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Smart Generator Control on Engine Efficiency Map

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Abstract

Even more the authorities have focused to create new laws and alternatives that minimize the impact of pollutants emissions on the environment, mainly in the reduction of the CO2, for it contributes to global warming. As the automobile industry is responsible for a significant part of these emissions, the companies increase the investments in their sectors, as an attempt to comply with this new scenario.

The automobile company, Adam Opel AG (subsidiary of GM Motors, located in Rüsselsheim, Germany), observing the increment of the electric components, whether for providing comfort to the consumers or to aid in the basic activities in the vehicle, the growing of the Hybrids and to adapt to the new rules. It has invested even more in solution involving electric power generation and management.

Thus, this project has as objective to improve the electric system, enhancing the efficiency in the conversion process from mechanical to electric energy and storage, mitigating the fuel consumption, taking into account the components efficiency: engine, battery and generator, maximizing the battery lifetime. Furthermore, the new solution needs to cooperate with the several operation modes existents in the car and improving the recuperation events, without making any physical changes. Moreover, in this report, we will show that it is possible to conceive a solution that can work on cycle and guarantee the benefits in real life driving.

Resumo

As autoridades tem se concentrado cada vez mais na criação de novas leis e alternativas que possam minimizar o impacto da emissão de poluentes na atmosfera, principalmente no que se diz respeito a emissão de gases como CO2, por contribuírem com o efeito estufa. Sendo os automóveis responsáveis por parte significativa destas emissões, as empresas tem buscado aumentar o investimento nos seus diversos setores como uma tentativa a se adequarem a este novo cenário.

Aliado ao crescente aumento do número de componentes eletrônicos, sejam eles para o conforto do usuário ou auxiliar as atividades existentes e juntamente com o desenvolvimento de veículos híbridos, o gerenciamento de energia, tem ganhado destaque na redução do consumo de combustíveis fósseis.

A empresa automobilística Adam Opel AG (subsidiária da GM Motors, localizada em Rüsselheim, Alemanha), numa tentativa de minimizar a emissão de poluentes e atender as novas leis, tem cada vez mais investido neste setor em busca de novas soluções. Desta forma, este projeto tem como objetivo, melhorar o sistema de gerenciamento de energia, melhorando a eficiência no processo de conversão de energia mecânica pra elétrica e armazenamento, possibilitando a minimização do consumo de combustíveis fosseis, levando em consideração a eficiência dos componentes envolvidos e maximizando a vida útil da bateria. Sendo todo este processo realizado sem que haja a necessidade de alterações físicas, garantindo a cooperação do mais diversos modos de operação existentes no veículo e o melhoramento de processos de recuperação de energia.

Contents

Simbology

Acronyms

WLTP – Worldwide Harmonized Light Vehicle Test Procedures

MVEG - Motor Vehicle Emission Group

ECM – Engine Control Module

IBS – Intelligent Battery Sensor

EPM – Electric Power Management

REC – Recuperation

SOC – State of Charge

RVC – Regulated Voltage Control

BCM – Body Control Module

RVC 4.1 – Closed Current Loop Control

RVC 4.2 – Closed Voltage Loop Control

CAN – Controller area network

HS-CAN – High speed CAN

LS-CAN – Low speed CAN

LIN Bus – Local Interconnect Network

RPM – Rotations per minute

ESFC – Electric Specific Fuel Consumption

BSFC – Brake Specific Fuel Consumption

i.e. – in other words

e.g. – for example

EffChargeMode – Efficient Charge Mode

FEM – Fuel Economy Mode

List of Figures

Chapter 1: Introduction

The legislation related to the emission of polluting gases, especially CO2, is being tighter in the current politic scenario. Forcing the companies to comply with these new rates of pollutants reduction to avoid being punished. This way, the companies are researching for alternatives in their different sectors, whether in the powertrain sector or in the power electric generation efficiency to handle it.

Nowadays, the electric system in the vehicle has gained greater importance due to the increase of the number of the electronics components in the car. This generates a necessity of improvement in the conversion of the mechanical to electric energy and the storage system, minimizing this way, the fuel consumption.

Improving the electric management system, besides bringing benefits in the fuel consumption, it enhances the lifetime of the battery. Since, the management of the battery state of charge mitigates undesired effects, such as the stratification, the separation of the electrolyte into distinct layers of acid and water, and sulfation, the crystallization of sulfate ($PbSO_4$) on the plates, which occurs due to low charge frequency and state of charge.

Due to this problematic and the benefits cited, followed by the new rules that will require changing the test cycle from the MVEG to WLTP[1] in Europe, demanding new battery discharge tolerances[2] and evaluation tools. The main goal of this project is to develop a management system, the smart generator control on engine map, considering the efficiency of all involved components: battery, generator and engine, using the existents structures in the vehicle without doing any physical change. Where in a first moment, accompanied by the improvement of the recuperation events[3], the objective will be able to generate the required amount of electric energy in the WLTP,

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[1] See Appendix A

[2] See Appendix C

[3] See Chapter 5

in the same time minimizing the fuel consumption and then extend these benefits for the real life drive.

Thus, in the beginning, this report will introduce the EPM[4] configuration and its main components, understanding how this system works. Explaining better the generator operation, the Body Control Module and its existents modes that must cooperated with the new solution, the Engine Control Module and mechanism that allows us to made a fast implementation and measurements in the vehicle prototype.

The Chapter 3, will address an overview about the problematic related with efficiency influences for the components involved in the process of the electric power generation and storage, such as the engine, generator and battery, presenting their maps of efficiency and the mainly influence factors and behaviors.

After comprehending better the electric system in the vehicle and its main influences, the next step is to present the development of each structure used to achieve the object for this project. Then the Chapter 5 will introduce the improvement in the REC strategy, the Chapter 6 the new alternatives in the Fuel Economy Mode and the Chapter 7 implementation of the controllers and its final structure, where in all these chapters will be treat the problematic, steps used to develop it and some individual results.

The Chapter 8 will present the final obtained results and improvements achieved from the combination of the individual solutions, being both for the WLTP cycle and for real life drive. Finishing, the Chapter 9 will discuss about the conclusion and perspectives of future work of this project.

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[4] Electric Power Management

Chapter 2: EPM Configuration and Components

Before going into details about the controllers' development, the Recuperation Logic strategies and the smart generator control strategy. It is important to learn more about the components existents in the Electric Power Management (EPM) and their main modes of operation.

For the development of this project, the following structure was implemented in the car, as shown in the Figure 1:

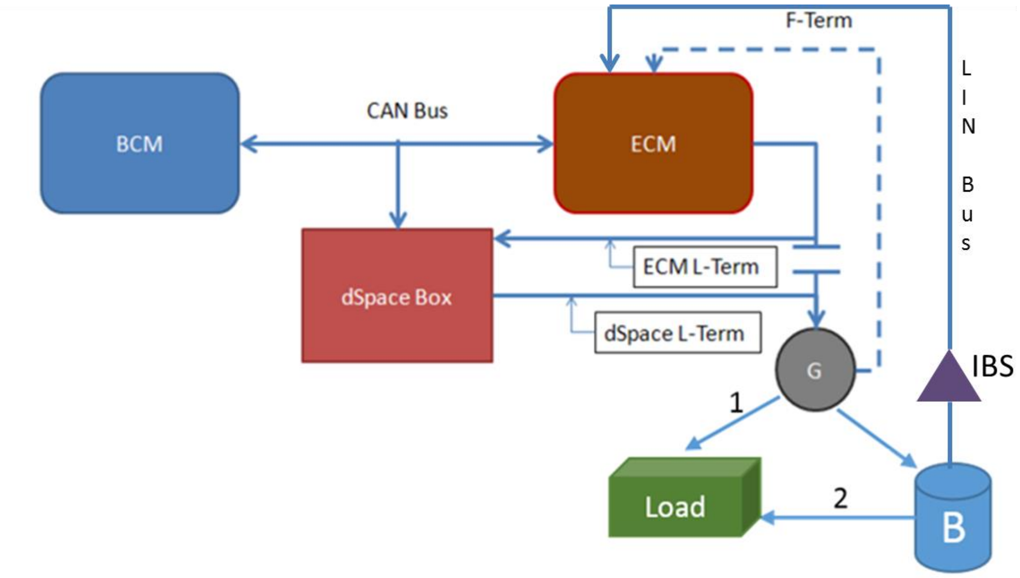

Figure 1: Hardware Implementation

The commercial cars do not have the dSPACE Box module and the communication between ECM and Generator been cut. This configuration was changed to be possible to implement all the functionalities existent in the BCM and ECM module to substitute them in this project. Generally, the BCM and ECM are responsible by their implemented tasks and modes to control the voltage that will applied by the generator. Then, this voltage will be used to supply the electric loads in the car (first way) to control the state of the battery and then supply the loads (second way), trying to increase the life of all components.

The main data from the battery, as the SOC, battery temperature, voltage and current, will be measure and sent it by the IBS sensor, where the ECM and BCM can read this data. Both modules can control the voltage of the generator, but the ECM has a higher priority than the BCM, so sometimes the ECM can override the BCM. The main functionalities of these modules and the generator operation will better explained in the next sections.

2.1 Generator Operation

The Generator is responsible to transform part of the mechanical energy provided by the engine into electric energy, which can be used to supply directly the components in the car or be stored in the battery to be used later.

The common generator has a stator wiring, where alternated current is generator due to the magnetic field variation by the rotation of the North/South poles of the rotor. The DC current in the rotor can be controlled to change the magnetic field, controlling the generated voltage and electric power. The energy produce will pass in the rectifier (diodes are used) to allow the current flow in one direction, 3 phases are used to have a positive output with ripple around the desired voltage. The Figure 2 shows better the generator schematics:

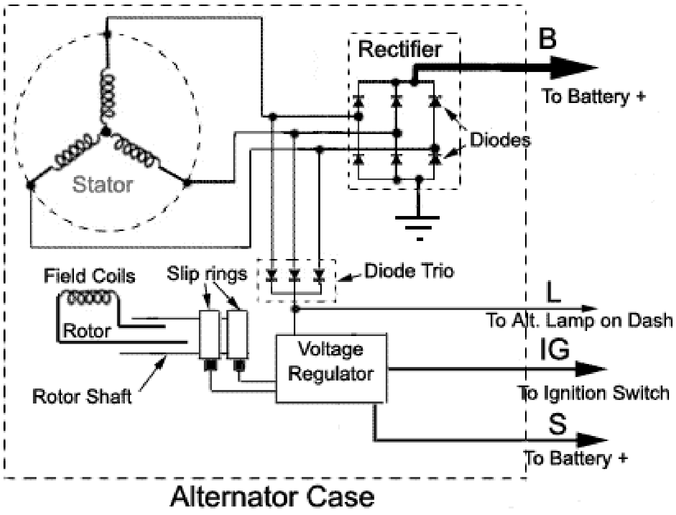

Figure 2: Generator Schematics

Thus, as it is already discussed in this chapter, the ECM as well as the BCM can change the voltage set points to control the Generator, but only the ECM has the physical connection to change the generator duty cycle by the L-Term, which ranges between 10 to 90% of the PWM wave.

In addition, as a feedback of the generator, the F-Term signal is provided to enable estimating the generator load on the engine by measuring the generator duty cycle.

2.2 Body Control Module (BCM)

This module controls many functions, such as lights, wipers, heat windows, etc., being the main controller in the EPM system. It is also capable to communicate on LIN Bus, HS-CAN and LS-CAN to get all the needed information to set different voltage set points, based on estimated SOC and battery electrolyte temperature, increasing the life of the battery.

The system sets several modes to control the needed voltage in the vehicle with a slow sample time (around 1s), using the RVC algorithm, where each mode has different conditions and priorities to entry or exit. Some of these modes are presented below:

- *Startup Mode*: After a key crank, as an attempt to recover the energy lost. This mode will raise the voltage to charge the battery and help in post glowing for a certain period of time;
- *Headlamps Mode*: When the Headlamps are on for a specific time, this mode starts to keep the voltage high enough for the lights can work properly and also charge the battery. Its priority is higher than the FEM and when this mode is active, the REC will not occur, avoiding visual effects, such as changes of luminous intensity.
- *Wipers Mode*: If the windshield wipers are active and a lowering voltage mode is active (like FEM), the BCM will boost the voltage.
- *FEM*: It is responsible to reduce the voltage after a key crank and during a vehicle driving conditions. Its main purpose is minimizing the fuel consumption. Entering or exiting in this mode, if some necessary conditions are checked, such as high electric load or high voltage is requested, temperature and battery conditions.

  This mode has two controllers that share the same structure, a voltage and current control. Switching the controllers is based on SOC and voltage thresholds which can decide discharging (the battery supply the loads), maintain a voltage in the car (generator and battery supply the loads) or keep the battery in idle (zero current), avoiding the battery cycling. However, this will better explain in the Chapter 6. Finally, when a lower SOC threshold is reached, the system goes out of FEM and starts to charge the battery until the entry conditions will be achieved again.

- *Normal Mode:* When the others mode are not active, this mode will entry, setting the optimal battery voltage, based on the battery electrolyte temperature and SOC.

2.3 Engine Control Module (ECM)

As its name suggests, it is responsible for several tasks related to the engine. Maximizing the engine power, reducing fuel consumption and control the gas emission. Besides, estimate several data, such for the engine as for the battery.

How this module is the unique that has physical connection with the generator and a faster sample time, this module presents the best features to implement controllers, which require fast response time. For this reason, the voltage control for the recuperation events is implemented in it.

2.4 dSPACE MicroAutoBox (MABX)

It is a real-time system for performing fast prototyping in full pass and bypass scenarios. It is based on Matlab Simulink models and it can support CAN communication, analog and digital outputs with several I/O functionalities. For this, it is widely used in the automotive industry.

Furthermore, there is the possibility to use its own development interface (Control Desk), creating real-time supervisor systems, where the model parameters can be set in online mode and be measured for pre or post signal processing. In addition, export the measured data can be exported in different file extensions.

Chapter 3: Influences on Component Efficiency

This chapter will discuss about the influences on the component efficiency and its main behavior for better understand it. Then, enabling what should be the most important characteristics to consider into the development of the efficient charge strategy, building in the end, the whole logic behind the smart generator control.

3.1 Overview of the Problem

Physic laws govern the electric power generation in the vehicle. First, the energy contained in the fuel is transformed by the combustion in mechanical energy with some loss. Depending on the engine speed, braking torque and temperature, it is possible to have a good estimation about its efficiency in relation to the produced torque and fuel consumption. Then, this mechanical energy will be converted into electric energy by the generator with more losses. The generator, like the engine, has some influences on its efficiency based on the F-Term, shaft speed and temperature.

If the energy provided was free, i.e. the extra load applied by the generator doesn't influence on the fuel consumption and the generator hasn't any limitation to provide energy, then the last step would be supply the car loads, where the last loss would be the existent in the cables and connectors.

However, sometimes it is important to store part of this electric energy to be used later. Making this happens it, a battery is necessary as an intermediate component in this system, including another efficiency factor to store the energy, which will vary its efficiency by SOC, temperature and load current.

Illustrating all these steps and giving a better idea about these transitions of energy with their influences, the Figure 3 can summarize it, as shown below:

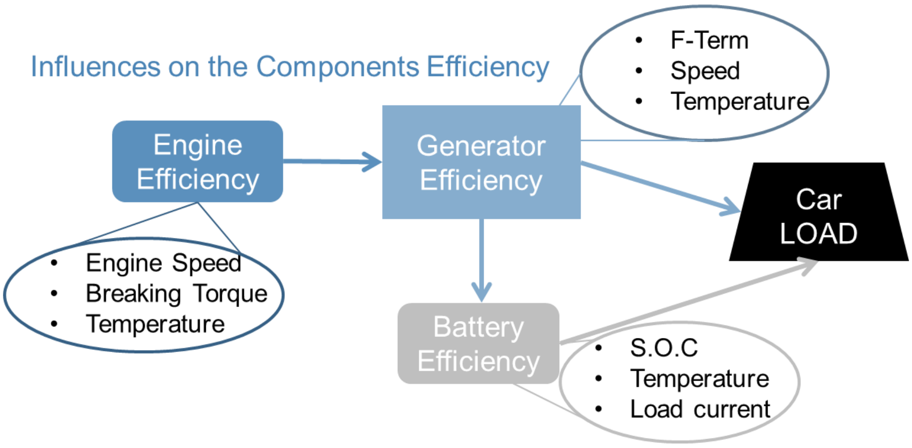

Figure 3: Influences on Component Efficiency

After this overview about the components and their influences in general, the next sections will give more detail about these issues.

3.2 Engine

How it was commented on the page 5, at the moment the EPM doesn't have a smart way to use the generator to charge the battery, this will happen in the modes that the voltage should be higher, charging the battery. Without consider any aspect of the engine and others components efficiency, only considering the improvement of the battery life (cases where the mode use the optimal battery voltage).

Estimating the fuel consumption in an engine requires complex models. Because, this consumption suffers from different influences and these influences are not only occasioned by manufactory issues or related with the normal work conditions, but also by the way of driving.

The aerodynamics, drags, engine temperature, quality of the fuel, how much the driver press the clutch, brake, accelerator pedal, the way the controllers were built in and a lot of others factors can rise or decrease the engine consumption. Despite of all these difficulties, it is possible to have a good approach for the fuel consumption, using only the engine speed and the braking torque, as generally it is used to calculate the BSFC (Brake Specific Fuel Consumption) to make possible to compare different engines.

Trying to use similar thoughts from the BSFC maps, the powertrain department, created the ESFC, Electric Specific Fuel Consumption, based on the braking torque (x axis), engine speed (y axis) and the fuel consumption by the energy for different supplied currents from the generator (g/Kwh). For the Astra GTC with a diesel engine, the follow ESFC map was built:

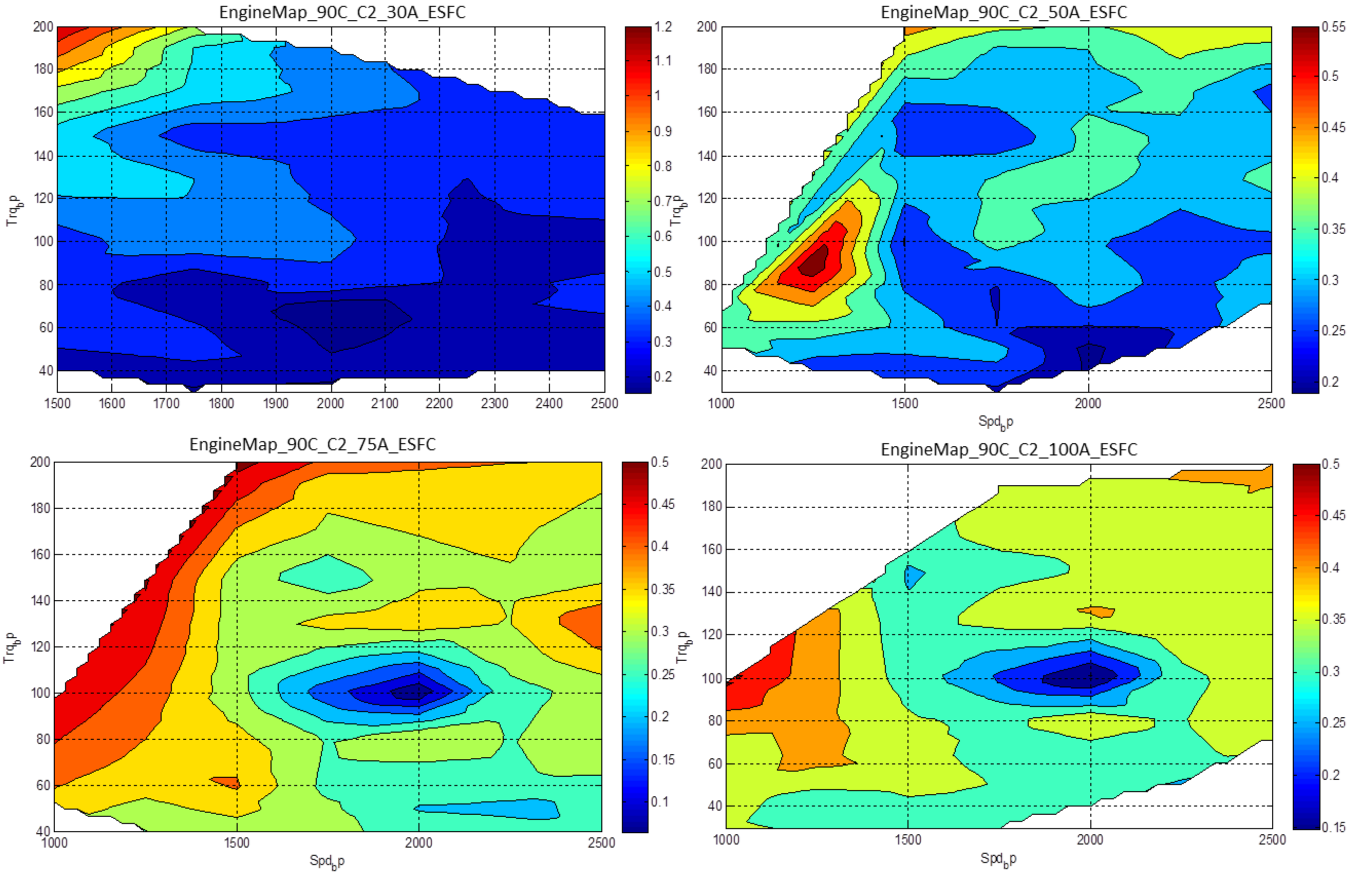

Figure 4: Diesel Engine ESFC Map

From the Figure 4, at a first look, it is not so easy to have a good clue about the behavior of the electric efficiency of the car. Nevertheless, comparing the map with the lowest current in relation to the highest ones. Despite of the idle speed is not showed (800-820 RPM) in these maps, looking for the tendencies of the increment of the fuel consumption for lower speeds, as it increases the current compared to the low current (30A) provided by the generator, the maps shows that the consumption has not a significant increment for lower braking torque (below of 100 N.m). It should be better to use lower currents than higher ones, being a good hint to supply the car on these situations, instead of charge the battery (This will better discussed in the Chapter 6), since supplying the car the current provided by the generator will be around of 25-30A[5]

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[5] See Appendix D

While for the other situations, it will be better to use the values founded in the maps to take better advantage of the maximum current that can be provided to charge the battery.

On the other hand, using the engine efficiency, the solution will be dependent of the engine presented in the car, i.e. for each engine, a different map should be created. Furthermore, as will be better detailed on the Chapter 8, developing a way to validate these data will be a tricky task. Because the reduction of fuel consumption is less significant for low currents supplied from the generator and repeating the same driver conditions for the measurements are practically impossible, which creates the necessity of getting a big amount of measures to validate it.

Despite of these difficulties, using the ESFC map to develop a smart generator control on engine efficiency and take into account that this solution is to be only a software change, then each reduction of fuel consumption without reducing their lifetime will be a good step of improvement for the system and for the environment (CO2 reduction).

3.3 Generator

The generator is responsible to convert the mechanical to electric energy. However, this process has an efficient factor too. This efficiency is calculated from the provided electric energy divided by the applied mechanical energy. For this, it will depend on the voltage, the current supplied from the generator, the speed and the torque of its axle.

The vehicle does not have a sensor to measure the current or voltage in the generator. The voltage measured in the electric network is the voltage of the battery measured by the IBS sensor, but as they are connected in parallel, the voltage should be the same if there was no voltage drop, however this it is not true, since there are losses occasioned by the connectors and cable resistance.

What concerns to the current, estimating it, requires a test bench to do it, since the current supplied by the generator depends on the capacity of absorption of the battery, which has many influences as presented in 3.4., the electric load existent in the car and the own current influences in generator that depends on the axle speed and temperature.

However, having an idea about the generator efficiency, the F-Term can be used. As this signal is a feedback of the duty cycle of the generator and it can give a clue about the influences of the generator loads on the engine and the supplied current. It is a good way to estimate the efficiency based on this available signal in the vehicle.

Thinking in these issues, the following map provided by the supplier of the generator can be used to observe the efficiency of the generator:

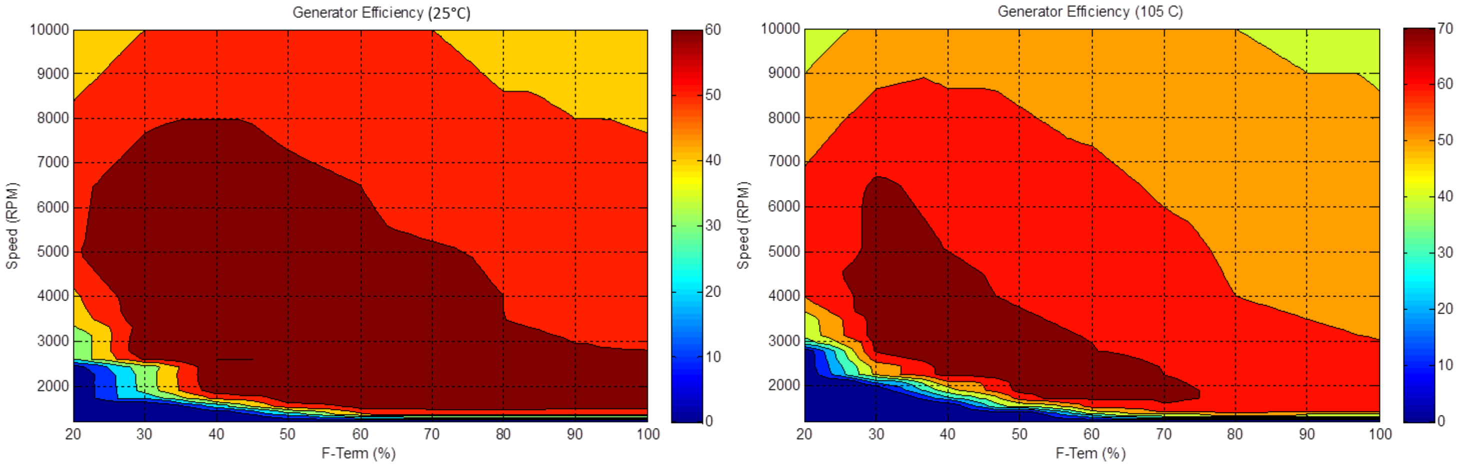

Figure 5: Generator Efficiency - KDAC NP14 140A

The Figure 5 shows that for low F-Term and low axis speed, the generator will work in a bad efficiency area. For idle engine speed if the F-Term is so low, i.e., the generator loads on the engine and the supplied current are low, for the same speed, charging the battery or raising the supplied current will move the operation point to a much better area of efficiency. Although, charging the battery in idle speed as showed in 3.2, it is not good for the engine efficient and supplying more current cannot be possible, because depending on the speed, the generator cannot provides this current and the battery current absorption capacity has its own influences. Finally, high speed and F-Term should be avoided too.

Giving a better way to visualize the desired work area, a chart was built to represent the variations of the efficiency in relation to the changes of the F-Term for the same speed as shown in the Figure 6. Looking for this chart, it shows that the desired work area for the presented solutions should take into account to work on the regions where the variations of efficiency are less, i.e., in the flat regions, which the most problematic regions will be the regions with low speed and F-Term.

In relations of how to handle this, the Chapter 6 will explain it.

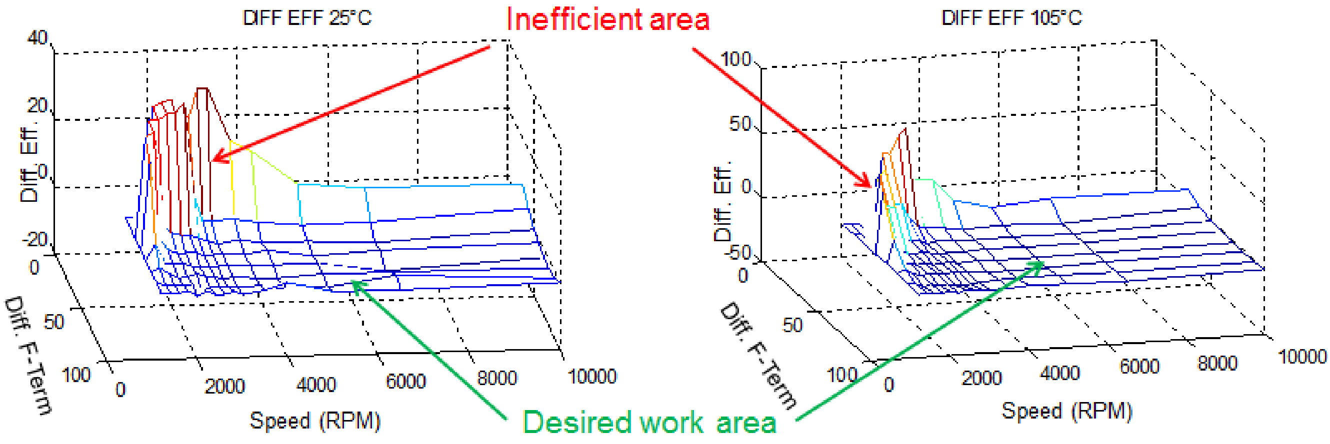

Figure 6: Efficiency variation in relation to F-Term changes

Moreover, using the representation on the Figure 6, the drag will be filtered, allowing to observe only the real electric efficiency variations on the generator.

3.4 Battery

Taking into account the battery efficiency has a huge importance for any electric power strategy. Because, minimizing the fuel consumption in the vehicle demands to choose the right moments to charge or discharge the battery based on the produced energy from the generator and the charging efficiency.

In this process, the battery has its own capacity to absorb energy, this means, if this was not take into account the generator will provide a huge amount of energy, but this energy will not be utilized when the battery is charging and consequently, the fuel injected in the engine to produce such energy will be lost it.

The capacity to absorb energy is strongly correlated to the electrolyte temperature and the SOC. For the temperature, when it is cold, the reactions are more difficult to happen what requires a high voltage to enable charging and consequently the capacity of the inrush current is reduced. Otherwise, with higher temperatures, the reactions are easier, lower voltage required and higher inrush current. However, if the temperature is too high, the voltages applied on the battery should be monitored to avoid the gassing effect and “cook” the battery.

In relation to the SOC, for the same temperature, low level of SOC implies a better capacity to absorb current and its increase. Furthermore, this capacity will reduce in an exponential decay, as Figure 7 shows it.

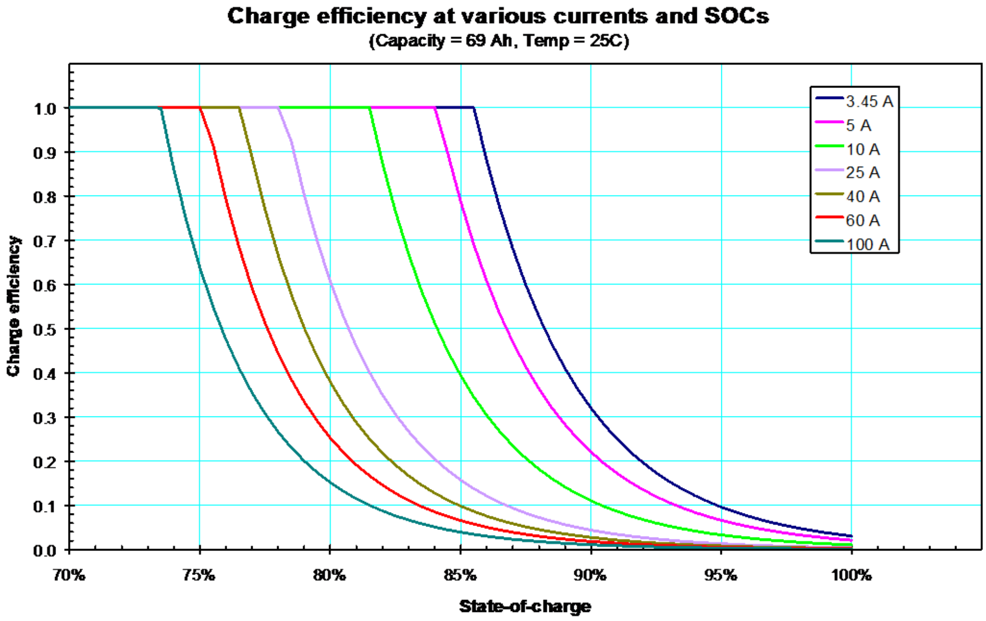

Figure 7: Battery Charge Efficiency - AGM, 69Ah, 25°C

Furthermore, another important fact to be considered about the battery efficiency influences is the cycling effect. Charging and discharging the battery several times will reduce its life time and as the battery gets old, its capacity of absorbing energy will reduce, which will change the time response, requiring changes on the applied controllers.

Thus, building a battery model that can include all these issues is not an easy task. This will require complex models, and in practice, such solution cannot be feasible due to the controller's physical limitations, as processing time and memory capacity.

Chapter 4: Attempt to Generator Modeling

As an attempt to estimate the current provided by the generator to be used on the Smart Generator Control, since the commercial vehicle does not have such sensor. On this chapter, it will be discussed the attempts to develop the current and the temperature estimator, since the current supplied depends on the temperature[6].

4.1 Temperature Estimation

How the temperature data is not available in the vehicle, an estimator need to be built. This way, it was tried several models with the existents tools in the Matlab. However, in this document will be cited only two of all the attempts to build it.

4.1.1 Hammerstein-Wiener Model

Developing a good temperature estimator, it is not an easy task. Getting all the thermic coefficients and influences, such as, friction heat, the engine heat transfer and others, it requires a lot of time, resources and know the thermal behavior of all components under of the hood.

Furthermore, as this was not the focus of the project, using the data available from the sensors, measurements made as an attempt to understand the behavior of the temperature inside of the generator and the Matlab tools, it was chosen a faster way to build this model. Based on the signals measured (F-Term, Engine speed and engine coolant temperature) and the Hammerstein-Wiener model, using the identification tool from the Matlab, it was obtained the following result showed in Figure 8.

This model was chosen, because the temperature has a nonlinear behavior, three signals as input for one output, besides it can represent the nonlinearity based on real measurements, using some tables, reducing the complexity and representing the linear behavior for a simple state equation for multiple variables.

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[6] Understanding all the influences, see the 3.3

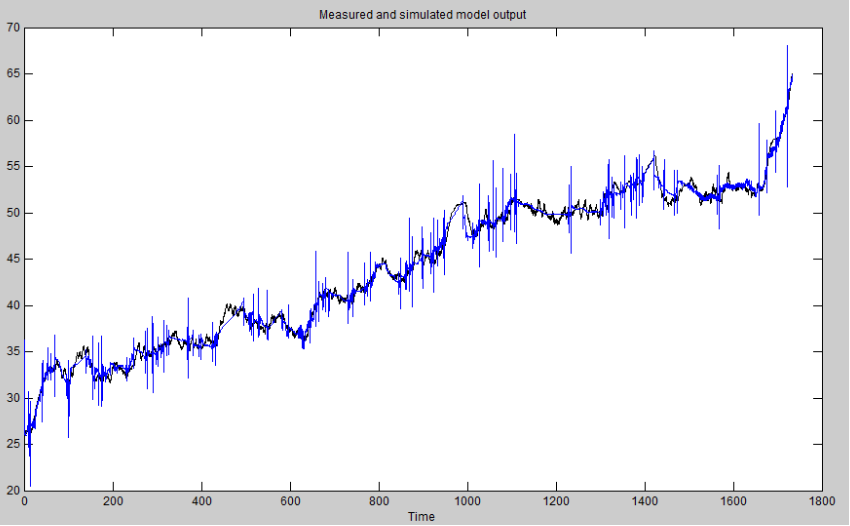


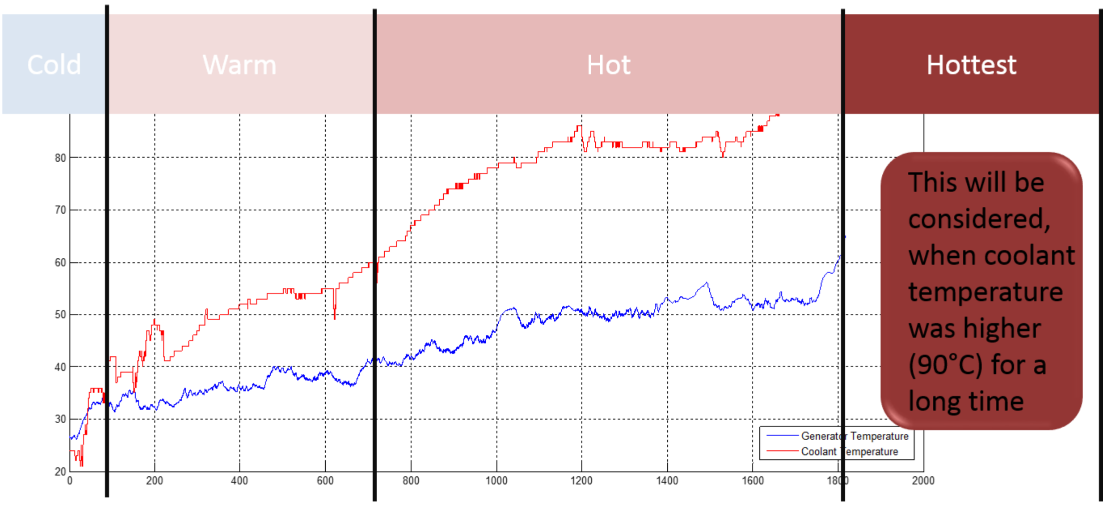
Figure 8: Hammerstein-Weiner Temperature Model on WLTP cycle

Despite of the results on Figure 8 can be considered a good approximation (blue line) for the behavior of the temperature on the WLTP cycle (black) in the offline model, when this model was used for real life drive and implemented in the car, some gaps on the measurement started to appear. Showing us that the processor used in the car works on the limit with all the tasks and a simple solution should be used, instead of a complex model or a nonlinear model, making us to go to the next solution presented.

4.1.2 Changing Set Point

After the problems with the nonlinear model discussed before, it was tried a simple way to get good results without the necessity to go deeply with the thermal theory or waste a lot of time and resources with this.

It was proposed to use a temperature changing set point, based on some measurements made on the WLTP cycle, analyzing the behavior of the engine coolant and the generator inside temperature. Using these data, it was divided into four temperature set points regions (Cold, Warm, Hot and Hottest), as it shows Figure 9. Having as a trigger to change the inside temperature to estimate the generator current, where the inside temperature in these regions to be used is setting from constant temperature set points and the running time of the engine.



This will be considered, when coolant temperature was higher (90°C) for a long time

Figure 9: Temperature Changing Set point Model

With this simple solution accompanied with the current generator estimator, it was possible to get good results as will be showed on the next section. However, this goods results seen on WLTP cycle was not reproduced for real life driver and changing the trajectory to use the Smart Generator Control only on FEM[7] due to the improvements of the REC strategy, a simple solution could be used (next Section).

4.2 Current Estimation

On parallel to the development of the temperature estimator, it was made many efforts to build a current model, using the temperature estimation as an input signal, engine speed, F-Term, battery voltage and others. Based on these signals, it was tried to build a Hammerstein-Wiener model, but with the problems presented the previous section, this solution was dropped.

Then, a simple solution was tried to solve the problem, using the data provide by the supplier: the generator torque and the efficiency, where these data depends on the engine speed, F-Term and the Temperature (using the changing set point solution) and applying the follow equation:

$$Generator\ Current = \frac{PulleyRatio * EngSpd * Torque}{Battery\_Voltage} \tag{4.1}$$

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[7] This will be better discussed on Chapter 6

This equation comes from the conservation law, assuming that all the mechanical energy will be transformed on electrical one. Although this is not true, because we have part of the energy lost by losses, mechanical, thermal or electrical. A good result was obtained on WLTP cycle as showed:

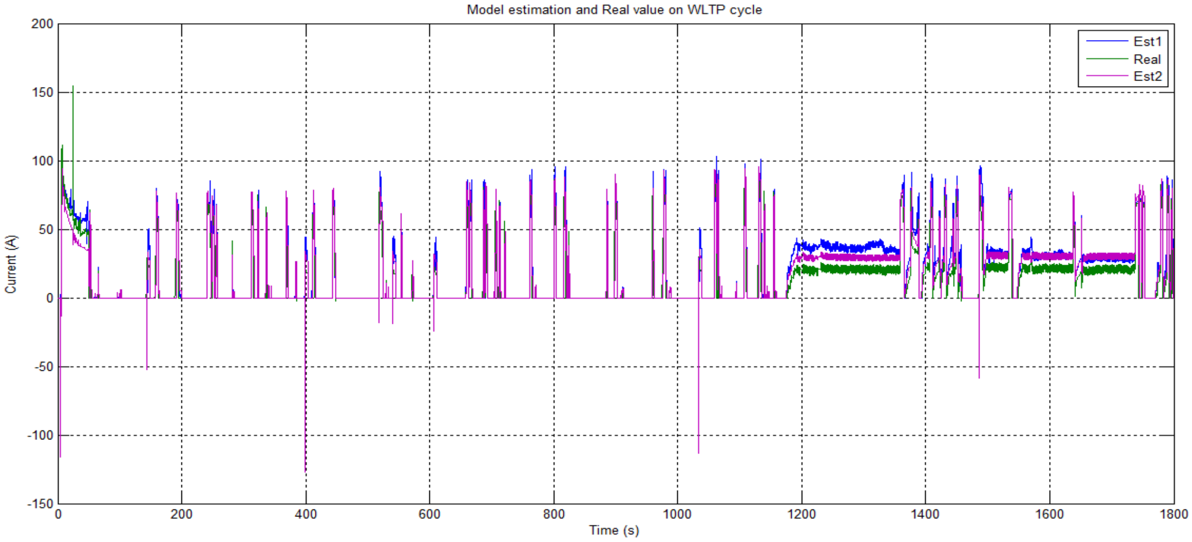

Figure 10: Real and Estimation values for Generator Current on WLTP

The Figure 10 shows the generator current estimation for the equation 4.1 (blue), the real value (green) and the estimation using the average of electric load (purple) on WLTP. Despite of the encouraging results on cycle using the equation 4.1, this model has some limitations: depend on the inside temperature estimation, the accuracy of the data provide by the supplier, turn the solution dependent on the generator type and brand, besides to increase the memory used on the modules to store such tables.

Thinking to simplify the current estimator, the final solution for the Smart Generator Control and knowing that with the improvements of the REC strategy[8] the solution should work only on FEM, it means that the average of electric load consumption on the car is practically constant in the vehicle[9], a new model was created. This model is based on the average of electric load consumption in the car (around 30 A) added to the battery current and looking for the F-Term, the lowest F-Term to determine when the generator is off. This simple solution could have good

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[8] This will be discussed on the Chapter 5

[9] See Appendix D

results as showed the measurement on the cycle (Figure 10) and in real life drive as the Figure 11 shows the difference between the real and the estimated from the both models:

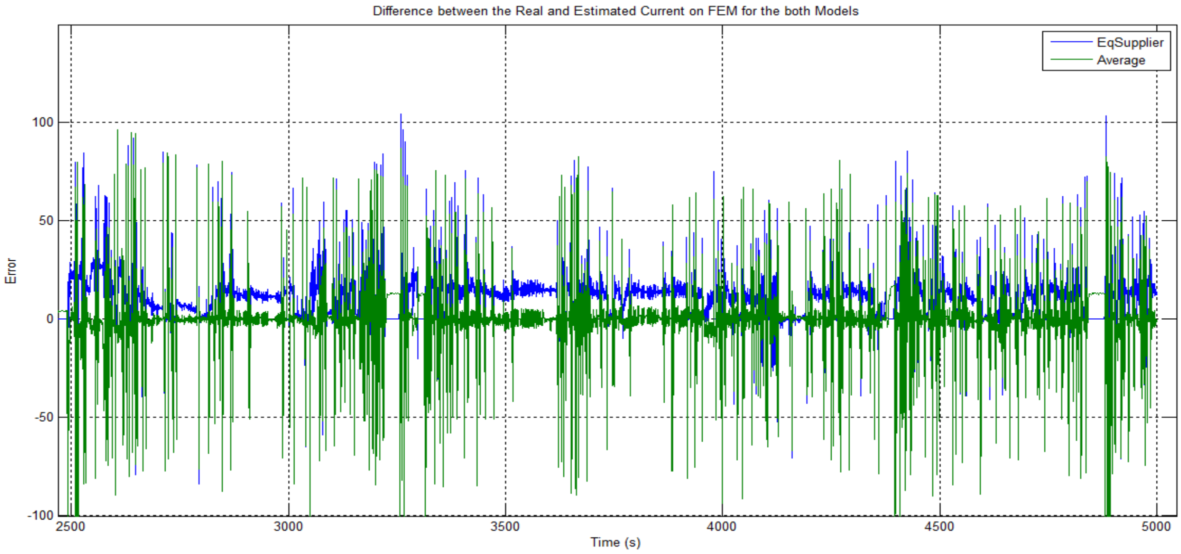

Figure 11: Real and Estimation Difference for Generator Current on Real Life drive

Analyzing Figure 11 is possible to observe that the Average model (green) presents a better result compared to the equation 4.1 model (blue), since the average model has the average in zero for the difference between the real and the estimated values. Then, with a simple solution could cover better the real life drive and the cycle to estimate the generator current, without the necessity to depend on the inside temperature estimation and the generator type and brand, only need to know the average of electric load consumption in the vehicle.

Chapter 5: Recuperation Strategy

There are already commercial cars with recuperation technology and researches to improve it. Although with the adoption of the new test cycle profile, changing from MVEG to WLTP, a new attention was given to it. At a first moment, it was thought that the recuperation events could not provide the necessary amount of energy to stay inside of the allowed discharge window in the cycle[10]. Moreover, along of this chapter and the Chapter 8, it will be presented that can be possible to provide this energy, making some changes in the recuperation strategy and its voltage control.

5.1 On the ECM

Initially, the recuperation events occurs when the Fuel Economy Mode (FEM) was active and a “free” energy can be observed, i.e., where the generator can provide energy without any fuel injection. However, this assumption does not take into account the time to ramp up and down the generator voltage, which can take more than 2 seconds for each step. Besides this, the logic assumes that if the clutch was pressed, independently if was for a down shifting moment, the recuperation will not happen.

In order to illustrate better this situation the follow measure is shown:

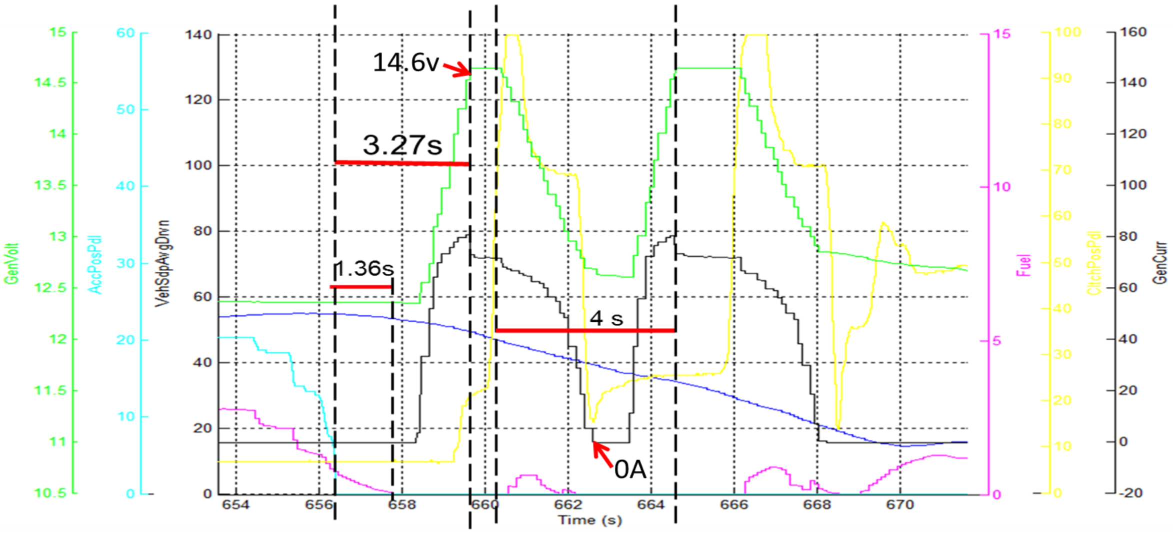

Figure 12: Recuperation with ECM

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[10] See Appendix C

As Figure 12 illustrates the ECM controller did not take advantage of the transition points, when the accelerator pedal is released the fuel injected take around 1.36s to reach zero and this situation can be seen on different engines. This way, the ECM loses time waiting for no fuel injection to then ramp up the voltage, which takes around 1.8s. Then, when the clutch is pressed, the logic says to go out of the recuperation. In the worst case, some measurements were seen that in a good point of recuperation we could lose around 52% of the whole recuperation time.

Thus, the new strategy need to take into account this and other situations that will be better explained in the next section.

5.2 The new Recuperation Logic

The considerations for the ECM logic for the REC events was enough for the MVEG test cycles, but with the adoption of the WLTP, the time without fuel injection was greatly reduced. Extending the REC events for the regions where the impact of fuel are less significant, was necessary, avoiding to charge in regions where the fuel injection is higher, such as the acceleration points.

The dSPACE model utilized in the vehicle, had already an implemented REC logic as an attempt of improvement of this strategy. However, this logic could be generalized for a simple model, reducing its complexity and include some situations that was not covered by it, such as downhill events, idle speed and cruise mode.

Thus, improving the REC logic, an offline model was developed, which contains the old solution and the developing logic using the signals available in the measurements in the cycle and real driving.

Compared to the old existing model, detecting a deceleration events will be based on the vehicle speed, instead of looking for the engine speed. Since the engine speed is not so constant due to the gear shift events, using the engine speed only to detect the up shifting and not reaching an idle speed. Furthermore, using battery voltage threshold to avoid REC in others modes must be avoided, as will be explained on the Section 6.4. Besides this, other signals and conditions were used to avoid REC in wrong areas and allow in downhill and cruise mode, where the deceleration can happen, but the accelerator pedal will not be used.

The car used to this development has a Stop/Start system, it means if the battery conditions are observed, the idle engine speed will not occur, but for real life and other cars that have not this system, the idle speed need to be detected. Beyond that, after discussing with the powertrain department, a fuel injection will start even if the accelerator pedal was not pressed in REC event; the engine does this for stability issues. Moreover, if the generator is active in these cases, the impact of fuel consumption can be higher, as compared on the Figure 13 and Figure 14.

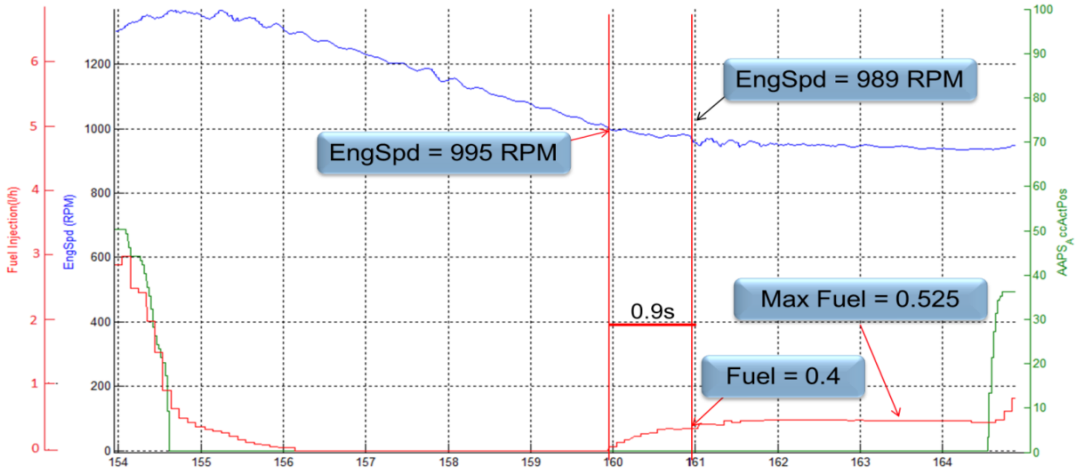


Figure 13: Fuel Injection on Idle Engine Speed with Generator off

For the same situation presented on the Figure 13, if the generator is not active, the fuel consumption will be less than 0.525 l/h, otherwise the fuel injection is higher than 1.025 l/h, increasing the impact of the fuel injection.

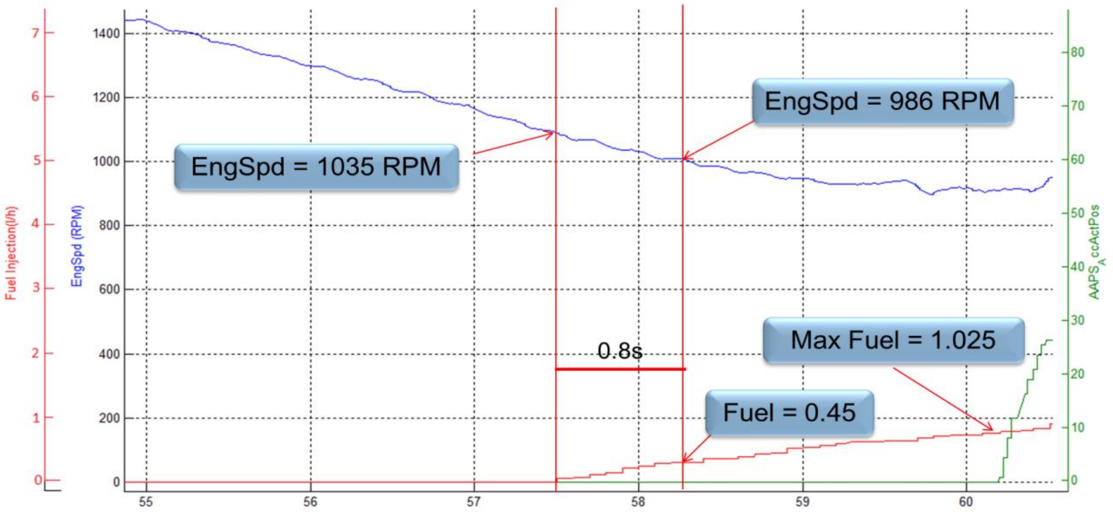


Figure 14: Fuel Injection on Idle Engine Speed with Generator on

Based on the idle engine speed concerns and the issues addressed in this chapter, a new logic to detect the REC events was developed. This strategy was built in a single task that can be divided into three parts: entry, keep and mandatory conditions, as presented below.

```
Mandatory:
If Engine speed > idle_spd_Threshold AND
If Headlamps are not on AND
If Vehicle speed > min_VehSpd_Threshold AND
If Clutch is not pressed > max_ClutchPressed_Time AND
If Entry or Keep conditions are true
Then REC is Active
Entry:
If (Fuel < min_Fuel_Threshold AND Fuel decreasing) AND
If (BrkPdl > Offset_Threshold OR VehSpdDecelLogic is true OR Fuel is zero) AND
If (AccPosPdl decrease gradient > Acc_Step_Threshold OR AccPosPdl is zero) AND
If (NotUpShifting(CltchPosPdl, VehSpd,EngSpd) is true)
Then Entry Condition is true
Keep:
If (in REC before) AND
If (AccLogicCond(AccPosPdl, AccCondOnEntry)) is true AND
If VehSpdDecelLogic is true OR Fuel is zero AND
If MinimizeFuelRECLogic isTrue
Then Keep Condition is true
```

The mandatory part includes the main conditions that need to be observed, before start or continue the REC event. The engine speed condition and the clutch condition are there to avoid recuperation in idle speed due to the problem already discussed in this Section. In addition, the headlamps condition is there because when the lights are on and a REC occurs the lights can blink due to the higher voltage applied by the controller and for the customer this is an undesirable effect.

Moreover, the entry conditions, as its name suggests, are responsible to start the REC. Basically, this logic tries to predict when a deceleration point starts, as showed in Figure 12, respecting some fuel conditions and observing if the deceleration is not caused by an up shift event. In that case, the system presents no fuel injection and a vehicle deceleration for a little moment.

Continuing the REC, the logic will observe if the vehicle still decelerating and the driver does not press the accelerator pedal again. How this logic looks for the accelerator pedal and the vehicle speed, when in cruise mode, the logic can stay in or go out of REC without considering the accelerator position. In addition, the MinimizeFuelRECLogic was created to mitigate the impact of fuel injection, when a deceleration can be observed, it is not an up shift event and the fuel injection is decreasing, but the fuel injection will not reach zero.

Finally, the Fuel condition (Fuel is zero) in the Entry and Keep part is there to cover the downhill events, where the vehicle speed can increase without any fuel injection.

Testing the new REC logic developed based on the same situation presented in the Figure 12. It is almost impossible to reproduce the same condition, so for this, the offline model was used to test it. Then, as it was possible to have a constant REC signal, enjoying the transitions of fuel, increasing with this, the average energy in the real REC events (No Fuel) was increased. As showed below:

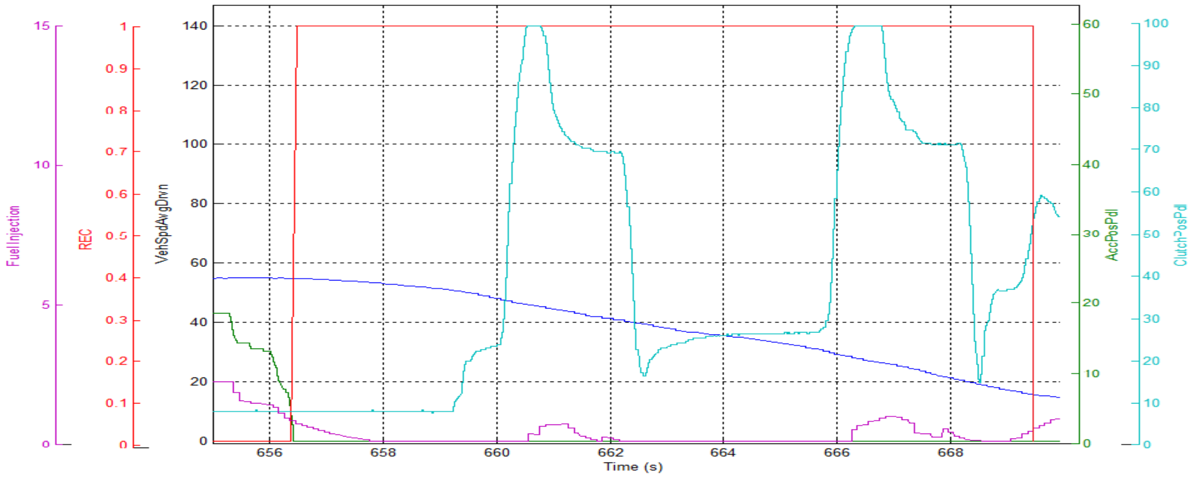


Figure 15: Offline Test for the New REC Logic

Utilizing the same offline model for the cycle, this new logic raises the amount of REC events compared to the ECM controller, from 50% to over than 85% and compared to the old dSPACE model, it increases by 15%. Chapter 8 will show this improvement better for real applications on the test cycle.

In addition of this new logic, to be able to set the new thresholds, the following calibrated parameters were included in the Control Desk interface:

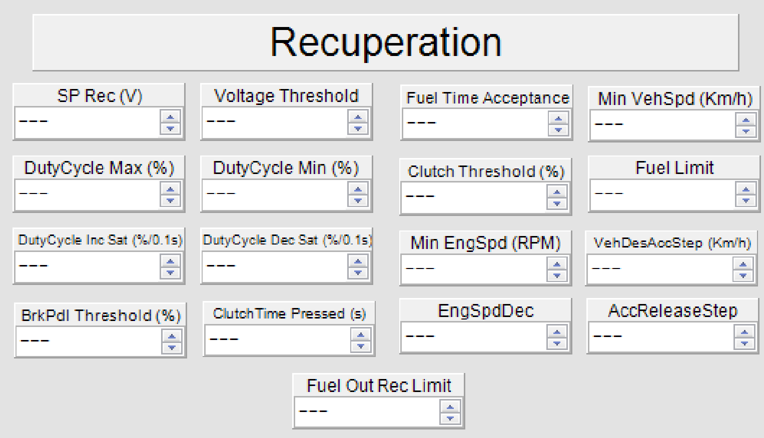
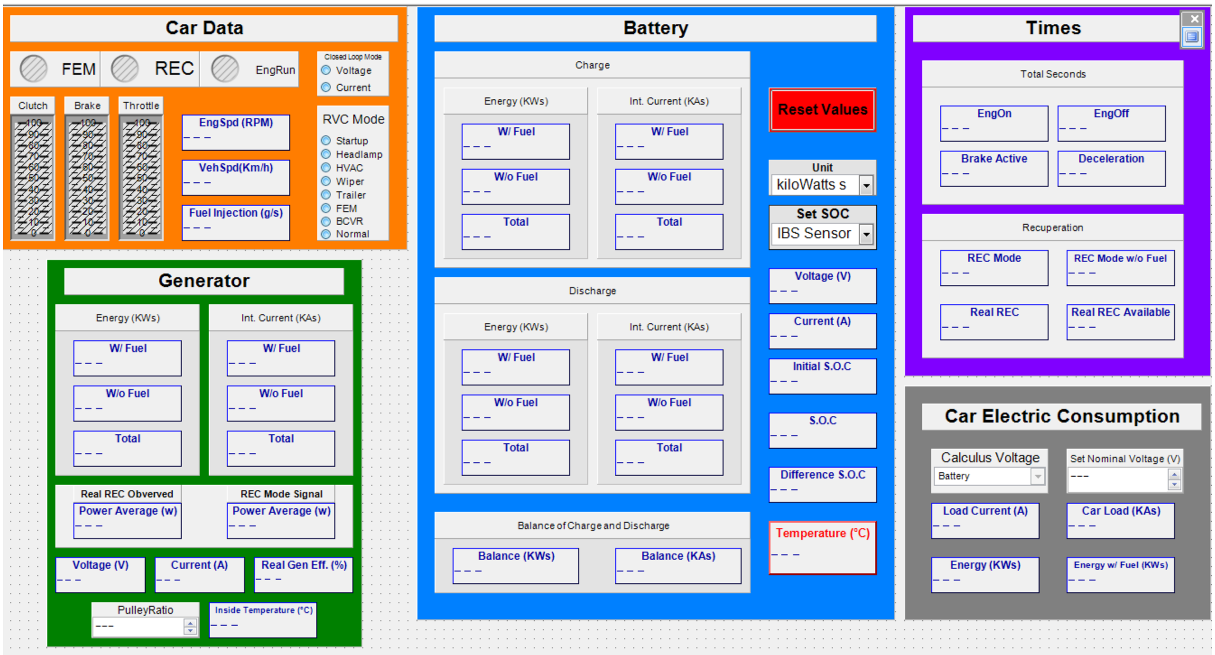


Figure 16: Calibrateable Parameters Included in REC logic

Following the real time measurements and analysis them, evaluating the results of the new strategy, the following interface was developed:



Unit: kiloWatts s

Set SOC: IBS Sensor

Calculus Voltage: Battery

Figure 17: Real-Time Evaluating Interface for REC

Finally, in case that some data was not measured in the vehicle and to enable the post signal processing, an interface for offline measurements to evaluate was built, utilizing the Matlab GUI interface. In Appendix B, it is possible to visualize the interface windows.

Chapter 6: Alternatives for the Smart Generator Control

This chapter will discuss about the developed alternatives that were combined with the improvement of the REC (Chapter 5 and Chapter 7) will construct the main purpose of this project, the Smart Generator Control. Moreover, it will justify all the realized choices and steps, to develop these alternatives and bringing up the problematic of the legacy alternative existent on the EPM system.

6.1 Legacy Alternative in the FEM

Analyzing the influences presented on the Chapter 3 and the main existent modes on the BCM, in 2.2, the necessity of improvement of EPM strategy is concentrated in the FEM, because in this mode the system will work in inefficient areas. Looking at the components efficiency cannot be an easy job, since depending of what the system is prioritizing, what can be considered efficient for one component can be completely different for another.

For example, when the normal mode is active, the system is prioritizing the battery life by choosing the optimal battery voltage without caring about the fuel consumption. In analogy, the Headlamp and wiper mode will increase the battery voltage to support these devices and enhance their lifetime too. Nevertheless, throughout this study, we will see that the wiper mode is obsolete, since a high voltage is not necessary and no visual effect can be detected from increasing the applied voltage.

The unique mode where all the conditions are convenient to improve the components efficiency and enabling to reduce any fuel consumption, it is in the FEM. Since, in this mode, the electric load in the vehicle is not high, which does not require raising the voltage in the power grid, allowing to develop a strategy to choose the rights moments to discharge, supply (zero battery current) or charge the battery and how do it.

Based on this, the legacy alternative for FEM presents some problems on its concept, in relation to the components efficiency as the Figure 18 shows:

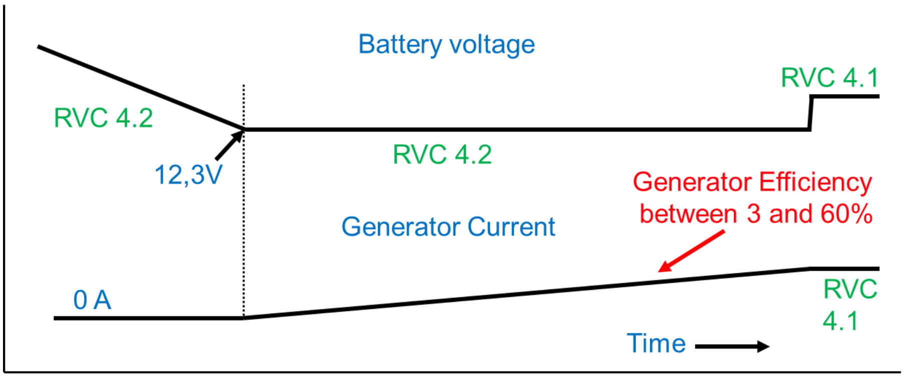


Figure 18: Old RVC Control

Figure 18 shows that the legacy FEM alternative discharges the battery until the battery voltage reach 12.3v, using the RVC 4.2 (voltage control) and then try to keep the battery voltage at this threshold. However, when this happens, the voltage control does not care about the generator efficiency, supplying small current from the generator; independently if the F-Term or Engine speed are low (see Figure 5).

When a SOC threshold is reached, the system will switch from RVC 4.2 to RVC 4.1 (current control) supplying the car. This will not stop to discharge the battery, but it will be slower.

The alternative has not an efficient way to charge the battery; the mode presents small charge times, but only to avoid the stratification and sulfation in the battery. This way, the mode is based only on the REC to charge it, which can take a long time to increase the SOC (this will better explained on Chapter 8).

Thus, as it takes a long time to charge it, the system, at some point, will go out from FEM raising the system voltage, which probably will be caused for another mode, such as the normal mode, headlamps or any other mode, charging the battery.

The next Sections of this report will try to illustrate all the steps of the development and improvements of this strategy until to achieve the final version that could work not only in the WLTP cycle but also in real drive.

6.2 First Solution Proposed

At the beginning as an attempt to solve the problem with the change of the cycle, since that the REC points were reduced and the old REC logic was not enough anymore to stay in the allowed discharge window(consult Appendix C). This solution tries to maintain the same principle that was observed in the previous section, i.e., continuing to discharge the battery and reducing the battery cycling, but now taking into account the generator efficiency. Then when the problem on the cycle is solved, the next step must be to extend this mode for real life driving (include the engine efficiency).

The first change on the RVC in the FEM was lowering the SOC threshold that controls the discharge of the battery on the preparation cycle compared to the old logic, as a way to increase the charge acceptance on the REC events. Although, all the structures from the REC and RVC controllers are kept the same, changing only the logic to switch the RVC mode from 4.2 to 4.1, as the Figure 19 shows it:

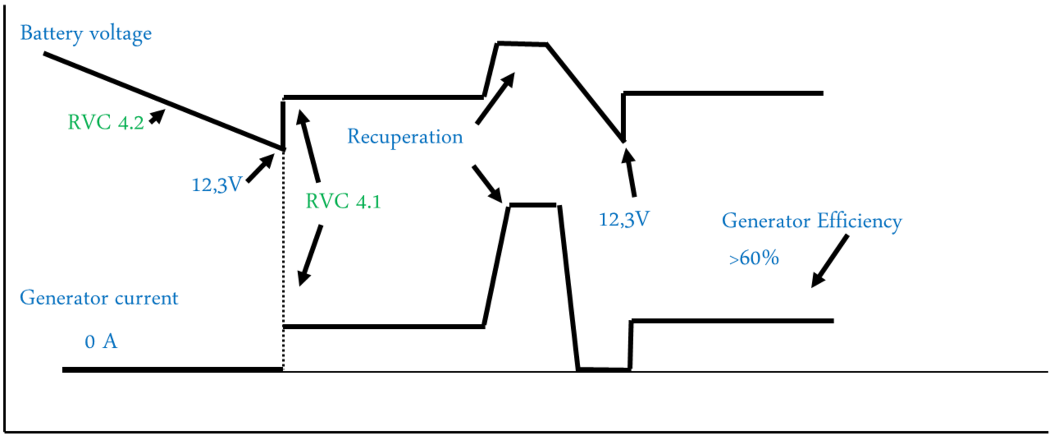


Figure 19: First Alternative for FEM

In this alternative, the startup mode will still occur after a key crank to cover the necessary energy to start the engine. Nevertheless, if the battery presents a high SOC level and all the conditions to enter into FEM are verified, it makes sense to remove this mode, since we will discharge the battery after charging it (Section 6.4).

Furthermore, after the startup mode, the vehicle will go into a discharging mode (RVC 4.2) until a voltage threshold is reached. When this threshold is reached, different to the old alternative, instead of keep the voltage in this threshold, the RVC will switch for the current mode (RVC 4.1) to keep the battery current around zero. In case of the engine speeds is low or in idle and the F-Term measured on the generator is below of the efficient threshold, the RVC will switch to the discharge model, avoiding that working in inefficient areas for the generator. In addition, other additional points of discharge will occur in Autostop and after a REC event until reaching the voltage threshold again and switching for the RVC 4.1 mode.

For this new strategy, the following signals are necessary: the voltage battery signal (from the IBS sensor), engine speed, F-Term, REC mode and the RVC mode signal as a trigger to detect when the system needs to switch the controller mode.

Then, with these simple modifications, followed by the improvements of the REC logic and the adjustments in its own controller. It was possible to develop an alternative that could work in the efficient areas of the generator and in the same time enhancing the battery lifetime without going out of the allowed discharge window on the cycle, as will be shown in the Chapter 8.

6.3 Second Solution Proposed

This solution was an improvement of the previous alternative. After some measurements on cycle (Chapter 8), using the previous alternative as a basis and accompanied by the new REC logic and controller. It was observed that the REC could provide more energy than we could discharge from the allowed window and with the change of the battery for a new one, the acceptance of energy was increased, enabling even more energy to discharge.

Thus, in this alternative were included new points of discharge, adding new signals, such as the SOC, the initial SOC, a discharge threshold with the allowed SOC difference in the cycle and a calibrate time to stay in the RVC 4.1.

This new part of the alternative will look for the instantaneous SOC level and the initial SOC after the key crank. If the mode switch from the RVC 4.2 to 4.1 and the system is still inside of the allowed discharge window, the vehicle will stay on RVC 4.1 until the calibrated timeout and then switch to RVC 4.2 to allow more discharge until the voltage threshold is reached again. Case the system is still inside the allowed window this will repeat; otherwise, it will stay only in RVC 4.1, supplying the car. As it can be shown in the Figure 20:

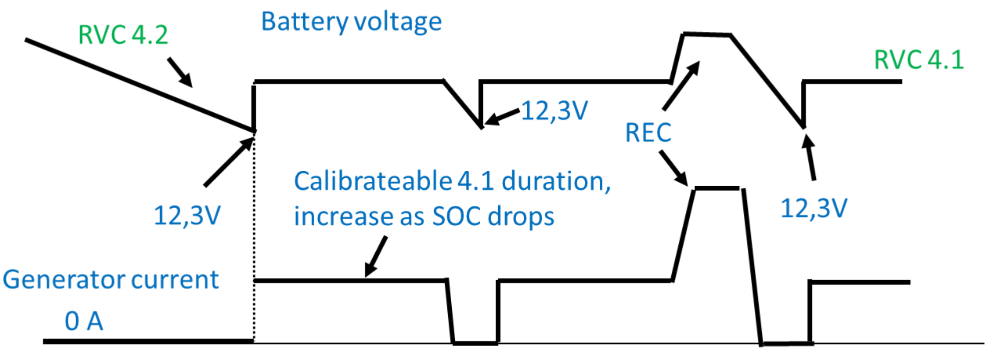


Figure 20: Second Solution for the FEM

Despite of the fact this solution was created to cover the WLTP cycle, with the change of the battery and improvements of the REC, this alternative will show only the discharge behavior, since that we will never reach the lower limit of the allowed window.

6.4 Improved Solution for Real Life Drive

As addressed on the end of the previous Section, as the problem on the WLTP cycle is solved, since with the improvement, the generator will be off in the whole cycle. Moreover, in case the battery conditions are not good; at least the alternatives will keep the system in the allowed discharge window, looking for the generator efficiency and battery lifetime. The next step, it is enhancing the FEM outside of the cycle, i.e., for real life driving.

The first thing that needs to be changed is the exit FEM SOC level, lowering this value to include a region to implement an efficient charge mode. This way, the FEM can still have a discharge region, where the generator can be off and it presents the best reduction of CO2 emission as possible and taking advantage of the low electric loads in the vehicle to use an efficient strategy to charge the battery.

Thus, the new FEM strategy developed will be divided in five distinct regions as the Figure 21 shows it:

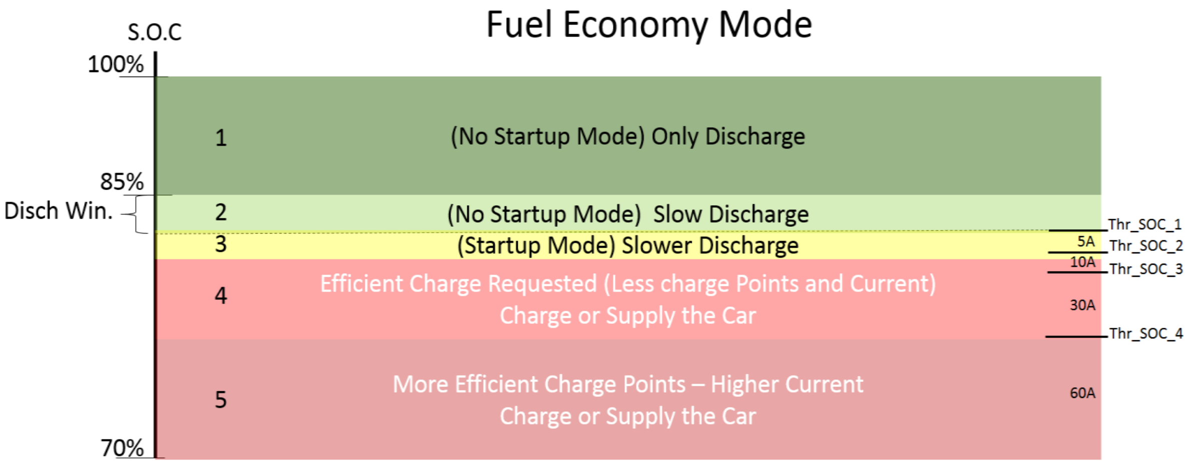


Figure 21: New FEM Strategy

The first region is responsible to discharge the battery, only the REC events will charge the battery and in this phase, if all conditions are observed to entry in FEM the Startup mode will not execute it. In the second region, the same behavior for the Startup mode will be seen in analogy of the alternative presented in 6.3, a slow discharge will occur switching from the RVC 4.2 to RVC 4.1 according to the voltage conditions. In the third, as the system is outside of the allowed discharge window, if this happen during the driving and stay in this region for certain calibrateable time, a slower discharge will still happen in the battery as similar in 6.2. Otherwise, if the initial SOC detected after a key crank is inside of this region or the calibrate time is exceed it; an efficient charge will be requested. When the car is not charging the battery, the logic will only supply the car, discharging will be not allowed anymore as an attempt to fast charge the battery and come back to the middle SOC threshold, allowing again a slow discharge and slowing cycle the battery, increasing its lifetime.

The efficient charge region is divided into two regions (red regions in Figure 21). In these regions the Startup mode is allowed and for these area the strategy will try to equilibrate the efficiency of the all the involved components, battery, engine and generator. As the first region is near to the middle SOC threshold, in this region (fifth region), the amount of efficient charge and current are reduced and as the SOC level is lowering the current and charge points will be increased to enjoy the battery charge acceptance.

Implementing this strategy, the solution was divided into two tasks with different sample time. As the battery SOC changes are slow, all the FEM logic to detect when discharge, supply or an efficient charge is requested can be implemented in a slower task (sample time around 1s). However, the battery current set point according to the battery charge efficiency (Figure 7) and the logic behind of the detection of where to charge it efficiently needs to be in a faster task (sampling time 0.1s).

Thus, this solution is based on the battery charge current and engine efficiency (Figure 4) to choose the right points to charge it by using a battery current control (as showed it in the Chapter 7). Initially, the FEM controller was kept supplying the vehicle when no efficient charge is requested. But, how the sample time of this controller is slow and the way of this controller was built it, since first the controller reach 13v (it can take more than 3.8s depending the SOC level) to then control the battery current to zero. After some measurements in the vehicle, it shows to switch from the REC controller to supply the car (FEM Controller) could take more than 20s and in all this time, the battery will be discharged to provide energy for the components. Furthermore, depending on the battery current set point in the efficient charge, it can discharge more than charge it, taking a long time to raise the SOC level and also cycling the battery. This problem is illustrated in the figure below:

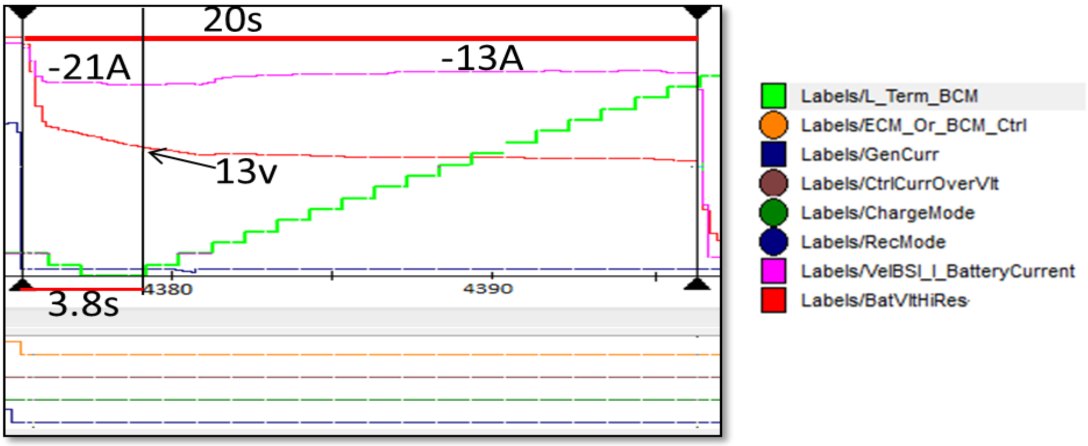


Figure 22: Problem using FEM current control to supply the Vehicle

Avoiding this problem, when an efficient charge mode is requested, instead of using the FEM current control to supply the vehicle for low battery current set points (below of 25A), it is better to use the fast current control due to its high dynamics. And when a high battery current set points is used to charge (over than 25A), use the FEM control, to increase the step variation of voltage, introducing a little discharge to go to charge, allowing to increase the observed current absorb for the battery.

The logic to detect where to charge efficiently will try to conciliate the efficiency of the battery, engine and generator and their influences (Chapter 3). First, based on the SOC level, the logic will select among four set points, the maximum current that can be used to charge the battery with efficiency over than 75%[11]. With the selected current, the logic needs to estimate the generator current to provide such set point. However, estimating the generator current is not an easy task and getting a good estimation requires complex models. Although in FEM how the electric loads are low and almost constant, simply using the average of the electric consumption to estimate the generator current can be enough.

Assuming that the set point current can be provided, the estimated generator current, engine speed and braking torque will be used to get the ESFC[12] value to be used in the conditions to detect where to charge. Then when the EffChargeMode is active, instead of using the battery set point, the logic will use the measured battery current to estimate the generator current.

The ESFC will pass through the following conditions to decide for EffChargeMode:

If (ESFC ~= 0 **AND** ESFC < ESFC_Thres) **AND** FilterCond(ESFCThres, ESFC) **AND**

If Vehicle Speed > VehSpd_Threshold **AND**

If UpShiftingGear(VehSpd, Clutch, EngSpd) **OR (**Brake Torque > 0) **AND**

If FEM **is Active**

Then EffChargeMode **is Active**

If EffChargeMode **is Active,** It **will be Active:**

If (NotIdleSpdCond(EffChargeMode, EngSpd) **OR** HighTorqNotReq(AccPosPdl))

The logic will look for an ESFC value over than zero and below of the maximum threshold for considering an efficient value from the ESFC map. The FilterCond was a created function to avoid chopping the Efficient Charge Mode signal due to a possible

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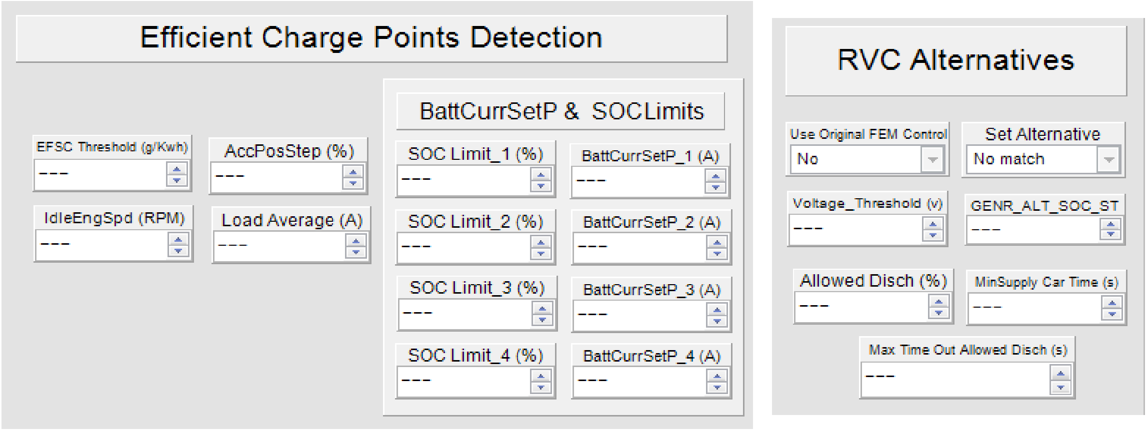
[11] See Section 3.4 to understand better the efficient charge current for the battery

[12] See the ESFC map in the Section 3.2

instable ESFC value from the map. In addition, the third condition is used to stay in the efficient mode if an up shifting gear is detect (UpShiftingGear function) and avoid efficient charge in deceleration, i.e., negative braking torque to not interfere in REC events.

Avoiding EffChargeMode in inefficient areas of the generator, the logic will use the NotIdleSpdCond to detect if an idle speed can be detected and other actions will be used to avoid waste energy by the generator[13]. Furthermore, the HighTorqNotReq function will be used to prioritize the performance, it means that a high torque will be requested the generator will only supply the car to reduce load on the engine.

Making the solution adjustable, some calibrateable parameters were introduced on the real time interface. Setting the main parameters in this solution, such as the SOC thresholds, battery current set points, option to choose the alternative that you want to use in the measurements and others parameters. These introduced parameters are presented on the Figure 23.



EFSC Threshold (g/Kwh) ---
AccPosStep (%) ---
IdleEngSpd (RPM) ---
Load Average (A) ---
SOC Limit_1 (%) ---
BattCurrSetP_1 (A) ---
SOC Limit_2 (%) ---
BattCurrSetP_2 (A) ---
SOC Limit_3 (%) ---
BattCurrSetP_3 (A) ---
SOC Limit_4 (%) ---
BattCurrSetP_4 (A) ---
Use Original FEM Control No
Set Alternative No match
Voltage_Threshold (v) ---
GENR_ALT_SOC_ST ---
Allowed Disch (%) ---
MinSupply Car Time (s) ---
Max Time Out Allowed Disch (s) ---

Figure 23: Calibrated Parameters for the RVC and EffChargeMode

Following the measurements in real time to see the behavior of the solution and see if the detection of the efficient charge points is properly, the interface below was implemented:

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[13] It will better discussed in the Chapter 7

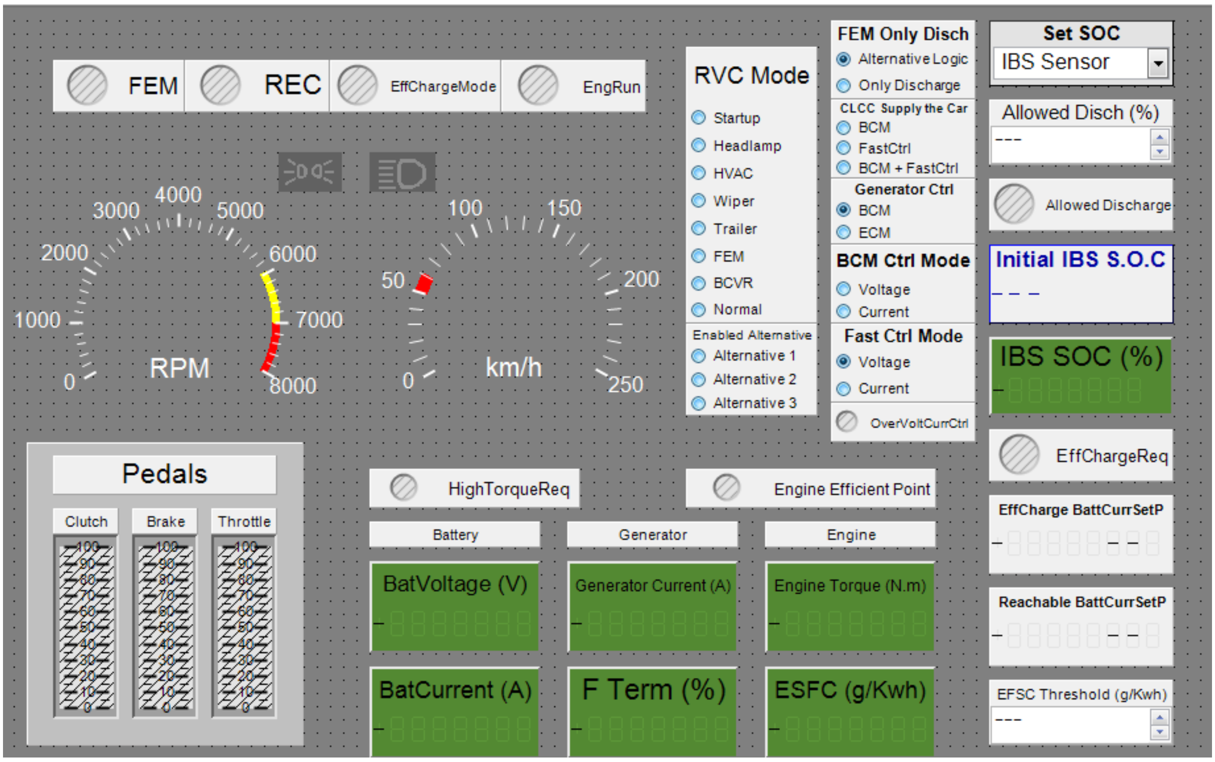


Figure 24: Real Time Interface for the Smart Generator Control

Chapter 7: Controllers Development

Achieving the necessary amount of energy to keep inside of the allowed discharge window on the cycle and extending the alternatives in FEM for real life driving. Building the smart generator control on engine map was possible due to the improvements made on the REC logic, the modifications on its own voltage controller and the current controller. This chapter will explain the problematic related the old voltage control in the dSPACE model compared to the control in the ECM, the modifications made to improve it, the development of the current control for the EffChargeMode and then the final structure for the both controllers.

7.1 REC Voltage Control

From the ECM controller for the REC events, it is not possible to know exactly when the REC starts, but observing the generator voltage, the setting time for the battery can be determined. The ECM controller takes around 1.8 s to reach 14.6v for the battery, as it showed in the Figure 12. In contrast, the voltage controller implemented in the old REC model takes more time than the ECM controller does, as showed it in the Figure 25.

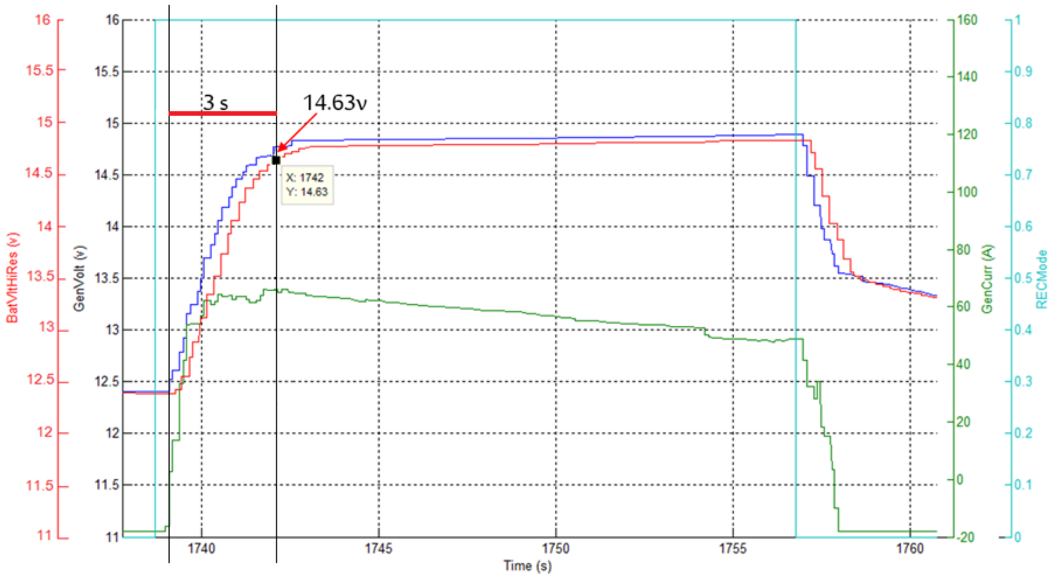


Figure 25: Voltage Control on the Old REC model

Based on the values presented in the Figure 12 and Figure 25 and assuming that the dSPACE voltage control will take around 2.8s to goes from 12.38v to 14.6v and the ECM takes 1.8s (green line) for the same variation, as shown in the Figure 26. How the ECM controller is faster than the dSPACE model, the controller will lose around 26.31% of this area that could be used to charge the battery and depending of the value of the current supplied this value can be higher.

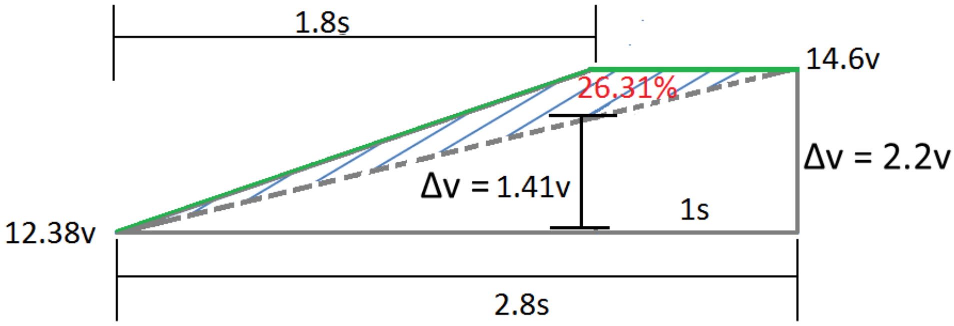


Figure 26: Voltage Control Comparison

Thus, making some modifications in the voltage controller, at least to achieve the same setting time of the ECM, the average of energy in the REC can be enhanced and allied with the new REC logic, it can provide the amount of energy to stay in the allowed discharge window.

Controlling the battery voltage in the vehicle requires knowing its behavior for several situations and getting a model with high fidelity is a tricky job. The battery voltage varies by different influences already addressed in the section 3.4, but the most import is the influences related to the electrolyte temperature, age of the battery and the SOC. Changing the response time, the plant gain, peak response and other features.

Despite the battery voltage has a nonlinear behavior and is dependent on others factors. The REC controller needs to work in the same area of operation, the same voltage set point, which allows estimating the battery voltage behavior as a first order plant, but taking into account that the controller will need to be robust enough for some gain and time response variations.

For the normal area of operation, the following model can estimate the discrete plant, where the L-Term will be the input to control the battery voltage:

$$\frac{Voltage}{L - Term} = G(z) = \frac{0.007994}{(z - 0.7339)} z^{-5} \tag{7.1}$$

Looking for simplicity, performance and the fact that an integrator action is required following the reference with zero error. A parallel PI controller was chosen it, since a derivative action was not feasible for this controller due to high variation of the voltage for some situations. After some adjustments occasioned to some limitations and new required specifications related to the desired generator current response (this will be better showed it in the Chapter 8), the final control was:

$$C(z) = \frac{12.06z - 9.046}{(z - 1)} \tag{7.2}$$

This controller shows in offline simulation, respecting the physical limitations of the generator that will be possible to reach 14.6v, in the same speed that the ECM does it.

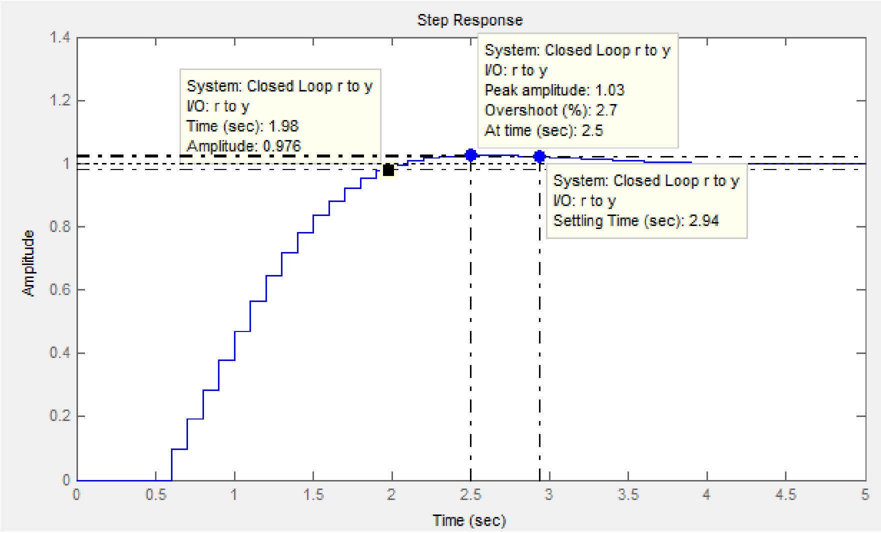


Figure 27: Simulated Response for the REC Voltage Control

However, it is important to analyze its robustness to make sure that even for some errors caused by non-modeled behaviors, the changes in the gain or time response of the plant due to SOC or electrolyte temperature variations e.g., it will not turn the system unstable. For this, considering a multiplicative model error, which is represented by $M(j\omega)$, $C(j\omega)$ is the transfer function for the controller and $G(j\omega)$ is the modeled battery voltage, satisfying the robustness, the following condition needs to be true:

$$|M(j\omega)| < \left|1 + \frac{1}{C(j\omega)G(j\omega)}\right|, \qquad \forall j\omega \qquad (7.3)$$

Using this concept and considering that the plant can have some gain and time response changes, considering a gain change of 50% and the time response changing 60%, the control could pass in the robustness test, as showed in the next figure:

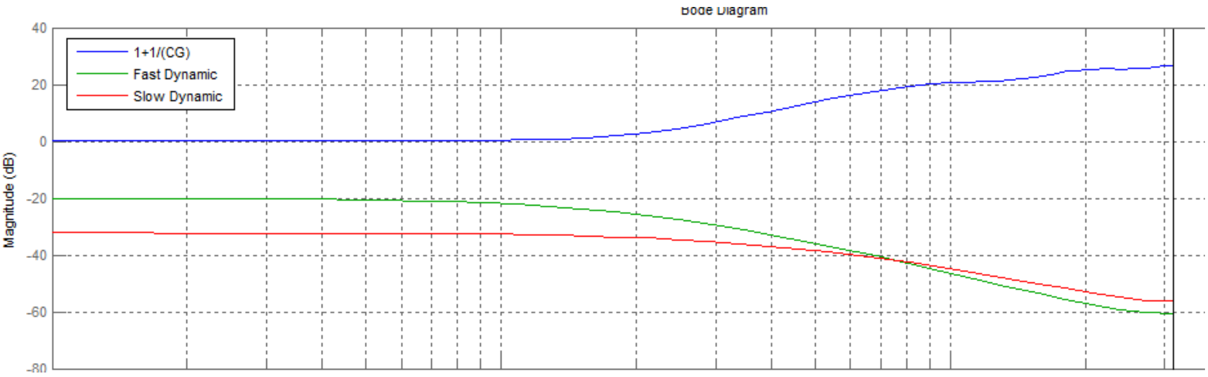


Figure 28: Robustness Test

In addition, as an attempt to further improve the controller robustness. It was included an anti-windup, to minimize the error of the integrator when the controller is saturated (remember that to control the plant we need to control by the L-Term and it has physical limitation, section 2.1). Finally, to reduce the delay effect was introduced a Smith predictor, obtaining the following structure:

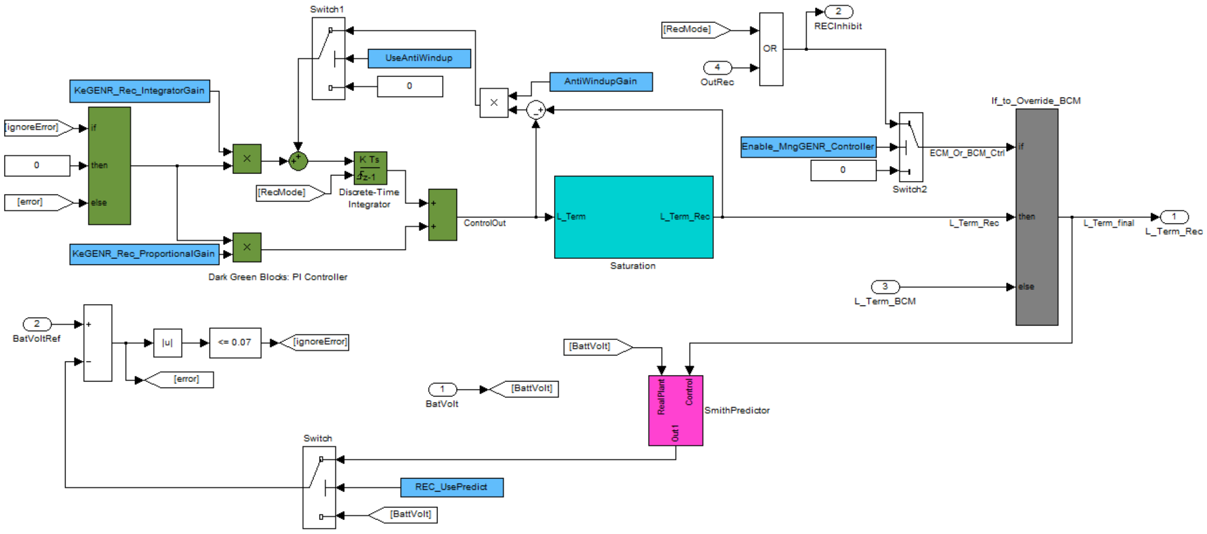


Figure 29: First Implementation of the REC Voltage Control

Thus, as the last step for the development of this controller, it was applied in the vehicle and the following measures were obtained for different battery conditions:

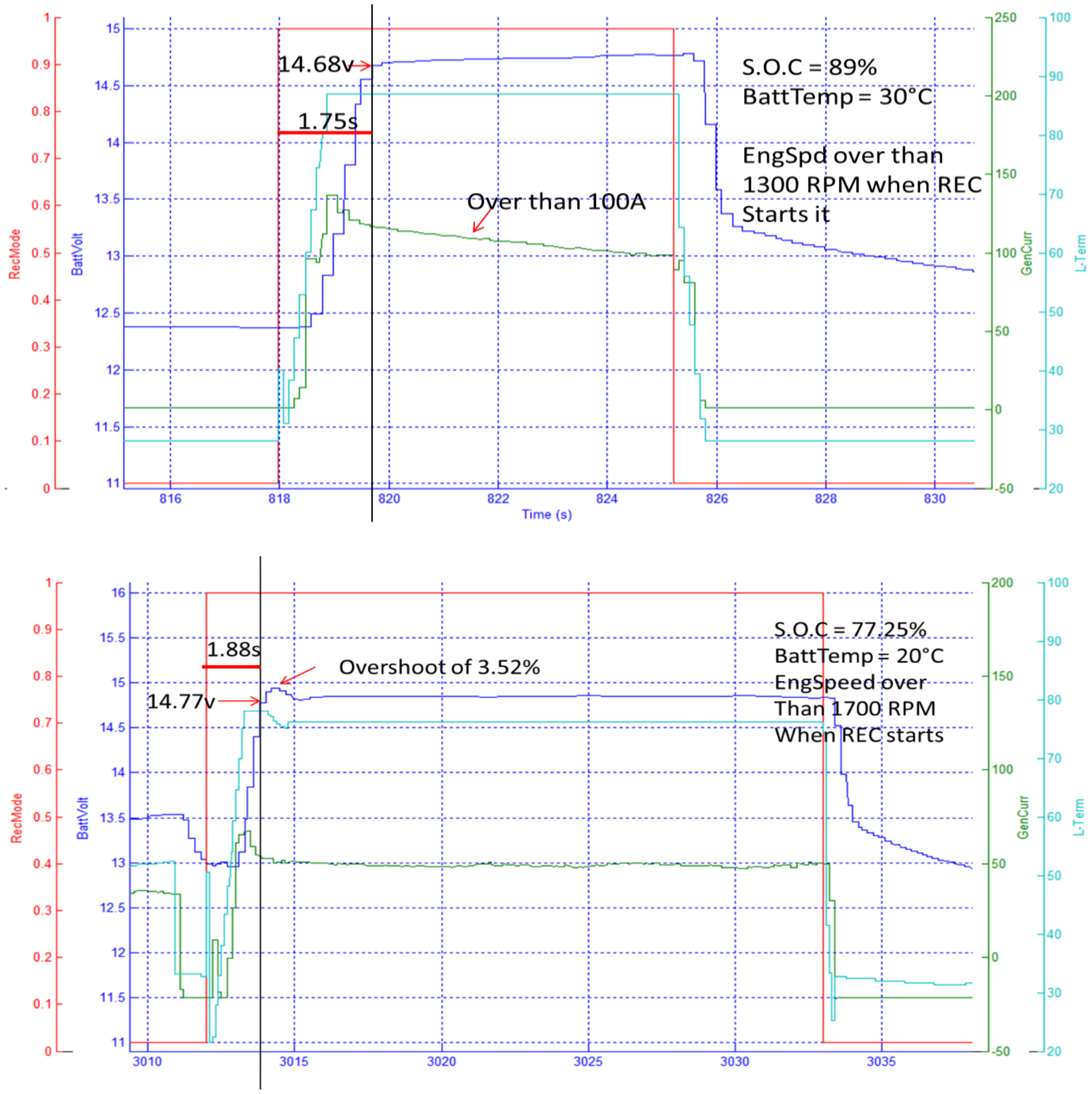


Figure 30: Evaluation of the Voltage Control in Real-time drive

Analyzing the Figure 30, even for different conditions of SOC and electrolyte battery temperature, the projected controller could work properly and with a shorter time, comparing with the ECM controller, since the projected one takes around 1.88s, in the worst case presented, to reach a battery voltage over than 14.6v counting from the REC signal, so counting the plant delay.

7.2 Current Control

Building the smart generator control on engine map generates the necessity of the development of a current control[14]. However, developing such control to be used in several work conditions and different set points can be even more challenging than build the REC voltage control.

The problem of controlling the battery current is that cannot be controlled directly, since in the vehicle we can control it by the generator duty cycle changes, applying different voltages. This way, besides of the influences related to the capacity of the current absorption from the battery and its non-linear behavior, depending of the engine speed, electric load, and temperature[15], the generator cannot provide the required current to the battery, in section 7.3 will discuss to how work out with this issue.

Thus, building a model that can include all this influences to tuning the controller and simulating all the different conditions can be very complex. This way, allowing the development in a short time and in a simple way, analogous to the steps realized developing the voltage control. Using Matlab the plant behavior, was modeled for one of the set points that the controller must work, where should be controlled the generator current from the L-Term, obtained the following equation:

$$G(z) = \frac{0.7(z - 0.643)}{(z - 0.786)(z - 0.639)} \tag{7.4}$$

Based on this model, a parallel PI control was built; its robustness was tested for some plant variations and then applied in the vehicle, tuning the controller to get the best benefit for all the work set points, achieving as the result the following values for the controller:

$$C(z) = \frac{0.15z - 0.1}{(z - 1)} \tag{7.5}$$

---

[14] Seeing more about the Solution go to the Chapter 6

[15] See the Generator influence in the Section 3.3

Thus, evaluating this controller for real application, the following measurements are made to observe its behavior and see if the developed controller respects the work specifications:

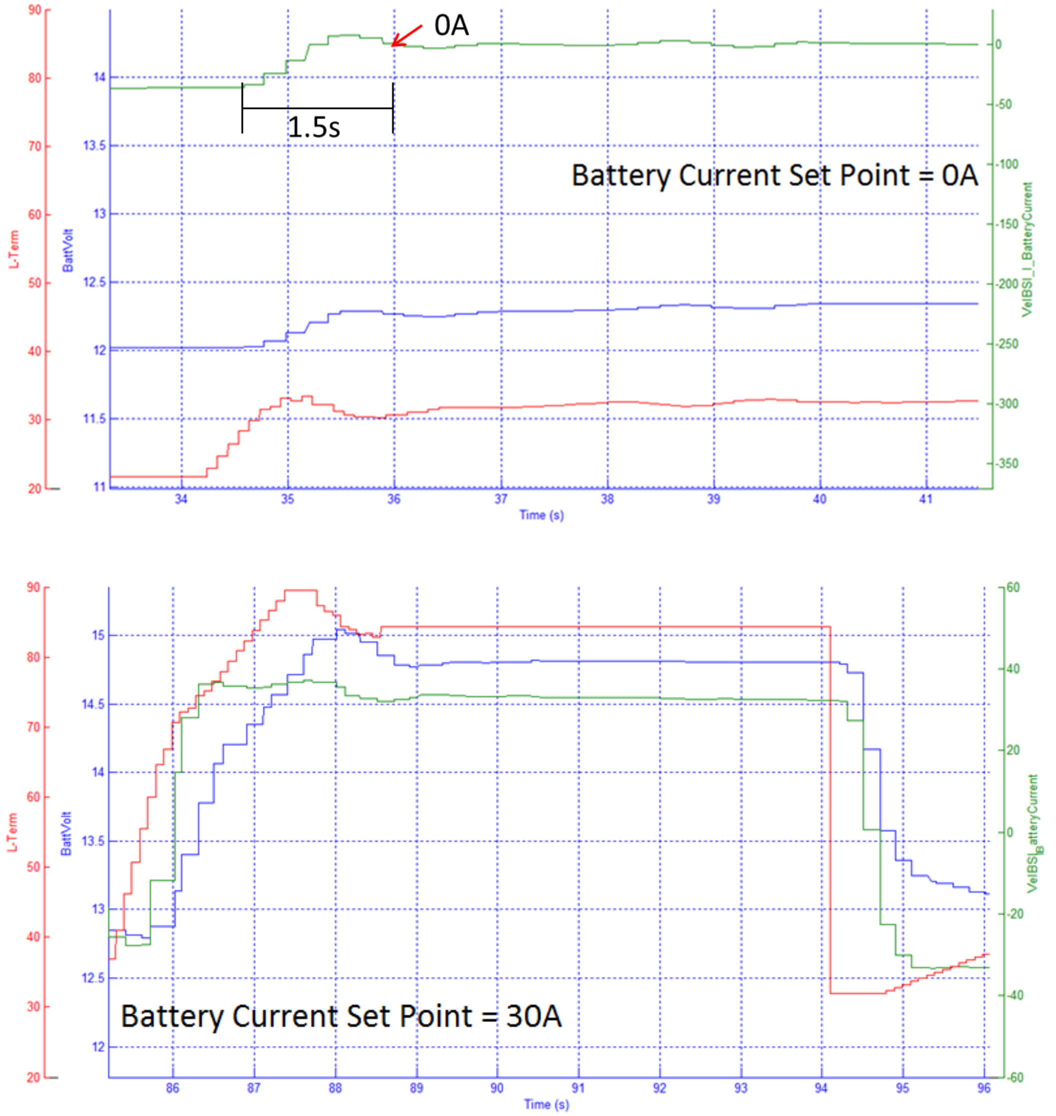


Figure 31: Measurement of the Current Control behavior

The Figure 31 shows that the controller will take around one or two s to reach the desired battery current, if the generator can provide such value. Despite of the figure shows only two work set points, this behavior extends to the others points of operation, getting good benefits for real drive as will be presented in Chapter 8 and obtaining a better response if compared to the current controller existent in the RVC controller.

7.3 Final Structure for both Controllers

The developed controllers were built to present simplicity and performance, operating inside of its technical specifications. For this, a parallel PI structure (Equation 6.6) was chosen for both controllers, as already exemplified in the previous sections, allowing the controllers to share the same structure by changing only its parameters when requested.

$$C(z) = \frac{U}{E} = \left(K_P + \frac{K_I T_s}{(z-1)}\right) \qquad (7.6)$$

Besides, of the switching advantage, model simplicity and avoiding redundancy in the model. It is possible to take advantage of this structure to solve the problems related to the current control. As already addressed it, sometimes the generator cannot provide the desired current and if this happens, the generator will raise its voltage until it cannot raise it anymore, trying to reach such reference, as shown in the next figure:

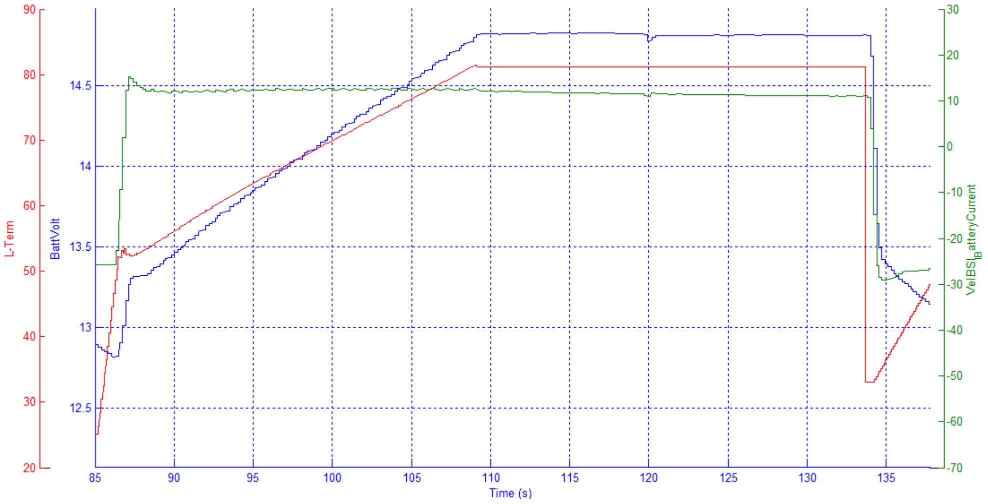


Figure 32: Battery absorption capacity problem on the Current Control

This situation (Figure 32) needs to be avoided. Then first, a voltage limitation is necessary to prevent the generator voltage reach over values that can injury the battery and the others components health. Solving this problem, a logical structure (red subsystem in the Figure 33) was developed to switch from current to voltage control when a voltage problem is detected, keeping the voltage in the limit, as shown in the pseudo code below:

```
If (BattVolt > Voltage Threshold) AND EffChargeMode is TRUE
Then Use the Voltage Control UNTIL
```

If Goes **out** of EffChargeMode **OR**

If Current Control **is** Limited by Voltage Control **AND**

If Battery Current **<** Efficient Battery Current Set Point

In addition, the Figure 32 shows another problem related to the battery acceptance of energy. The objective of this current controller is to be used in an efficient charge mode, for this; raising the voltage without changing the current must be avoided, since doing this, the generator will waste energy and put an extra load on the engine without increase the capacity or the efficiency to charge the battery, consequently increasing the fuel consumption. Thus, a logic strategy (green Subsystem in the Figure 33) was included to monitor the maximum battery current to stop raising the generator voltage unnecessarily.

Finally, switching the controllers properly, a subsystem (orange one, in the Figure 33) was added to decide when to choose the right controller for REC or EffCharge events, setting its parameters, such as the Integrator and Proportional gain, what to use as feedback and reference in the controller and other parameters related to it.

Thus, the final version for both controllers is presented in the following figure:

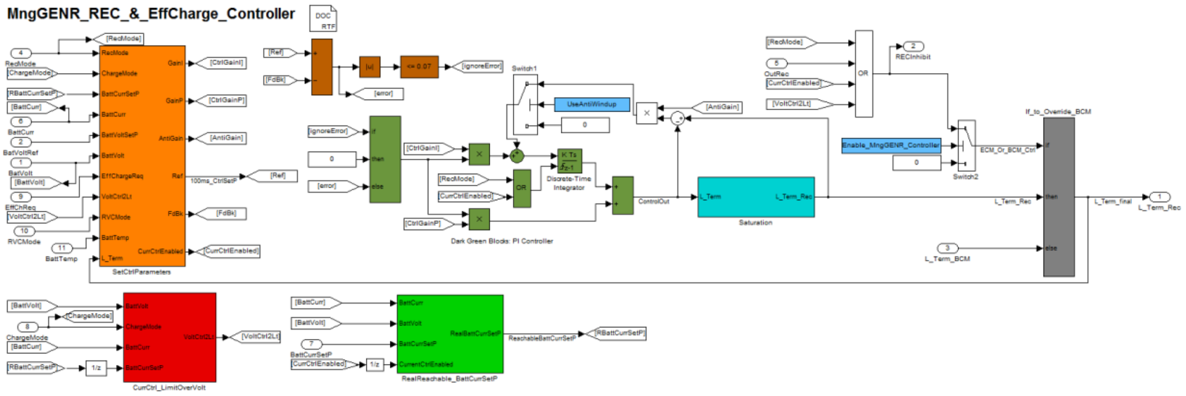


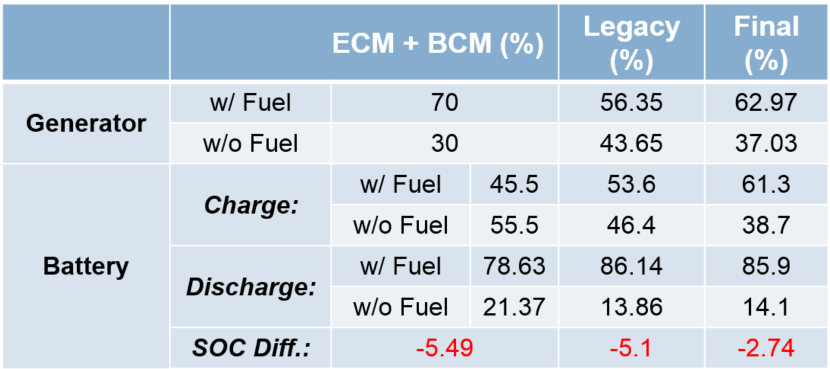
Figure 33: Simulink diagram of the two implemented controllers

Chapter 8: Results and Improvements

Developing the solution, for each component was built its own offline simulation using old signals available in the stored data based on measures in or out of the WLTP, tested in the vehicle and discussed the individual results. Now, this Chapter will analyze the results and the improvements for the combination of each single solution to create the global one for the WLTP and real life driving.

8.1 On the WLTP

Before starting to present the results and improvements, it was realized some measurements on the WLTP for the existents controllers in the car (ECM + BCM) and the previous dSPACE model (in this chapter we will called as Legacy) to be used as basis for comparison of the new solutions. The Figure 34 shows parts of these measures in terms of percentage:



	ECM + BCM (%)			Legacy (%)	Final (%)
Generator	w/ Fuel		70	56.35	62.97
	w/o Fuel		30	43.65	37.03
Battery	***Charge:***	w/ Fuel	45.5	53.6	61.3
		w/o Fuel	55.5	46.4	38.7
	Discharge:	w/ Fuel	78.63	86.14	85.9
		w/o Fuel	21.37	13.86	14.1
	SOC Diff.:		-5.49	-5.1	-2.74

Figure 34: Measurements for ECM and old dSPACE model (Legacy)

Analyzing these values, the Legacy solution presents a better power generation distribution for the generator, since its impact is more balanced in relation to the fuel injection. The battery does not observe such benefits; there is a little increase of the amount of energy on charging the battery with fuel. Besides, the SOC difference is still outside of the allowed discharge window on the cycle[16].

Realizing the first measurement with the new REC logic, first REC voltage controller and using the first Alternative presented in 6.2. The observed improvements

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[16] See Appendix C

were quite satisfactory, but it still needs some adjustments. In relation to the supplied generator power, the results were similar with the Legacy solution, where 56% was spent with fuel injection and 44% without fuel, however there was a significant increase on the battery charge behavior, which 51.54% and 48.56%, with and without fuel injection respectively. Allowing the decrease of the SOC difference, which reached -1.176%. In relation to the REC logic, there was an increase in its accuracy rate, 85.8% against to 50.4% of the ECM, but with an increase of the generator CO2 production from 1.6 g/km (ECM) to 3.6g/km in total. Nevertheless, this increment is accompanied with the increase of the generator power and comparing the CO2 impact and the recuperated energy in relation to the total produced. From the ECM, the CO2 impact was 38.41% and 61.59% CO2 recuperated against to 34.72% and 65.28% to the new strategy, showing a little decrease in the impact, beyond to stay in the allowed discharge window in the cycle.

Despite of these benefits and the possibility to decrease even more the SOC difference in the hot phase in the WLPT (observed a SOC difference of -0.39%) due to the improvement of the battery acceptance of energy. The controller presented an aggressive behavior with a faster response, but with voltage and current peaks in the generator that can could damage the battery due to gassing effects, or even damage others components in vehicle.

This problem could be solved by adjusting the parameters of the controller again, turning less aggressive, i.e., with a slower response time. Although, doing this, the impact of the fuel injection for the generator will be bigger. As an attempt to maintain these values without such changes, it was considered that the battery had a middle age; it means that its capacity of absorption is reduced. Then change it for a new battery could increase this capacity.

After changing for a new one, the measurements present for the same parameters used before, the controller had a slower response time compared to the old dSPACE model (Figure 25). Showing that we could take advantage of the new capacity of absorption of the battery and adjust the controller parameters, achieving the final controller presented in 7.1. However, it shows that shall be interesting to have in the future an adjustable controller parameters based on the age of the battery.

Using the new battery, the adjusted voltage controller and the second Alternative in the FEM, addressed in 6.3, another measurement was made in the cycle. Despite of the new Alternative in the FEM has supplying points in its strategy, due to the good conditions of energy acceptance of the battery, the voltage threshold will never be seen it, then the battery will only discharge or charge by recuperation, in the whole cycle. Moreover, the generator fuel impact suffer an increase, going to 65.5% for energy with cost, despite of the charge improvement in the battery that goes to 64.65% without fuel injection and keeping the SOC difference null. Analyzing the data, this increase occurs due to the controller changes, since the controller should be a little slower to avoid the voltage and current peaks in the generator. Furthermore, this measurement shows a question that was not given much attention, the fuel consumption in idle speeds in the REC logic, due to a premature neutral gearshift in the deceleration event. Generating the necessity to study these cases, allowing achieving the final REC logic, as presented in 5.2.

Finally, with the new REC logic and using a tool to standardize even more the WLTP, saying the exact point where it is needed to shift the gear in the test. The results, still showing a high value on the provide generator energy with fuel, around 63%. However, it is needed to take into account that with these tools and with the idle speed constraint, the available REC time decreases, 36.94% of the REC time with fuel is occasioned with the clutch pressed and the other part of fuel consumption observed in the REC occurs in the transitions, where these values cannot be reduced. In addition, the results still keeping the system in the WLTP allowed discharge window with a SOC difference of -2.74%, which makes this a good solution.

8.2 Real Life Drive

Reaching the necessary amount of energy with the improvements on the REC logic and controller, staying in the allowed discharge window and after the obtained results, the efficient charge mode should be developed only for extend the results on real life driving. Although, demonstrating the benefits of this new strategy on FEM, it is not so simple, as for offline estimation or for using the real data measured.

Since for offline simulation, it should be necessary to estimate the model for all the components involved, such as the generator, battery and engine with fuel consumption modeled, getting these models are not simple due to their influences and requires a long time that was not available for this project. Moreover, justifying the solution in its whole context in the practice requires a huge amount of measurements to take the average of these results to detect the real benefit that can bring for the smart generator control on engine efficiency map, even it was used the WLTP to get such results.

Despite of these difficulties, it is possible to prove the benefits for the new strategy for the smart generator control by showing the improvements in particular situations, as long as they occur in real life driving. This way, the first benefit that can be shown is related to supply the vehicle, as the next figure shows:

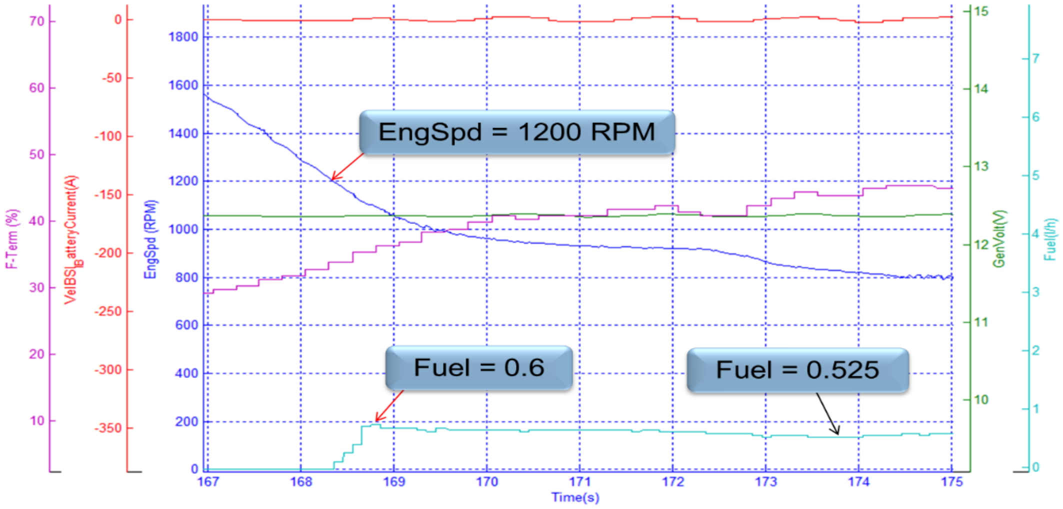


Figure 35: Benefit of Supplying the Car in Idle speed

Figure 35 shows the behavior of the fuel injection in low speed to keep the battery current in zero, how the electric load on the vehicle are low and almost constant for several situations, supplying the components in low speeds, below of 1000 RPM, can reduce the fuel consumption. It compared to the fuel injection that occurs with the generator on, as presented in the Figure 14. Moreover, comparing with the generator off, Figure 13, the fuel injection supplying the car does not increase so much, having a little increase in the beginning and stabilizing in the end for the same level observed with the generator off.

Thus, supplying the car will bring some advantages in the fuel consumption for such situations, instead of charging the battery independently of the engine speed, as it is made now for the others modes. Although, the generator efficiency goes down, if the F-Term is below of 30% (presented in 3.3), how the priority of the efficient charge is balance the fuel consumption and in the same time, enhancing the battery lifetime, even with this decrease of the generator efficiency, it will be an advantage.

In addition, looking at the acceleration phase in the car, the Figures Figure 36 and Figure 37, show the influence on the fuel injection in a diesel engine for similar situation for braking torque and accelerator position pedal, differing only by the applied generator voltage.

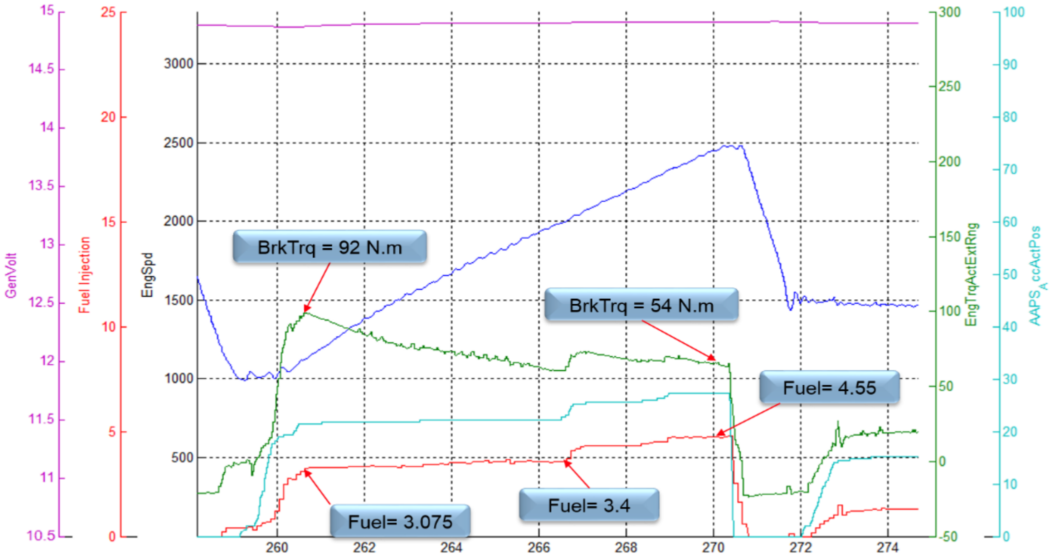


Figure 36: Fuel consumption in Acceleration phase with the Generator on

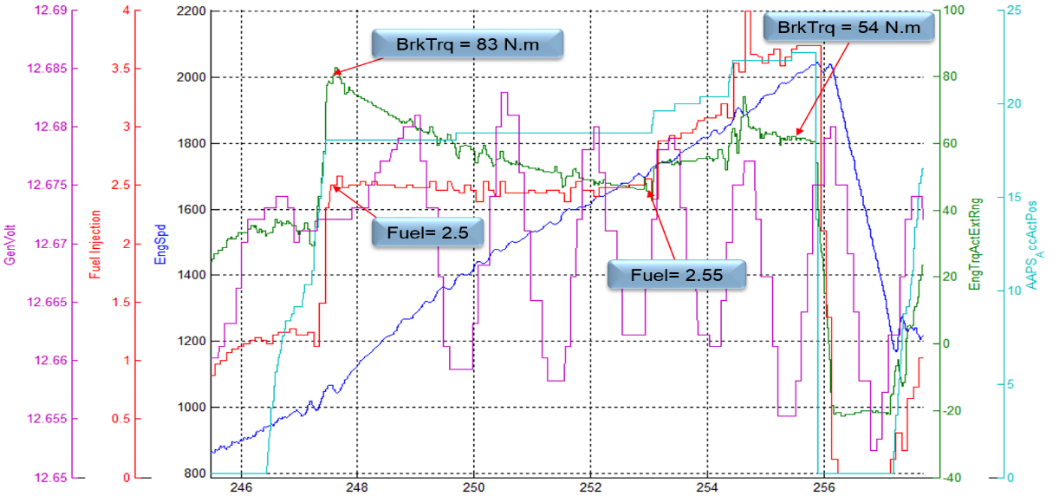


Figure 37: Fuel consumption in Acceleration phase with the Generator supplying the car

Analyzing the Figure 37, it shows a reduction of the average of fuel injection due to the reduction of the generator load by supplying the car. This reduction can be incremented for higher torque requested and high engine speed, as showed some measurements in the car. For this, switching from charging to supplying the electric load in the vehicle, in the smart generator control, can bring a fuel injection reduction even for short moments.

Furthermore, as a benefit that can be cited with the efficient charge mode, it is the spent time to increase the battery SOC. In the critical charge phase, where the battery current is 30 to 60 A, it is possible increase the SOC in 5% in less than 15 minutes by switching from supplying the car to a little discharge and then to efficient charge, as the next figure shows it:

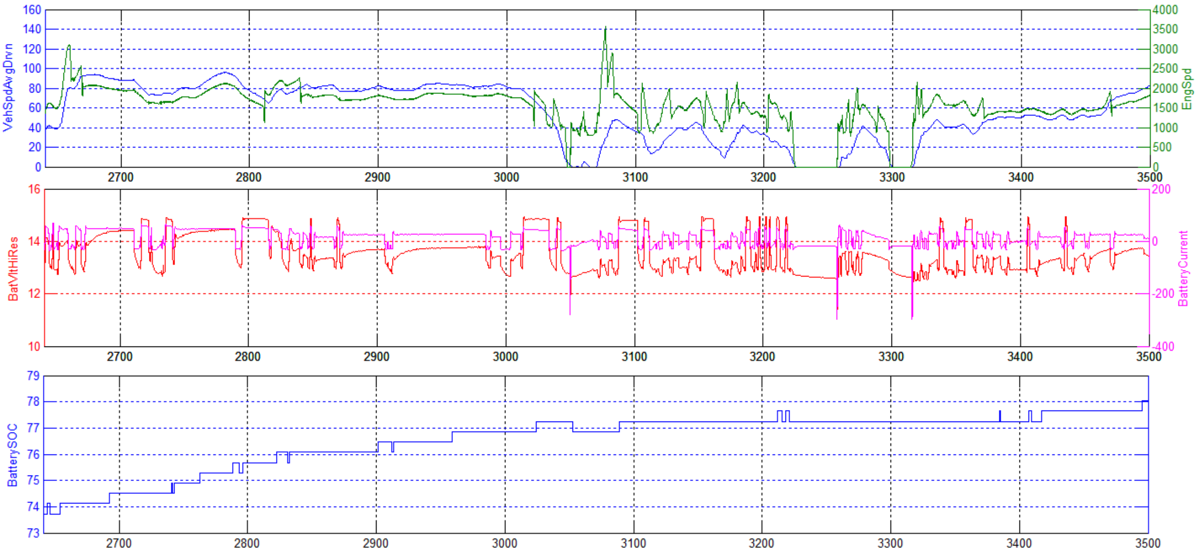


Figure 38: Efficient Charge Behavior, battery current 30-60 A

Continue comparing Figure 37, the measurements in the vehicle show that charging the battery with a constant voltage, e.g. as the Headlamps makes it, it will take more time to charge the battery than the EffChargeMode, since with the voltage variations, it is possible to increase the amount of provided energy to the battery. Remember that the battery has a capacitive behavior. Therefore, with high variations of the applied voltage step on the battery, the transition energy can be enhanced and then keeping that voltage constant will observe only the decay of the current, being the maximum current provide in the transition phase.

In relation to the increase of the battery SOC from the REC events and supplying the car. Figure 39 illustrate the time to increase the SOC value in 3%, taking around 41 minutes to achieve it. Showing that the REC event can be used to support the energy dropped in the Autostop, however, charging the battery only by REC needs a long time, which in general it is not observed in real life drive.

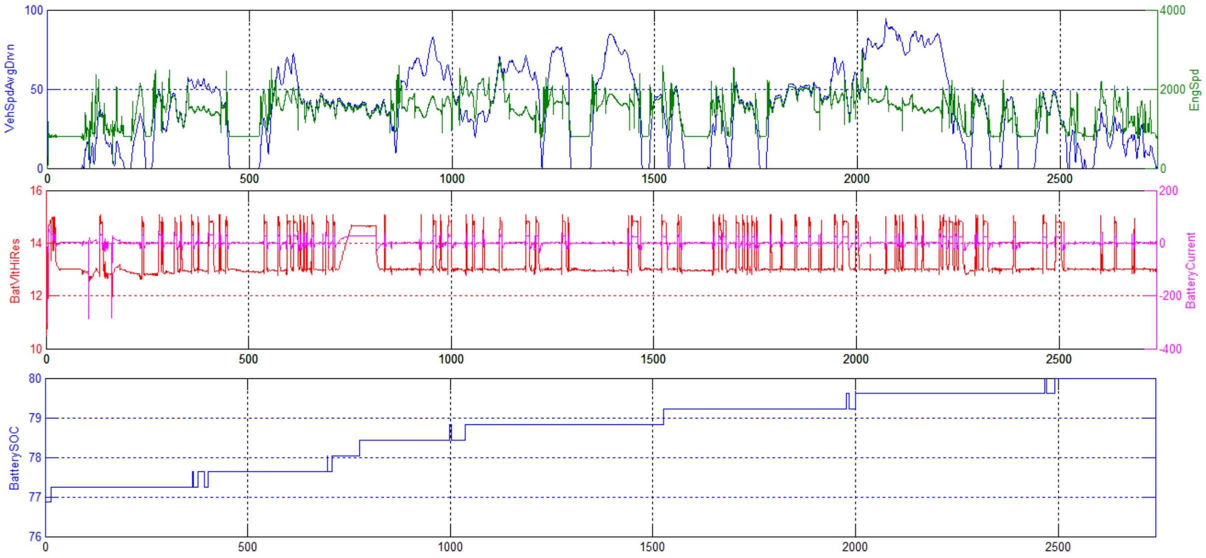


Figure 39: REC behavior on the SOC by supplying the Vehicle

Finally, summarizing the benefits of the new smart generator control, it will present the advantages observed in the WLTP cycle from discharging the battery until reaching the middle SOC threshold, the maximum fuel reduction that can have it and also, increasing the battery capacity of energy absorption in REC events, working with low SOC. In addition, extending the FEM mode with the efficient charge mode based on the engine, battery and generator efficiency, allowing a small reduction of fuel injection and small battery cycling.

Chapter 9: Conclusion and Outlook

Initially, with the change of the cycle and the new battery discharge tolerance, it was thought that the REC events could not provide enough energy to keep in the allowed discharge window without suffer any penalty in the test. Generating the necessity of developing a new charge strategy with fuel cost combined with the REC, considering the components efficiency.

Thus, trying to include better the generator efficiency to develop such strategy, at least a sensor to measure the generator current will be necessary. Although, now the vehicle does not have such sensor, requiring a model to estimate it, furthermore how it depends on the generator temperature, another model must be developed.

Several attempts were made to try to create such models, but along of this work was observed that had not a feasible time and this problem could be solved by a simple solution due to the new course taken in the project. Furthermore, Opel does not have a test bench for the generator, which makes it impossible to isolate all the influences on the generator to get a good temperature and current estimation in short time. Therefore, in the future to include better the generator efficiency, it is important to have a current sensor in the car or at least providing a test bench for the generator to enable to estimate its behavior.

Despite of these limitations, with this project was possible to improve the REC logic strategy (Chapter 5), changing some concepts and adjusting its voltage controller, which caught the attention of the GM Motors for showing that with the REC we could still providing the required amount of energy on the cycle (in 8.1). Allowing discharge the battery in the whole cycle and in the same time, minimize the fuel consumption without the necessity of insert new mechanisms in the cycle to charge the battery.

However, the purpose of this project was not to develop a solution that works only on the cycle. Extending the benefits for real life driving, it could be reached by the new alternative in the FEM (in 6.4) accompanied by the new current control (in 7.3), besides bringing the benefits observed in the cycle, including a chance to charge the battery in an efficient way by the EffChargeMode.

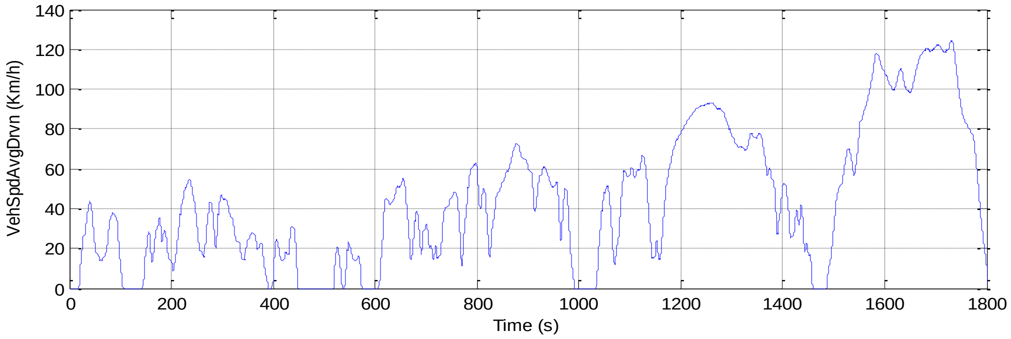
Despite of some limitations of this solution, such as the fact of the solution was implemented only for diesel engine, the used maps are not so easy to build and are not completed and optimized yet, which makes the solution dependent of the accuracy of these maps. The results show (8.2) that are possible to have a reduction of the fuel injection, consequently minimizing the emission of CO2. Although this reduction are not as high as was expect and it is hard to prove in real life drive, how this solution is based only on software changes without the necessity to spend money in the production line, each gram of save fuel counts, making this solution applicable in practice.

In addition, it was possible to observe that some existents modes in the car were not necessary anymore, such as the Sulfation mode, the recuperation event already provide the enough charge events and the wiper mode, since no visual effect can be detect for different voltage set point. Moreover, the Startup mode could be dependent of the SOC, allowing only discharging the battery in FEM, minimizing cycling the battery unnecessarily.

Appendix A – Descriptions

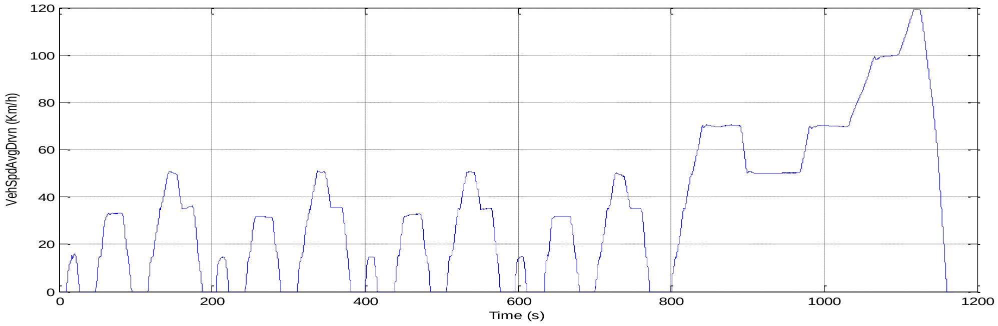
WLTP Cycle:

The Worldwide Harmonized Light Vehicle Test Procedures is a cycle test created to be more realistic with the real life drive compared with the MVEG, presenting two speed profiles: urban and highway. Presenting an oscillatory speed, as showed in the figure below.



MVEG Cycle:

The Motor Vehicle Emission Group test cycle was used for a long time and began to be substituted from the WLTP for more similar with the real life drive. However, analogous with the WLTP cycle, this cycle will present an urban and highway profile, with smoother vehicle speed variations, as showed below.

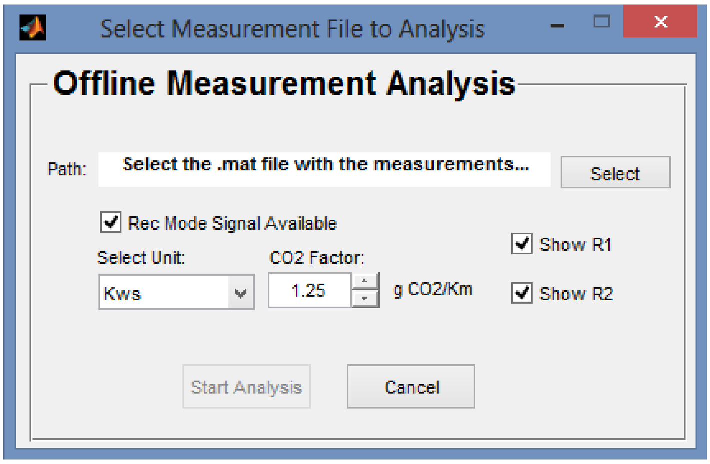


Stop/Start:

When the engine is on, fuel is injected to keep it running and consequently emitting CO2 to the environment. Minimizing this situation on idle engine speed, this technology was developed to enter in Auto Stop mode, turning off the engine and saving fuel.

Appendix B – Offline Interface Measurement Analysis

This offline Interface automatizes the calculus of the essentials comparison values and organize these data, in case that these values were not measure with the real-time interface, generating a presentable sheet that can be export in pdf file. At moment, only the dSPACE measurement was implemented, but this interface can easily be extending for others signals. The picture shows the selection data window:



Select Measurement File to Analysis

Offline Measurement Analysis

Path: Select the .mat file with the measurements...

☑ Rec Mode Signal Available

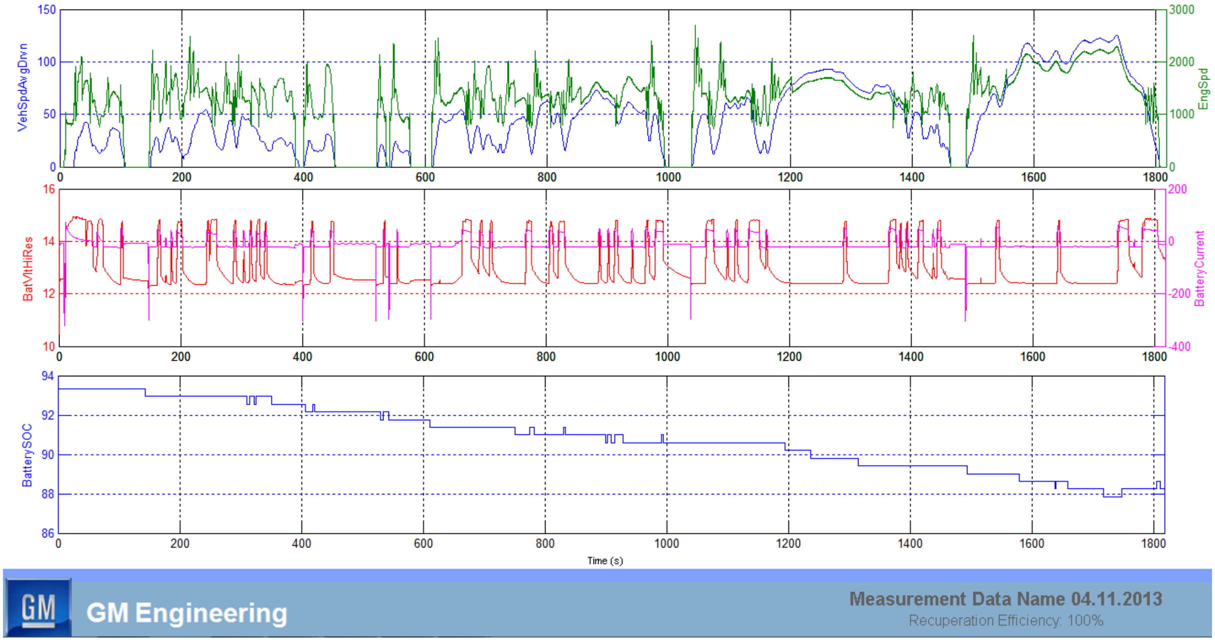
Select Unit: Kws

CO2 Factor: 1.25 g CO2/Km

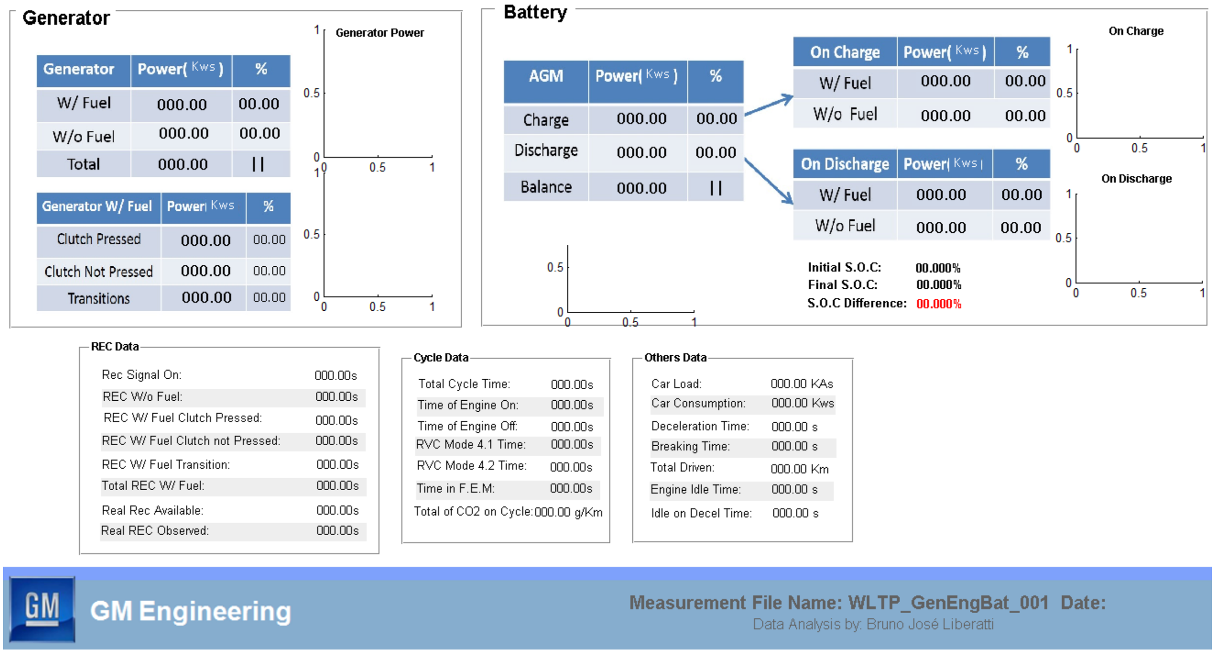
☑ Show R1

☑ Show R2

Example of sheet for the REC results, observing the battery voltage and current and the SOC behavior:



Sheet to organize the main comparison data in a presentable way:



Generator

Generator	Power(Kws)	%
W/ Fuel	000.00	00.00
W/o Fuel	000.00	00.00
Total	000.00	||

Generator W/ Fuel	Power(Kws	%
Clutch Pressed	000.00	00.00
Clutch Not Pressed	000.00	00.00
Transitions	000.00	00.00

Battery

AGM	Power(Kws)	%
Charge	000.00	00.00
Discharge	000.00	00.00
Balance	000.00	||

On Charge	Power(Kws)	%
W/ Fuel	000.00	00.00
W/o Fuel	000.00	00.00

On Discharge	Power(Kws	%
W/ Fuel	000.00	00.00
W/o Fuel	000.00	00.00

Initial S.O.C: 00.000%
Final S.O.C: 00.000%
S.O.C Difference: 00.000%

REC Data

Rec Signal On:	000.00s
REC W/o Fuel:	000.00s
REC W/ Fuel Clutch Pressed:	000.00s
REC W/ Fuel Clutch not Pressed:	000.00s
REC W/ Fuel Transition:	000.00s
Total REC W/ Fuel:	000.00s
Real Rec Available:	000.00s
Real REC Observed:	000.00s

Cycle Data

Total Cycle Time:	000.00s
Time of Engine On:	000.00s
Time of Engine Off:	000.00s
RVC Mode 4.1 Time:	000.00s
RVC Mode 4.2 Time:	000.00s
Time in F.E.M:	000.00s
Total of CO2 on Cycle:	000.00 g/Km

Others Data

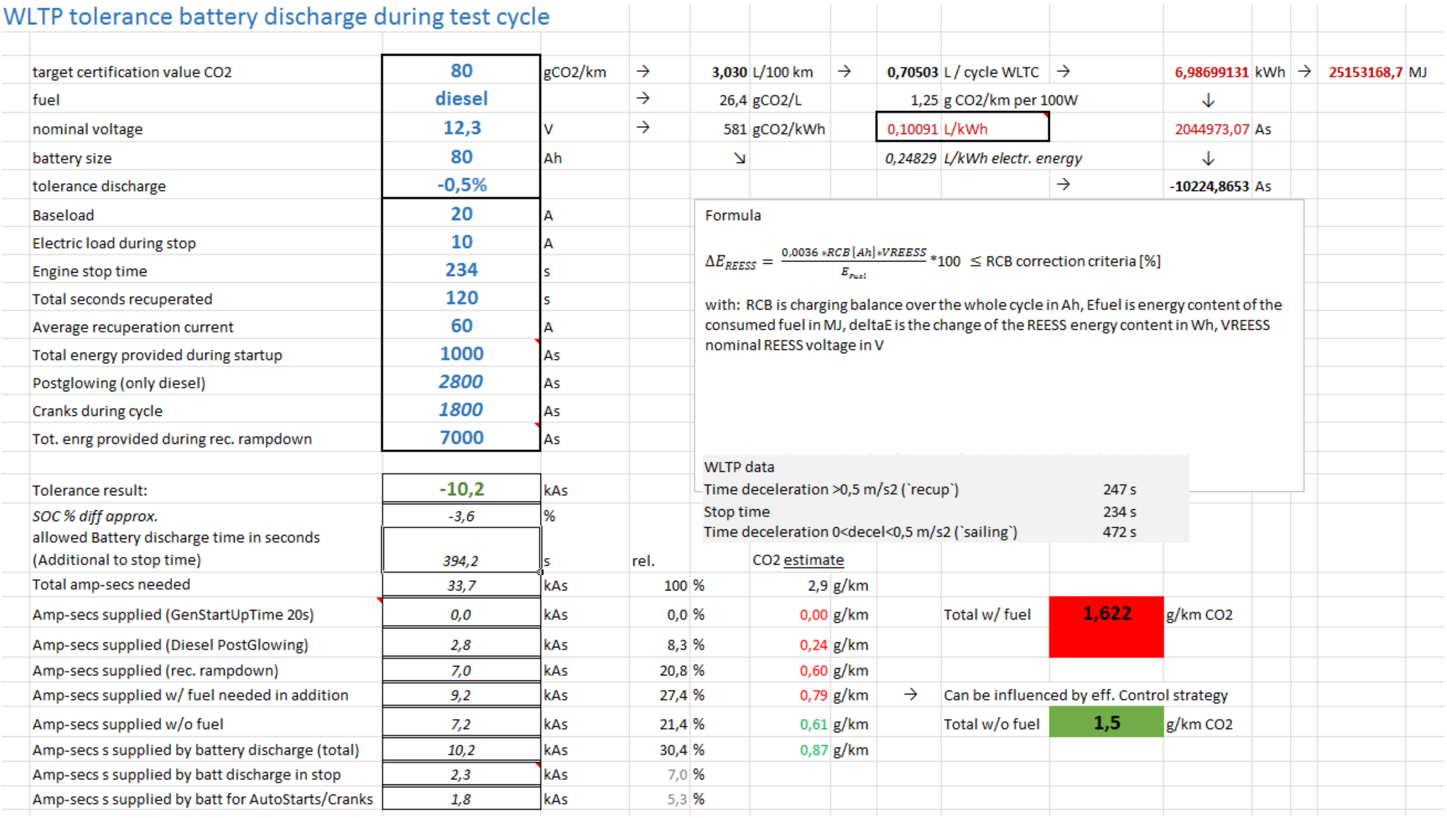
Car Load:	000.00 KAs
Car Consumption:	000.00 Kws
Deceleration Time:	000.00 s
Breaking Time:	000.00 s
Total Driven:	000.00 Km
Engine Idle Time:	000.00 s
Idle on Decel Time:	000.00 s

GM Engineering

Measurement File Name: WLTP_GenEngBat_001 Date:
Data Analysis by: Bruno José Liberatti

Appendix C – Battery Discharge Tolerance on WLTP Cycle

Changing the test cycle from the MVEG to the WLTP, the discharge tolerance for the battery changes it. Calculating this allowed window, some assumptions need to be done, as showed in the figure below:



WLTP tolerance battery discharge during test cycle

target certification value CO2	**80**	gCO2/km	→	**3,030**	L/100 km	→	**0,70503**	L / cycle WLTC	→	**6,98699131**	kWh	→	**25153168,7**	MJ
fuel	**diesel**		→	26,4	gCO2/L		1,25	g CO2/km per 100W		↓				
nominal voltage	**12,3**	V	→	581	gCO2/kWh		0,10091	L/kWh		2044973,07	As			
battery size	**80**	Ah		↘			*0,24829*	*L/kWh electr. energy*		↓				
tolerance discharge	**-0,5%**								→	**-10224,8653**	As			
Baseload	**20**	A												
Electric load during stop	**10**	A												
Engine stop time	**234**	s												
Total seconds recuperated	**120**	s												
Average recuperation current	**60**	A												
Total energy provided during startup	**1000**	As												
Postglowing (only diesel)	***2800***	As												
Cranks during cycle	***1800***	As												
Tot. enrg provided during rec. rampdown	**7000**	As												

Formula

$$\Delta E_{REESS} = \frac{0{,}0036 * RCB\,[Ah] * VREESS}{E_{Fuel}} * 100 \le \text{RCB correction criteria [\%]}$$

with: RCB is charging balance over the whole cycle in Ah, Efuel is energy content of the consumed fuel in MJ, deltaE is the change of the REESS energy content in Wh, VREESS nominal REESS voltage in V

WLTP data	
Time deceleration >0,5 m/s2 (`recup`)	247 s
Stop time	234 s
Time deceleration 0<decel<0,5 m/s2 (`sailing`)	472 s

Tolerance result:	**-10,2**	kAs								
SOC % diff approx.	*-3,6*	%								
allowed Battery discharge time in seconds (Additional to stop time)	*394,2*	s	rel.		CO2 estimate					
Total amp-secs needed	*33,7*	kAs	100	%	2,9	g/km				
Amp-secs supplied (GenStartUpTime 20s)	*0,0*	kAs	0,0	%	0,00	g/km		Total w/ fuel	**1,622**	g/km CO2
Amp-secs supplied (Diesel PostGlowing)	*2,8*	kAs	8,3	%	0,24	g/km				
Amp-secs supplied (rec. rampdown)	*7,0*	kAs	20,8	%	0,60	g/km				
Amp-secs supplied w/ fuel needed in addition	*9,2*	kAs	27,4	%	0,79	g/km	→	Can be influenced by eff. Control strategy		
Amp-secs supplied w/o fuel	*7,2*	kAs	21,4	%	0,61	g/km		Total w/o fuel	**1,5**	g/km CO2
Amp-secs s supplied by battery discharge (total)	*10,2*	kAs	30,4	%	0,87	g/km				
Amp-secs s supplied by batt discharge in stop	*2,3*	kAs	7,0	%						
Amp-secs s supplied by batt for AutoStarts/Cranks	*1,8*	kAs	5,3	%						

Appendix D – Vehicle Electric Load Consumption

These measurements are taken on the WLTP cycle without any extra electric load and in a rainy day outside of the cycle with the wiper on, showing the average of electric load on the vehicle. Despite of the peaks, the average of load still practically constant on the vehicle, around 25-30 A, even with the wiper on. What give us a clue that the wiper mode should be not necessary anymore and a simple current estimator can be done to be used on the FEM, since on FEM an extra electric load is not required.