Design and development of a light electric vehicle for 'energy-efficient' endurance race

Krzysztof Slósarczyk, Krzysztof Kowalski, Wojciech Slósarczyk, Błażej Mika, Marian Błachuta, Wojciech Skarka, Jacek Smołka, Roman Czyba, *Silesian University of Technology*

Abstract

This paper describes the design and development of a light electric vehicle (LEV) for participation in an `energy efficient' endurance race. The objective of the race was to maximise the vehicle range with a limited energy source, thus the vehicle was required to maintain a high level of efficiency over the race duration. A basic vehicle dynamics model was developed to aid the vehicle design and simulate vehicle dynamic behaviour on the real track prior to the event. Computer Aided Design (CAD) software employing Finite Element Stress analysis (FEA) was utilised for development of the mechanical components such as chassis, steering and axles. The aerodynamic shape of the LEV's upperbody was designed with an extensive use of Computational Fluid Dynamics (CFD) analysis. High level of motor efficiency was maintained by an electric fan cooling system. Uniform energy consumption during the race was achieved by an in-house developed control system. Functionality and robustness of the drivetrain control unit and motor cooling system has been performed on a specially developed laboratory rig. A suitably tailored telemetry system based on a GPRS network was devised, enabling remote monitoring of vehicle parameters.

1. Introduction

Although electric motors have been around for many years, they have not been widely utilised in the automotive industry for propulsion. Recent years have shown significant research in this area.

Fig. 1 Silesian Greenpower LEV at GCC 2010

This work is subjected to the design and development of a light electric vehicle (LEV) for participation in an `energy efficient' endurance race. The aim is to maximise the vehicle range during a four hour race, whilst having a limited energy source. The latter is a set of four 12 V automotive batteries. The electric energy contained is required to be converted into mechanical propulsion energy in an optimal manner. The latter is affected by an air drag, powertrain loses, unnecessary weight and high rolling resistance, hence the LEV's design has been focused on optimisation of the above attributes.

1.1 Silesian Greenpower project

The Silesian University of Technology (SUT) was the first participating international team in the history of Greenpower Corporate Challenge (GCC), the race of electric vehicles taking place every year at Goodwood Motor Circuit, United Kingdom. The work begun in September 2009 with a deadline defined by a race date being 25th of April 2010, within a framework of joined student's final year project. In order to develop a competitive vehicle, being able to beat the current race record of 200km and win the race, a deep insight into all fields of automotive engineering was required. This involved three faculties at SUT specialising in vehicle aerodynamics, mechanical engineering, control and electrical engineering to join forces. The LEV developed at SUT is shown in Fig. 1.

2. Basic vehicle dynamics model

Designing the LEV from scratch within the given time frame defined by a race date is deemed to be a challenging task. This forced LEV's designers to predict possible design issues prior to the manufacturing phase. In order to facilitate identification of design issues and guide the LEV's development a basic vehicle dynamics model was developed. This provided an ability to perform a closed-loop simulation of various characteristics of different automotive components under various situations. A simulation output was chosen to be a number of laps covered on one set of batteries, which served as a performance index for the parameter's sensitivity analysis. The latter was extensively utilised to compare different drivetrain control strategies and gearing system variations. The high level design objective is to maximise the magnitude of the total mechanical available power (P_m) [W], given by [10]:

$$P_m = (F_{te} - F_{tr} - F_{br})V \quad (1)$$

where, F_{te} is the vehicle tractive effort [N], F_{tr} is the vehicle tractive resistance [N], F_{br} is the braking force [N] and V is the vehicle velocity [m/s]. This is realised by maximisation of F_{te}, which is the force produced by an electric motor to traverse the vehicle in the desired direction, which is given by (*ibid*):

$$F_{te} = \frac{T_m \eta_{pwt} G_t}{r} \quad (2)$$

where, G_t is the overall powertrain gear gain, T_m is the motor torque [Nm], η_{pwt} is the overall powertrain efficiency and r is the vehicle rolling radius [m]. F_{tr} that acts in opposite direction to F_{te} is required to be minimised and is defined as (*ibid*):

$$F_{tr} = mg(R_{roll} + \sin\alpha_r) + \frac{1}{2}\rho C_d A(V + V_w) \quad (3)$$

where, m is the vehicle mass [kg], V is the vehicle speed [m/s], V_w is the head-on wind speed [m/s], g is the gravitational acceleration of 9.81 [m/s^2], R_{roll} is a rolling resistance coefficient, α_r is a road incline [°] [4]. The vehicle distance travelled, denoted S [m] and V can be obtained by integration of vehicle acceleration, denoted a [m/s^2], which is given by:

$$a = \frac{F_{te} - F_{tr} - F_{br}}{m} \quad (4)$$

To make the simulation realistic, a real track profile has been fed into the model as a change in α_r with respect to S, assuming the track length is known. The simulation loop is closed by calculation of DC motor speed, denoted ω [rad/s], as follows:

$$\varpi = \frac{VG_t}{r} \quad (5)$$

and repeats from calculation of T_m as follows [18]:

$$T_m = \frac{U_m - \varpi K}{R} K - T_{fr} \quad (6)$$

where, R is the DC motor electric resistance [Ω], K is the electromotive force constant [Nm/A] and T_{fr} is the DC motor friction torque [Nm]. U_m is the voltage applied to the DC motor [V] as a result of the control strategy output implemented using two term proportional, integral (PI) controller. The basic vehicle dynamics model has been implemented using Simulink, and is shown in Fig. 2.

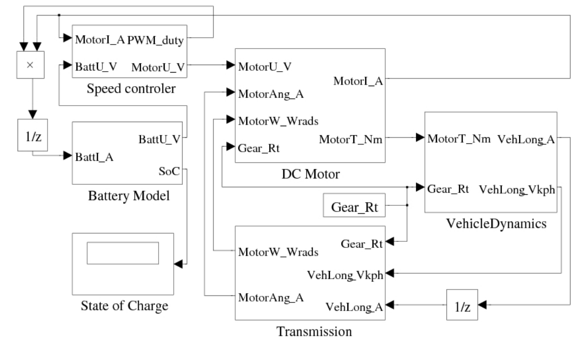

Fig. 2. LEV's vehicle dynamics simulation model

2.1 Model utilisation and simulation outcome

To make an efficient use of simulation aided vehicle design model, its validation against the real vehicle performance is required. This focuses on estimation of the following parameters: m, C_dA, R_{roll} and η_{pwt}. Due to the time constraints, the initial simulations had taken an assumption about the above parameters, which were continually refined during the vehicle construction. Choice of a suitable gearing mechanism was an important design milestone. The simulation shown that a light, fixed ratio, single gear spur type arrangement of gain 2.4, offering high efficiency of 98% was a promising solution. Due to the low elevation variation of the track profile, it enables the vehicle to cover more laps than any three-speed gear hub solution available on the market, which exhibits lower efficiency and introduces unwanted additional weight and driver effort during gear selection. Furthermore, in order to maximise the vehicle range with a limited energy source, a suitable control strategy was desired. Using a series of simulation test cases, a control algorithm combining both, constant motor current (CMC) and constant motor voltage (CMV) strategies was proposed. CMC improves `from stand still' vehicle acceleration and offers a `turbo' mode when overtaking as well as regenerative braking. In steady state operation CMC ensures the motor temperature to remain constant. CMV enables constant vehicle dynamical properties, resulting in a constant lap time. During the race the vehicle has driven 80% of the time at CMC with set point of 40A and 20% at CMV with set point of 21 V. The model satisfactory performance has been achieved once the vehicle was built, using roll down test, [15]. Eq. 3 can be expressed as a second order equation with constant variables x and y, as follows:

$$\frac{dV}{dt} = gR_r + \frac{1}{2}m\rho C_d AV^2 = x + yV^2 \quad (7)$$

The value of x and y can be easily found using the following procedure: *1)* vehicle coast down to stop from steady speed level (V_{max} ≈15 km/h) performed in the non wind environment (V_w = 0 km/h), *2)* measurement of time and distance of travel, t_{end} and d_{end} respectively (cf. Fig. 3), *3)* cost down in opposite direction for α_r detection. The value of x and y can be obtained from:

$$x = \frac{2}{t_{end} - t_{mid}} = \left(\frac{d_{end}}{t_{end}} - \frac{d_{mid}}{t_{mid}} \right) \tag{8a}$$

$$\min_{x,y} \left(V - \sqrt{\frac{x}{y}} \tan\left(t_{end}\sqrt{xy}\right) \right)^2 \tag{8b}$$

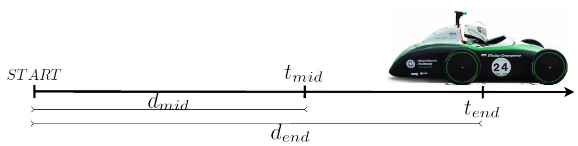

Fig. 3. Roll down test

The equations can be solved numerically, i.e. using Matlab *fminsearch* tool. The values obtained for Silesian Greenpower LEV were: m = 160kg, η_{pwt} = 98%, C_dA= 0.240 and R_r = 0.0083.

3. Mechanical design

LEV's underbody consists of chassis, steering system, powertrain and braking system. Its design has been strongly influenced by the GCC safety rules and other design guidelines. In addition, the aim is to reduce the vehicle weight with the component strength being uncompromised, therefore a study on number of solutions to find the most suitable one has been made. The final design also incorporates the manufacturing constraints, i.e. material availability, price and delivery time. Moreover, each system is required to work as a part of one fully integrated system, which defined a mechanical design challenge.

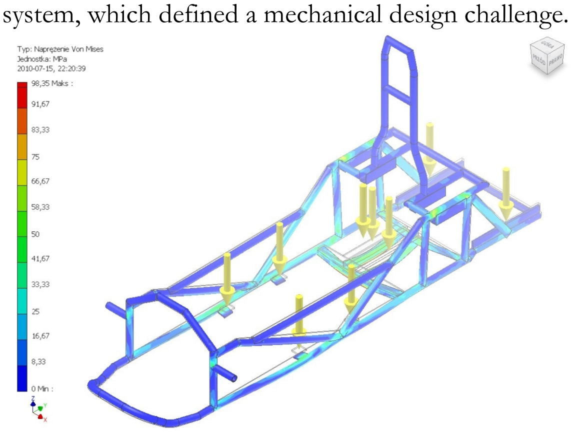

Fig. 4. Stress distribution in LEV's chassis

3.1 Chassis design

Vehicle chassis supports other vehicle systems and provides mounting capabilities to all mechanical components, like wheels, steering, etc. It also defines vehicle dimension, therefore its design is required to take various aspects into consideration, such as: driver position, safety, comfort, powertrain, durability, adjustability, battery accessibility and equal weight distribution. It is also required to provide enough packaging space for other components, such as: steering wheel, motor, batteries and vehicle electronics. Moreover, the chassis has to sustain significant stress, strain and tensional stiffness, whilst having good structural strength during stand-still and driving [12]. LEV's chassis is based on the spatial frame, which is characterised by high strength combined with reduced weight. Other frame types, such as self-supporting or honeycomb were considered. A 3-D geometrical model of the chassis was developed using Computer Aided Design (CAD) software and the Frame Generator module available in Autodesk Inventor software. The design of the chassis was aided by Finite Element Stress Analysis (FEA), which highlighted the main material stress regions, as a result of driver and battery pack weight. FEA of LEV's chassis is presented in Fig. 4. A lightweight aluminium alloy 6005, exhibiting good strength of 350 MPa, low density and relatively low price was used for chassis manufacturing.

3.2 Steering design

The main task of the steering system is to control the direction of the vehicle motion by the driver. This was realised by adjusting the angle of the steering wheels relative to the vehicle coordinate frame.

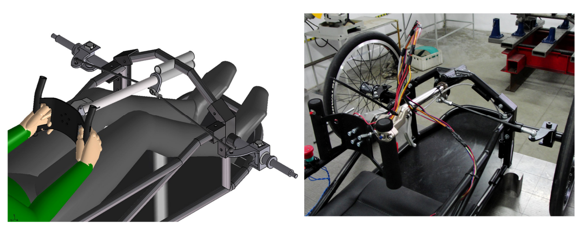

Fig. 5. LEV's steering system development

The vehicle steering mechanism is a feedback system, where the driver acting as a controller manipulates the steering wheel and through the vehicle behaviour (plant) obtains feedback information about the state of motion [14]. The LEV's steering system design has been inspired by a solution being used in commercial go-karts. It is based on spindle axels and tie rod brackets, steering rod joints, which when turned are steered by steering wheel column. LEV's steering mechanism also acknowledges the Ackerman's wheel geometry law. A

3-D model of the steering and the manufactured and assembled counterpart is presented in Fig. 5.

3.3 Mechanical parts of the drivetrain

The role of LEV's powertrain system is to produce a mechanical power output using an electric DC motor and through the gearing mechanism delivers it onto the road surface through the wheels. For weight and complexity reduction a one-wheel-drive solution has been utilised, with the driven wheel to be the outer rear, due to prior knowledge of the right handed track layout. The gearing mechanism was devised using a fixed ratio spur gear solution exhibiting high efficiency of 98%, which was made of lightweight polyamide material. Axles are the most loaded component in the entire LEV's construction. They are mounted to the chassis using four self-aligning bearings, whose advantage is the ability to sway a large arc, allowing offsetting misalignment errors that are difficult to avoid. The axles have been manufactured using steel.

3.4 Ergonomic analysis

The entire LEV's mechanical structure except the FEA analysis was subjected to a detailed ergonomic analysis. The aim was to identify the optimal driver position during driving in order to ensure maximum comfort and minimal fatigue during the event. Such a position is determined by the so-called comfort angle, which determines angles and bending of various parts of the human body. Fig. 6 presents the results of the analysis.

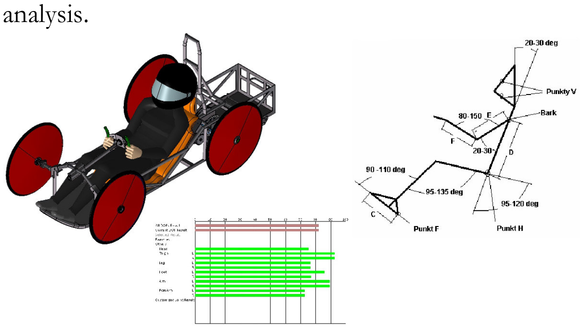

Fig. 6 The result of an ergonomic analysis and the comfort angles (DIN 33408)

Furthermore, driver field-of-view analysis was carried out as well as the analysis of the range of motion of the limbs (in accordance with the GCC rules). The analysis was performed using the Ergonomics Design and Analysis module available in CATIA V5 software.

3.5 Generative models

During the design of LEV's mechanical construction generative models of the steering system components were created [17] in order to aid design of other LEV's. Such a model is created based on the knowledge of the design process, the relationship between structural and functional characteristics. Created geometric models were stored in knowledge templates, which were enhanced with construction rules, control formulas and various component dependences.

4. Aerodynamics

The design objective is to reduce the air drag resistance defined as a C_dA parameter in Eq. 3. This was realised through the numerical analysis of air flow around the vehicle in a numerical wind tunnel, using Computational Fluid Dynamics (CFD) analysis, supported by ANSYS CFD software, [1]. The CFD enabled the detailed analysis of nature of air flow and dispersion around the object. It also identified the potential issues related with air vortex or air stagnation. The motion of fluid is described by Navier -Stokes and continuity equations, [11], which describe exchange of mass and momentum.

Fig. 7. Field static pressure, Pa on the plane of symmetry of the vehicle

As a result, the CFD simulations determine both the velocity and pressure values around a vehicle at a given point in space, from which drag force can be found. Furthermore, the design of the LEV's upperbody requires identification of an environment in which the vehicle will traverse during the race. This comprises of definition of the air properties like density, viscosity and definition of road texture, which also affects the air flow. In this environment, a number of 2-D models were examined, with the initial body shape taken from the NACA airfoil profile due to its low air resistance, [5]. Further models were modified and refined according to the dimensions of the vehicle underbody. The 2-D models are composed from the vehicle longitudinal cross-section, therefore to improve LEV's aerodynamics the 3-D models had to be examined as well. CFD indicated a stagnation of air in the driver seating compartment and high air vortex area at the back of the vehicle. To eliminate this, a windshield deflector had to be introduced to the vehicle body to direct the air to flow above the driver's helmet. Furthermore, the nose of the vehicle was lowered and rounded, the back of the vehicle was elongated and an extra body work was introduced at the back of driver's helmet. In addition, the vehicle ground clearance was reduced to minimum. These improvements contributed to the final shape of the LEV upperbody having the following parameters A=0.3032 m^2 and C_d=0.296. Fig. 7 illustrates the static pressure field on the plane of symmetry in the final version of the LEV upperbody. The upperbody was manufactured using acrylonitrile-butadiene-styrene (ABS) of 4 mm thickness using heat-vacuum forming technology. Fig. 8 presents both the LEV upperbody as a 3-D model and the photo of the manufactured part.

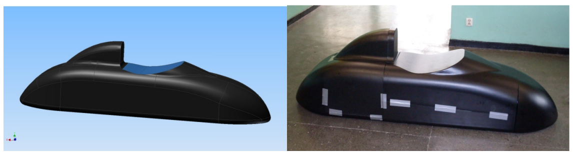

Fig. 8. LEV's underbody development

5. Cooling system

The nominal operating power of the DC motor provided by GCC organisers is 240W. In order to be competitive on the race more torque must be produced, i.e. up to 4Nm, which corresponds to 40A of the current. Since the motor is supplied by 24V, its nominal current rating is only 10A. In order to allow the continuous flow of 40A through the motor windings without causing a permanent damage, a suitable cooling system was required. In addition, the operating efficiency of the motor was reduced due to the heat generation, denoted P_{diss}, given by [19]:

$$P_{diss} = I^2 R \qquad (9)$$

where, I is the current flowing through the conductor [A] and R is the conductor temperature-dependent resistance [Ω]. The dissipated heat causes the rise of conductor temperature, which increases R linearly. Assuming I remain constant, i.e. 40A, P_{diss} increases causing more electric energy to be converted into heat rather than torque.

5.1 Effective cooling system

Design of the LEV effective cooling system comprised of two basic concepts: *1)* the use of two NACA ducts to force the external air to flow and cool the motor, *2)* the use of electric fans to cause the forced air flow. Since, the first concept does not utilise limited electric energy, its drawback is that NACA ducts introduces a significant air drag, hence more electric energy will be required to achieve the desired vehicle speed. Taking the latter into account the second concept had been chosen. The motor coil is wound around the iron shaft, which absorbs significant amount of heat. The remaining amount of the heat is released via motor housing. Therefore, it was important to keep both shaft and motor housing cool. There was a 25mm steel spur gear attached to the shaft's end, which increases its heat sinking capability.

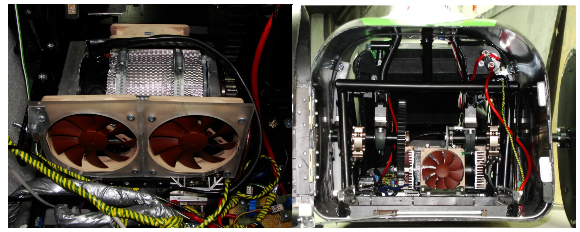

Fig. 9 LEV's cooling system. a) fans from the seat, b) fan from the cage batteries

The motor housing absorption capacity has been increased through the use of alloy radiators and thermal conducting paste. Both shaft and motor are cooled by the air flow from three Noctua NF-P12 electric fans, exhibiting high air flow rate of 184 m^3/h and low current consumption of 0.09A each. The complete motor cooling system is presented in Fig. 8. During the race, the LEV motor temperature read by sensor attached to the radiator remained around 80^{o}C, providing the current of 40A.

6. Drivetrain control system

Drivetrain is one of LEV's core systems. It comprises DC motor, gearing, batteries and a control unit. Successful integration of these components as well as design and development of suitable drivetrain control system determines vehicle competitiveness during the race.

6.1 Lead-acid battery model

One of the most important and delicate elements of the vehicle model described in sec. 2, is the lead-acid battery model. Without a good battery model one can not optimise vehicle components, evaluate control strategies and investigate their impact on the overall vehicle performance. There are two major groups of lead-acid battery models that can be found in the literature. The first group focuses on modelling of the electrochemical processes, [7], [8], [3]. These models are accurate since they model the real electrochemical object. However, the presence of many chemical phenomenon results in high model complexity. Moreover, the identification of the parameters of these models can prove to be difficult or sometimes even impossible.

Another group of lead-acid battery models are the so-called approximation models, [13], [2], [16], [9]. In these models, an electrical circuit with nonlinear elements is used as an approximation of the real electrochemical battery. These models prove to be more interesting from an engineering point of view. The major advantage of this kind of models is existence of good identification methods. With numerical procedures and measurement data taken from the real object, one can adjust the model parameters such that the model output matches the measurement data. The paper of Jackey [9] proved to be the most suitable for the needs of this work. Clear model structure incorporating: dynamics of battery charge and discharge characteristics, Peukert's law (*ibid*) and temperature dynamics are the major advantages of the model. Therefore, it was decided to investigate, modify significantly and implement it using Matlab/Simulink. Measurement data for different discharge currents and battery temperatures was collected with the use of a dedicated battery discharge and heating devices. Simulink Estimation Parameter Tool and Matlab Optimization Toolbox were then used to tune the parameters of the battery model. Fig. 10 shows the voltage across battery terminals during constant current discharge. One can see only a small difference between the model output (blue) and the measurement data (gray) indicating good model quality and parameter tuning.

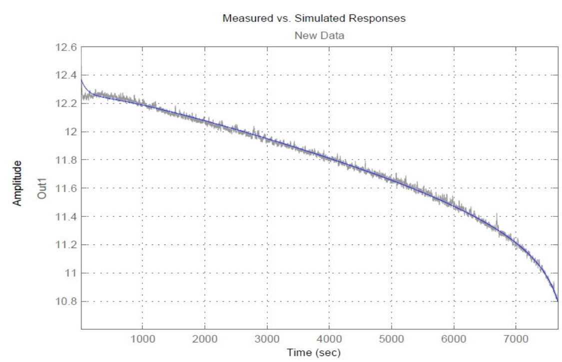

Fig. 10 Measurement data vs. model output

6.2 Drivetrain control unit

The control system design involves developing mathematical models of drivetrain elements, performing simulations and tuning the parameters of the regulators. Both, digital and analogue control systems were investigated. Moreover, the vehicle simulations show that CMC and CMV strategies exhibit comparable overall results, offering on the same time different vehicle behaviour. Therefore it was decided to design a control system capable of regulating both control variables. The control electronics of the LEV is divided into two layers. High-current power stage can be found in the lower layer, whereas the actual control system is implemented in superior, low-current layer. The division of the control unit into two parts proves to be advantageous with respect to one level solution.

During the design phase the proportional (P), integral (I) and PI controllers were examined. After simulations and experiments performed using a drivetrain test-rig described in section 6.3, it was decided to use PI controllers for both control strategies. The motor current measurement is realised using an analogue hall-effect transducer, whereas the motor voltage is measured with a circuit based on operational amplifiers and RC filters. The desired values of the control variables can be adjusted by the driver using a set of controls and potentiometers placed on steering wheel and on dashboard, as shown in Fig. 11.

Fig. 11. Steering wheel and HMI

6.3 Drivetrain test-rig

For the purpose of drivetrain stationary tests and development prior to the vehicle completion, a laboratory stand is of great value. One can test practical realisations of different control strategies before the race. The whole electric, electronic and telemetry system can be tested prior to vehicle implementation. In addition, it enables robustness test to be carried out and good development diagnostics of the control unit using laboratory equipment. Moreover, having a detailed vehicle dynamics model, as well as the race track model, one can try to simulate race conditions on a laboratory stand equipped with real objects like lead-acid batteries, electric motor and control unit. Such experiments are vital while investigating the performance and capabilities of the vehicle. The test-rig consists of two major parts: the drivetrain side and the mechanical load generation side. The first is a replication of the vehicle drivetrain system. The latter, loads the vehicle motor with a desired torque $(T \in (0.8,4)[N])$ defined by the user.

This is achieved with a DC motor acting as a generator, whose energy is dissipated on power resistors. The load torque control is realised by regulating the current flowing through the generator. The electric circuit of the mechanical load generation side resembles a boost DC/DC converter circuit, and is shown in Fig. 12. The dynamic equations of the circuit are given in Eq. (10) and in Eq. (11).

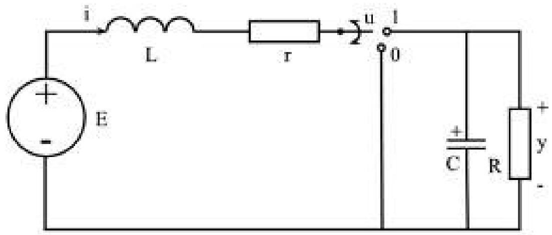

Fig. 12. Mechanical load generation circuit

$$L\frac{di}{dt} = -ir + E - yu \tag{10}$$

$$C\frac{dy}{dt} = -\frac{1}{R}y + iu \tag{11}$$

where, $u \in [0,1]$ is the control signal resulting from fast switching between terminals 0 and 1. A good study of DC/DC converters can be found in [6]. The test-rig development also involved deriving analytical conditions for all test-rig parameters, and required computer simulations of the whole system to be carried out.

6. Telemetry system

The motivation behind telemetry system is to transmit and demonstrate the parameters from the moving vehicle to the stationary pit crew. This enables an efficient electrical energy use by means of determination of suitable battery swap instance. This is realised by a continuous monitoring of voltage, current and temperature profiles of individual batteries and the motor. During the entire race time, there existed a continuous voice communication with the driver and the pit, realised using GSM network.

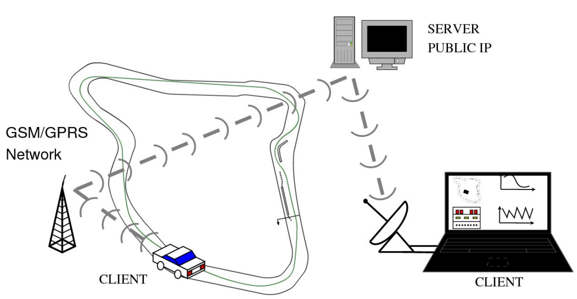

Fig. 13. Concept of LEV's telemetry system

This facility was used to command the driver to either take the pit stop or to modify the vehicle drivetrain control set points. The command was established as a result of analysis made taking the vehicle speed profile and actual battery state of charge (SoC) into account. The telemetry system functionality concept is presented in Fig. 13. The LEV is equipped with its own on-board computer realised by an ATmega 128 microcontroller. Its main telemetry features are: *1)* Data acquisition from sensors distributed around the vehicle, *2)* Signal conditioning and data processing for battery SoC estimation and lap number counting using information from a GPS module, *3)* Data packaging into a transmission protocol, *4)* A protocol output every 1sec to external transmitter, namely Westermo GDW-11, using RS232. The transmitting medium is the GPRS network enabling the TCP/IP communication session with a stationary external server having a \`public' and \`static' IP address assigned. The latter hosts an in-house developed LabView application dedicated for communication handling, received data extraction and display using a graphical user interface (GUI) (cf. Fig. 14).

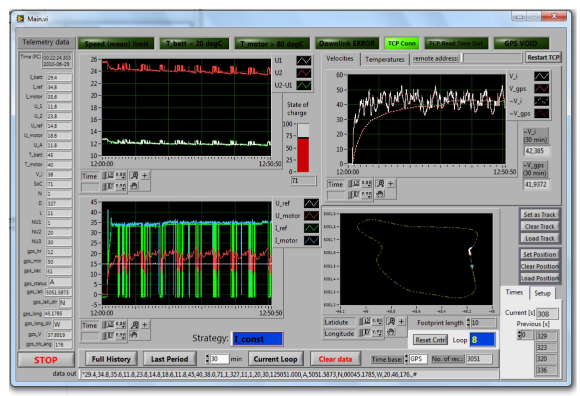

Fig. 14. Telemetry LabView application

The complete LabView GUI was seen on the remote pit laptop using a "Remote Desktop Connection" established with the server. This solution was chosen due to the limited properties of the pit laptop's internet connection, i.e. \`private' IP address. Furthermore, the on-board computer supports the vehicle human machine interface (HMI) (cf. Fig. 11). The amount of vehicle parameters displayed reduced to the minimum in order to retain high driving awareness uncompromised.

7. Concluding remarks

This paper has presented a design process for a fully functional electric vehicle, developed for an energy efficient endurance race, driven by a deep investigation in all fundamental automotive areas. An excessive use of professional engineering CAD software, CFD and FEA analysis and basic vehicle dynamic Simulink model has supported all design refinements. Successful completion of the test-rig allowed for drivetrain control unit development has provided many answers concerning the overall vehicle performance and robustness. During the race the vehicle endurance was achieved via in-house developed drivetrain control mechanism and telemetry system, enabling maximal utilisation of available electrical energy. This work has also presented LEV's main functionality and discussed methods for vehicle evaluation.

LEV's design and development is considered to be a demanding task as it involved many systems integration issues, nevertheless it is deemed to be an ideal final year project, exposing a number of theoretical and practical challenges. In the 2010 edition of GCC race, the Silesian Greenpower LEV was awarded with IMechE "Best Engineering Car" price, whilst covering 176km over four hours, resulting in 6/34 position, significantly beating all other new-comers. More information about Silesian Greenpower project can be found in [20].

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