the control program must be written which is a little bit more advanced. So after these problems are achieved the work can be laid on optimizing the parts and strategies. All results made can also be compared to a simulator making optimization a lot more effective.

All the control and measuring equipment of the test bench can be used to test a bigger vehicle. This may be very interesting to test and to see differences that may occur between small and large systems.

Another thing that can be investigated is how the control of the injector and ignition system can be optimized and controlled by the PLC-system to achieve optimal efficiency.

Economical aspects of developing a hybrid car could also be an interesting task.

Developing a converter to connect to the generators could also be interesting if this is done to be able to control the current in a very fast way and thereby removing the current peaks.

8 Sources

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[3] Image, Maxon DC motor, “Technology- short and to the point”, p.2, available 06-10-09: http://shop.maxonmotor.com/maxon/assets_external/Katalog_neu/Downloads/allgemeine_informationen/Technik_kurz_und_buendig/DC-Technik-kurz-und-buendig_08_EN_024-25.pdf

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[5] Björn Lindgren, OSO Konsult

[6] Image, starter_Bendix.jpg, available 02-16-09: http://www.scooterbrokers.com/images/starter_Bendix.jpg

[7] Unpublished data

[8] Unpublished data

Appendix A

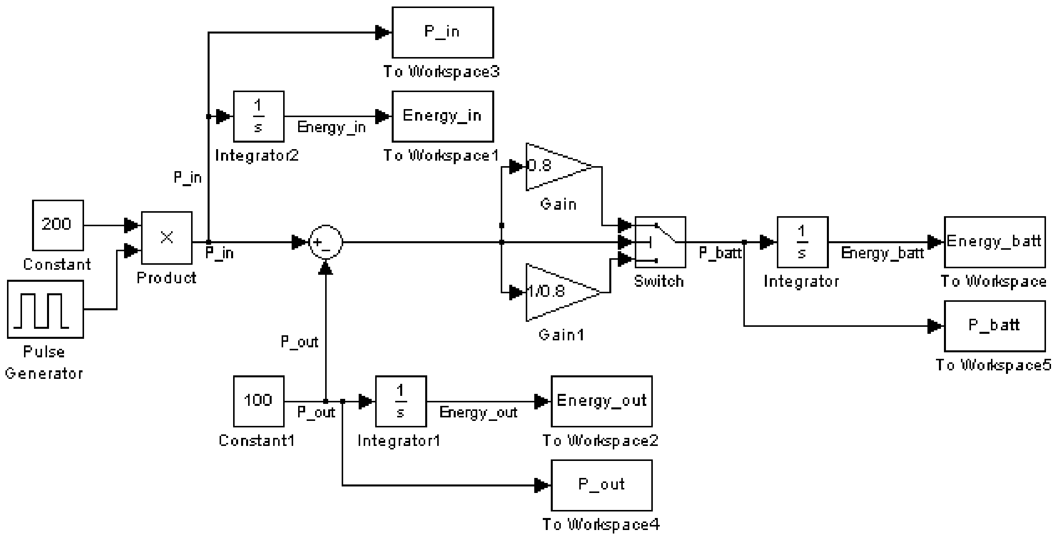

Figure 41, Simple simulation model of parallel hybrid

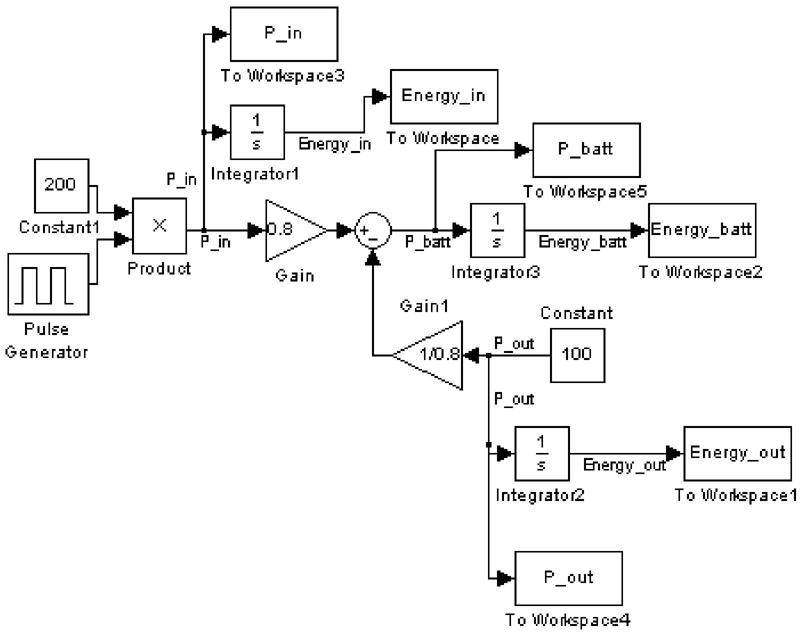

Figure 42, Simple simulation model of series hybrid