Advanced Simulation of Power Consumption of Electric Vehicles

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***Abstract*—**Electric vehicles are one of the most complicated electric devices to simulate due to the significant number of different processes involved in electrical structure of it. There are concurrent processes of energy consumption and generation with different onboard systems, which make simulation tasks more complicated to perform. More accurate simulation on energy consumption can provide a better understanding of all energy management for electric transport. As a result of all those processes, electric transport can allow for a more sustainable future and become more convenient in relation to the distance range and recharging time. This paper discusses the problems of energy consumption simulations for electric vehicles using different software packages to provide ideas on how to make this process more precise, which can help engineers create better energy management strategies for electric vehicles.

***Keywords*—**Electric Vehicles, EV, Power Consumption, Power Management, Simulation.

I. Introduction

ELECTRIC vehicles (EV) have been selected as the most perspective type of the sustainable transport for the nearest future. Modern electric vehicles architecture includes a larger number of systems and devices on board. As there is no other type of energy available in EV, all components only use electric energy as a main power source. At the same time, some systems, such as powertrain, are working in a multi-directional power flow, where they are consuming energy during acceleration and generating electric power during the braking process through recuperation mode.

Computer simulation is one of the key aspects for the development and optimization of systems for all types of engineers. There are many software packages available for different types of simulation, but the main problem is to develop and define accurate models for the simulation.

As a major part of development process, computer modelling is used to improve characteristics of electric vehicles. The main areas of study of power consumption in EV are limited to powertrain simulation, as the powertrain is the main consumer of electrical power and has a significant influence on different characteristics. There are some testing cycles available for powertrain simulation and optimization such as NEDC for European countries, JC-08 for Japan or EPA cycle in USA [1]-[4].

Some simulations are concentrating their efforts on the recuperation part of the electric vehicles [5], [6] and integration of the brake-by-wire system into safety systems of the vehicles [7], [8].

Some simulations for power consumption in electric vehicles include thermal and climatic systems as a key study [8], [9].

The purpose of this paper is to develop and define an advanced model for power consumption simulation of the EV, identify testing conditions for different systems and develop optimization principals for this model.

II. Systems Topology of Electric Vehicle

A. Key Elements

As there are many systems now available in the EV, some of them are more important, as without it EV will not be able to get registration or provide transportation functionality.

The main system and the key element of EV is energy storage. It can be battery pack or hybrid storage with hydrogen tank and fuel cell combined with battery pack and ultra-capacitor in one system unit. A bidirectional power flow, electric energy storage includes control computer based devices to monitor the state of charge of the battery and capacitor bank for an affective recuperation process, thermal state for temperature regulation. At the same time, energy storage system should include high frequency transformer for external charging from the local power network and, in some cases, for fast charging stations and modes.

Energy storage is a central element of the EV, as it provides energy for all of the EV's requirements and an accurate model is required for this system.

Second important system is powertrain with electric motors and transmission. These systems are providing the movement of the vehicles and consume the largest amount of energy. For modeling the powertrain plays role of consumer and generator.

The third most important are the safety systems. It includes active safety systems with CPU and controlling devices for Anti-Block System (ABS), Electronic Stability Control (ESP) and other additional features to prevent collisions. Passive safety devices are also includes in this.

B. Consumer Relevant Systems

These systems provide some important features, but they have a small influence on safety or movement characteristics for the vehicle. With these features, EV can still move without harmful effects, but it can be less comfortable or will require special conditions. Three systems here are lights, climate control and windscreen washing mechanisms.

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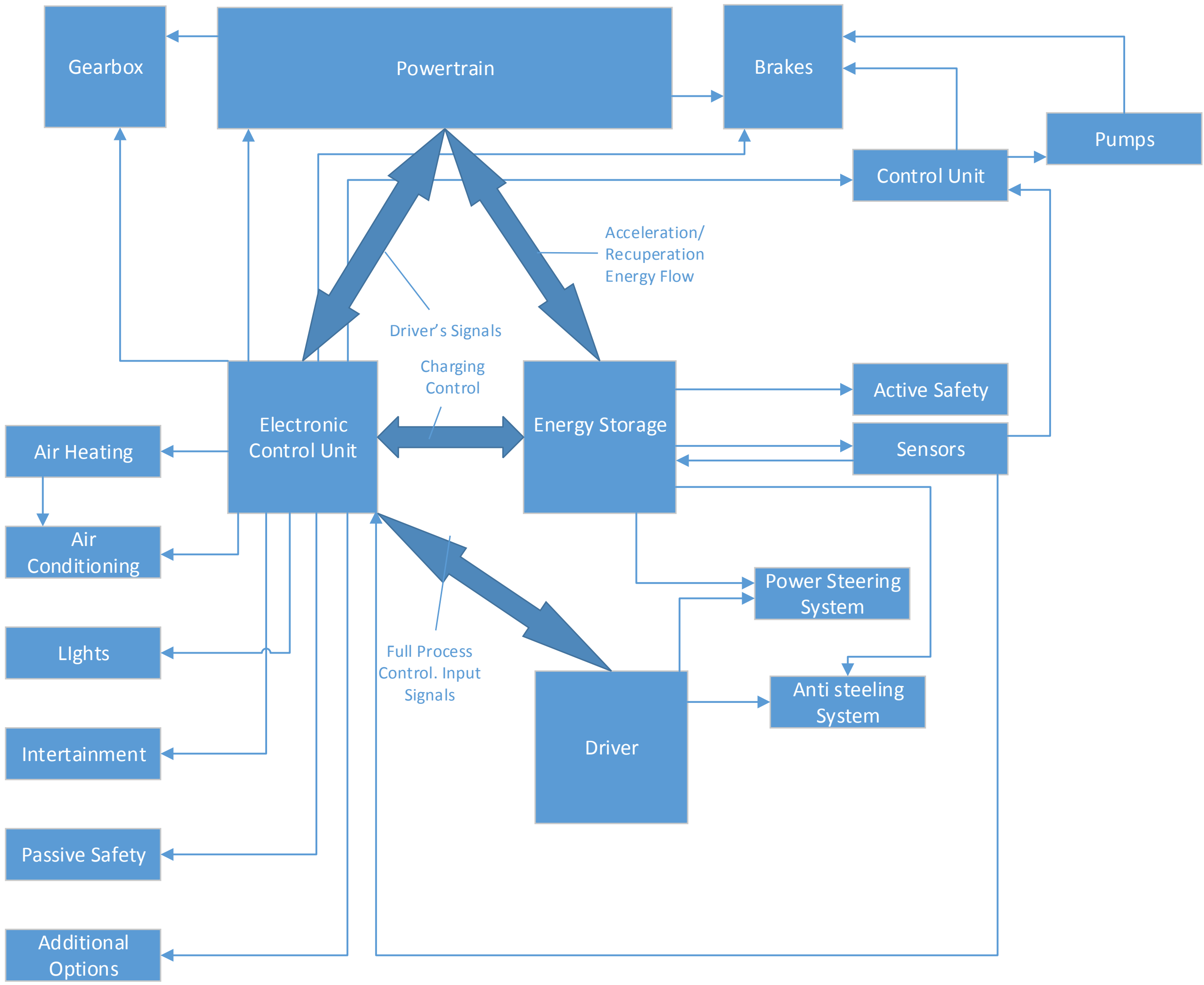

Fig. 1 Information and Energy Flows in General Electrical Vehicle System

All these systems are necessary for legalization of the vehicle, but in case of their fault or braking down; car can still operate without them and can transport the driver to the nearest service station. These mechanisms and devices have impact on the safety, but this impact is not very big. For example, driver can use special signals to replace the turning or braking lights.

The commonality of all these systems is their high energy consumption in special conditions. Air conditioner can consume high amount of electric energy and become a heavy drain on the battery.

C.Additional Features

These systems have been developed during last 30 years. This part includes additional features to make the driver's life easier. Systems, that provide entertainment or they can be used as a replacing of electric powered devices for mechanical analogous. Some of these features can be found only in special types of cars. For example, electric controlled roof are used only for convertibles vehicles and it is impossible to find it in the other types of the car.

For simulations, these systems can be represented all together, or just some of them can be included. Most of these consumers are not working for any length of time, which makes process of power consumption analysis very complicated. As a result, for different vehicles with different additional equipment simulation will be completely different. The more features the car has, the more complicated electric devices communication topology is.

D.Systems Connection

The whole design of the system can be represented on the Fig. 1. This figure represents the whole design of the network for electric consumption in electric vehicles indicating both logical and energy connections between the devices, consumers and controlling units. As we can see, there are three parts which plays the greatest role in power flow processes as they have significant influence and their interaction will lead to the more or less effective usage of power. Those elements are batteries, powertrain and driver.

The driver, as a system, is the biggest challenge for simulation. Modeling the driver requires special consideration and can be a case study on its own. Constructing an accurate model of the vehicle is affected by the driver as the driver influences the model due to having manual control on some systems and can apply non-optimal functions in inappropriate conditions.

III. Characteristics of the Key Systems

In this chapter, the main electrical characteristics of the systems are represented. All this characteristics are important for the simulation process, as they are describing the systems and its attributes. All power data were measured on the sample car a 2013 KIA Optima sedan with 2.0 diesel engine, Automatic gear box and single zone climatic control.

A. Powertrain

Characteristics of the powertrain are depends on the vehicle dimensions, its weight and required performance. Different vehicles can have completely different size and the type of Electric motor used can have a great influence.

There are different types of electric movers that are used in EV powertrains. The most popular type is brushless DC motor. This motor can easily play a role as a motor and as a generator to provide the braking torque. Control of this type of motor is not difficult and there are no special devices require between the motors and the batteries "theoretically", but in practice power electronics are used to reduce the current and organize the charging-discharging process.

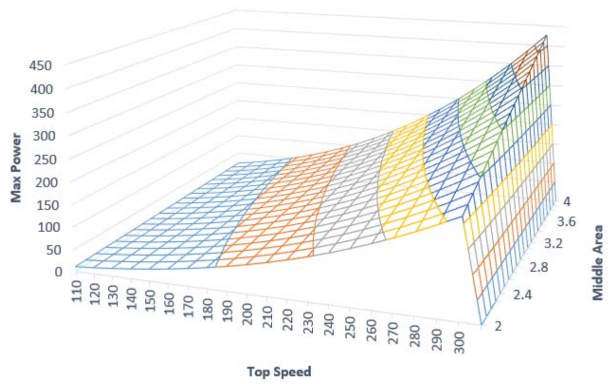

Fig. 2 Required Peak Motor Power

On Fig. 2 the required motor peak power is represented as a dependency from the top speed and size of the vehicle. The peak power was calculated based on vehicular power balance equation:

$$Pm = \frac{Pdr+Pwh}{\eta} \quad (1)$$

where: P_m- maximum motor power, P_{dr}- drag resistance power (2), P_{wh}- wheel resistance power (3), η- efficiency of transmission.

$$Pdr = \frac{1}{2}Cx\rho AV^3 \quad (2)$$

where: C_x – drag coefficient, ρ- air density, A- area of the car, V- velocity. For Fig. 2, C_x=0.31 as an average coefficient of the modern cars.

$$Pwh = mgV(0.005 + \frac{1}{25}(0.01 + 0.0095\left(\frac{V}{100}\right)^2) \quad (3)$$

where: m- vehicle's mass, V- velocity, g=9.81m/s^2- gravity constant for the Earth.

Efficiency of the transmission for electric vehicles depends on the powertrain design. For wheel-hub motors, when there is only a single transmission gear, the efficiency can be up to 97%. For more complicated constructions, such as the clutch-gearbox-differential, when one big electric motor is used, the efficiency can be 80% or less.

The energy consumption of the vehicle depends on the driving conditions. If there are lots of acceleration and braking procedures, the power consumption will be greater. For simulation and optimisation processes there are several different driving cycles. These cycles are providing a robust loading and speed-time characteristics for power train simulation.

Energy calculation study requires the data for working time of the system. As the powertrain is a key element, which provide acceleration and partial braking performance, its load should be continuous.

The second important element in energy consumption of the powertrain of EV is the gearbox. There are different constructions available. Some of them do not require any gearboxes and need only a main gear. One such system is an EV powertrain package with wheel hub motors. Other powetrains usually have automatic or continuously variable gearboxes. These gearboxes are based on hydraulics with electromagnetic valves. The more torque we have to transfer, the more pressure should be in the hydraulic transformer. As a result, the oil pump has to be powerful. The gearbox is working continuously as the car is operating, so this should be included the entire period of the simulation. Maximum power that is consumed by gearbox can be from 1.5 to 2 kW.

B. Energy Storage

As a power supplier, the energy storage cannot be represented in simulation, but all the devices that charge and manage the energy storage should be includes in the study.

Modern storage systems consist of hybrid storage. A combination of elements such as battery packs, capacitors, and/or fuel cells. For such storage the governor topology is more complicated and requires more energy. For model development, it can be crucial, as power consumed by these devices can go up to 0.5 kW.

C. Active Safety Systems

These systems are used to prevent dangerous situations. These groups of consumers include all braking related mechanisms and controlling devices around the car, such as blind zone control and adaptive cruise control.

The topology of this system is different from conventional vehicles. In EV, brake by wire mode plays the big role in energy management as it is used as a generator to charge batteries during braking. As a result, the CPU of the braking mechanisms should control two separate processes of electrical braking and hydraulic braking forces. As ABS system prevent the wheels locking, it adjusts the braking forces through additional hydraulic pumps within the braking pipelines. At the same time, the ABS uses hall sensors on the wheels to obtain information about the rotational velocity and adjusts the braking torque accordingly.

The hydraulic pump which controls the four braking lines is the main energy consumer in this system. They do not work continuously, but only when their action is required. For modelling during the NDEC driving cycle this pumps can be included in 5% of the braking time. For the hall sensors the duration of work is constant.

The biggest problem for simulation of energy management in EV braking system is combination of ABS controlling algorithms with generation processes and their control. For effective ESP implementation, some braking torque can be applied only via the electric motors and it will generate power to recharge the batteries only if the speed of the car is high enough to produce required torque. The same problem exists for fine logic control for the ABS system, as it has different control mechanisms through different electric braking torque or through hydraulic lines. For hydraulic release we need to spend some energy to power up the pumps, but for electric braking torque we will just decrease the regenerated energy and we can obtain finer controlling.

Other difficulties arise from the powertrain construction. For different vehicle schemes there should be different controlling mechanisms, as the braking force distribution is different.

For advanced simulation and control mechanisms, the passive safety systems should have the highest priority. Energy storage should always have enough energy to ensure the ABS works correctly.

Another important part of the active safety systems is the power steering mechanism. Modern cars have electric power steering as this is the most effective solution. Power steering systems consist of the additional motors on the steering rack to help the driver with wheel turning. According to the safety standards, steering rack should still have the mechanical connection between the steering wheel and turning wheels. Modern power motors consume up to 2kW of power in complicated conditions. Modern steering mechanism has an angle sensor, which is used by the ESP as one of its sensors. The power steering motor is operating continuously during all driving cycles.

D. Passive Safety System

This system protects the occupants when a crash occurs. The structure of this component is very simple, as there are accelerometers and deflection sensors in the car body to recognise the collision to activate airbags. Airbags systems fall into the next tier of energy consumption. The third item of energy consumption for passive safety is the seat belt holders.

The power consumed by all of these components is very small. Collision sensors are based on piezoelectric elements and do not require any power to operate. The airbags are given the highest level of importance in electric control network, but the working principal is based on exploding material, where a small amount of power is required to blow activate them. For more effective working conditions a separate battery can be used to alleviate the drain on the main battery.

The main consumer of power in the active passive safety system is the CPU module and belts pre tensioning mechanism. The CPU is works continuously as it analyses the data from piezo-elements to give signals to the airbags as required. The peak power usage can be up to 100W.

Belt tensioning mechanism can operate on electric power or on mechanical spring principals. Electric based construction provides better safety conditions and more flexibility. Such systems operate on servo motors with peak power up to 50W and they are used for less than 5second as the driver and occupants fasten their belts.

As we can see, passive safety devices can operate on very low power and it has pretty small influence on the overall power consumption, but as it has the highest priority, CPU and seat belt tensioning mechanisms should be include into energy consumption simulation as a consumer for passive safety systems.

E. Lights

Lights can be considered as a part of the safety system. The problem with this system is that while failure may have a minimal affect during the day it is a crucial system for night time driving. With modern LED lighting there has been great improvements in both energy efficiency and the robustness of automotive lighting.

There are five types of exterior lights that are used in modern vehicles: head lamps, turning lights, stop signals, reverse lights and fog lamps. Another class of lights that are using in the EV is the interior lights. For energy consumption study, those lights can be combined in one big load, as their power is less, than exterior lights. Power characteristics and working time for simulations of the modern vehicular lamps are presented in Table I.

F. Climate Control System

Cabin climate is one of the biggest problems for modern EV. In conventional vehicles, the heat of engine is used to heat the cabin. In electric vehicles, electric motors do not produce enough heat to make an effective heating construction. Moreover, the climatic system includes the air conditioning pump and fan. In conventional vehicles, the air conditioning pump which forms the main part of conditioning system, is powered by engine. In EV, the conditioning pump is powered by electric motors.

TABLE I
CHARACTERISTICS OF THE LIGHTS SYSTEM

Light Type	Power of the single lamp, W	Number of lamps	Peak Power, W	Working Time and Conditions
Headlamps	60	2	120	All time, as a daylights
Braking	21	3	63	During Braking
Turning	21	6	126	During turning manoeuvres
Anti-fog Lamps	35	3	105	During fog conditions
Reversing	21	2	42	During Reversing Manoeuvres
Number Plate	5	4	20	All the time
Cabin Lights	20	1	20	All the time
Total:			496	

But the most important part of climatic system is fans. Fans are using to defog windows and their airflow has significant influence on the safety. In modern vehicle there are at least two fans in climatic system to demist the windows in the shortest time. Each fan has peak power of 120W. Working time of each fan is usually the same, as the working time of the car. [10]

When it comes to the power of heating and conditioning system of an EV, the peak power of a separate heater can be up to 3kW, this is working together with both fans. Conditioning system uses two fans and its pump has the peak power usually up to 2.5kW. Conditioning pump and electric heater are working separately in EV, and never both at the same time. As the power consumption and working time range is high, usage of these systems have the great influence on range and performance. Some studies show, that the distance range can be reduced by half, when conditioner or heater is in use [11].

Another part of climate control that has influence on safety is windows heating. These systems are always based on the electric power and they are built into the windows. For northern countries, there are front and rear windscreen heaters accompanied by rear mirrors heating devices. Each heater, as the area of the glass can be large, has a power consumption of up to 200W for windows and 60W for each rear mirror. The working time for these systems is not very long, as drivers are normally using them in the mornings to clean the windows. For modelling purposes, the working time can be considered as 15 min per day. For NDEC simulation, the working time is required to be around 10% from the whole testing time.

There are some additional features that can be included in different energy consumption study. Most of these features have no influence on the safety of the vehicle, but they provide additional comfort for occupants. Seats and steering wheel heaters/coolers are the most popular additional features. For budget vehicles, seats heater is common features in cold countries. The power consumption of each seat heater is usually around 200W. Steering wheel heater has lower power-around 50W. Working time of these systems should be in line with windows heating, as they are mostly used in the morning to heat up the seats and steering wheel.

G. Wiper and Washer Systems

These systems include window wipers for front and rear windows, and wipers and washers for headlamps.

The front windscreen wipers are used in all vehicles and this mechanism is driven by one electric motor with different sets of speeds. The peak power of this motor is 80W. The washers consist of one water pump and have peak power of 100W to provide required speed and pressure of the cleaning liquids. Working time of this system can vary from 10% up to 50-60% of the car running time, depending on seasons and climatic regions. For a comprehensive simulation, it is better to consider the working time as 50% of the operation time of the car for wipers and 2-3% for washers. Second sets of washers and wipers are used in vans and SUV’s which are not used for sedans. The working time of the second wipers and washers should be added if the case of study is not sedan vehicle.

New xenon headlamps required clean lenses optimal performance, as the dirty lenses decrease the brightness significantly; the lamps washer is required system. For simulation, the pump power is the same, as for windscreen washer 100W and working time usually 10% of the windscreen washing time.

Another important part of this section is mirrors movers. To position the mirrors suitable for different driver’s position, there are special servo drives are using. Each mirror has its own motor with peak power of 20W. Working time is very short and can be negligible in comparison with other systems. As an addition to mirrors movers, this section should include the automatic windows devices.

Side windows are lifted by electric motors for a long time. For conventional vehicles, where we have fuel tank with almost unlimited energy capacity with low refuelling time, the high power consumption of the automatic windows are not a problem. In EV, where recharging time is a critical issue, including the automatic window system into a study is a critical issue. The power of each servo drive is 150W. Working time is 10% from the whole working time for different study cycles. As we can have up to 5 lifting mechanisms, the peak power is as high, as 750W for vehicles, with boot lifting drive.

H.Additional Features

All previous systems play a major role in modern vehicles. Most of them are providing appropriate safety conditions for drivers and occupants. Additional features are features that are installed for the purposes of comfort, visual appearance or owner preference. Some additional systems are important in modern vehicles, but they have no or very little influence on safety and some of these features are not available for all cars, while others are common and you can see them in 99% of vehicles on the road. Some of these additional features are used for specific transport or in special cases, such as heavy duty vehicles or sport cars. As modern vehicular design includes some of these features, the simulation data and profile can consist of these systems but they are not essential. The complexity and number of additional features show, that different models and options can create a very different power management process and engineers can and should take into consideration as many systems as possible during a simulation process, as the top versions of vehicle will have them.

Table II shows the most common or the highest power consuming devices that can be a part of energy study for EV. In Table II, there is also a proposed time to include in simulation processes for advanced testing.

One of the most advanced and energy consuming feature is air or hydraulic suspension. There are different models of the vehicles, which use this type of suspension to improve their comfort and loading performance. In such vehicles, advanced suspension can be used as a part of the active safety system and should be controlled together with them.

TABLE II
ADDITIONAL FEATURE AND ITS CHARACTERISTICS

Feature/Option	Peak Power, W	Working Time
Central Lock	15	Twice per cycle, 2 sec.
Music System	25	All the time
Suspension Pump	1000	20% of the time
Navigation	15	All the time
Roof Moving	300	Once per Cycle, 30 s.
Seats Moving	300	10s per cycle
Multimedia Screens	30	All the time
Cigarette lighter	100	60 s. per cycle
Rear View Camera, Parking Sensors	20	According to testing period
Blind Zones Radar	5	All the time

IV. RESULTS AND DISCUSSION

As we have discussed, the electrical circuit of an EV is a very complicated structure. The peak power of the all devices can add up to 10kW, this can be half of the rated motor power. To develop a comprehensive bus for all these systems, peak power and working time should be the variables to create a conclusive study of the power simulation.

The biggest problem in power simulation of different devices and components is the adequate working time, as consumed energy is:

$$E = P\tau \tag{3}$$

where P- peak power of the device, τ- working time.

For some devices, working time is equal to the working time of the engine, for others it can be 0. Different countries and regions will have different sets of systems. For example, hot regions will have a big influence from the conditioning components, where the cold regions will have various heating devices.

As all these devices are working from battery power, each system has effect on the others and cannot be discounted, if it is working. The powertrain is the most powerful and energy consuming device, but it also works as a generator during the recuperation process. As there are many different loading and speed cycles in different countries, simulation of the powertrain energy consumption is not as difficult as the simulation of the other systems together with motors. Peak power of the motor cannot be assumed the same for different vehicles, but for each vehicle with top speed and aerodynamic characteristics, maximum power can be calculated with little difficulty.

Controlling logic for some components is in line with controlling the power train. For example, braking system has a big influence on the recovery braking torque of the electric motors and a strategy should be included for both braking mechanisms.

Another problem for simulation procedure can be the intelligent connections between systems. For this part, EV is similar to the modern micro grid networks in terms of sharing loads and splitting the power. Optimization and proper energy usage of the all mechanisms is one of the key issues for future EV improvement. This process should be in line with energy storage management, especially when the hybrid storage is in use.

V.CONCLUSION AND WORK IN PROGRESS

The current research activities are focused on developing the optimal control strategy based on responses and required power consumption of the electric system for EV. This optimization process is based on the simulation data that was described in this paper.

As we can see, detailed power simulation process of the modern electric vehicle is complicated and time consuming process. An accurate and complete model should be developed, as the peak power of the secondary systems can be half of the motor power. Such simulations can be used for detailed planning of the consumption of the energy and, as a result, will increase the distance performance of EV. Another application of this process is developing the suitable energy storage and organizes charging process of it. Next outcome of this study is the bus design for power network inside the EV and logic communication between the systems.

REFERENCES

[1] A. C. Baisden and A. Emadi"ADVISOR-based model of a battery and an ultra-capacitor energy source for hybrid electric vehicles",*IEEE Trans. Veh. Technol.*, vol. 53, no. 1, pp.199 -205 2004.
[2] Sakhalkar, S., Dhillon, P., Bakshi, S., Kumar, P. et al., "Powertrain Model for Selection of Reduction Ratio and Estimation of Energy Requirement," SAE Technical Paper 2014-01-1781, 2014.

[3] Yamin, J. and Hamdan, M. (2010) 'Simulation of an electrical engine powered by fuel cell–solar energy hybrid system', *Int. J. Electric and Hybrid Vehicles*, Vol. 2, No. 4, pp.308–314.

[4] Zheng, L. and Zhang, J-W. (2012) 'Analysis and applications of the regenerative braking force in pure electric vehicles', *Int. J. Electric and Hybrid Vehicles*, Vol. 4, No. 1, pp.12–23.

[5] Ruan, J. and Walker, P., "An Optimal Regenerative Braking Energy Recovery System for Two-Speed Dual Clutch Transmission-Based Electric Vehicles," SAE Technical Paper 2014-01-1740, 2014.

[6] Danapalasingam, K.A. (2013) 'Electric vehicle traction control for optimal energy consumption', *Int. J. Electric and Hybrid Vehicles*, Vol. 5, No. 3, pp.233–252.

[7] Shyrokau, B., Wang, D., Savitski, D. and Ivanov, V. (2013) 'Vehicle dynamics control with energy recuperation based on control allocation for independent wheel motors and brake system', Int. J. Powertrains, Vol. 2, Nos. 2/3, pp. 153-181.

[8] Nagano, H., Miyamoto, I., and Kohri, I., "Numerical Analysis of Energy Efficiency of Zone Control Air-Conditioning System for Electric Vehicle using Numerical Manikin," SAE Technical Paper 2013-01-0237, 2013.

[9] Lee, G.H. and Yoo, J.Y., "Performance analysis and simulation of automobile air conditioning system, International Journal of Refrigeration, 2000.

[10] Dieckmann, J. and Mallory, D., "Climate Control for Electric Vehicles," SAE Technical Paper 910250, 1991.

[11] Lee, J., Kwon, S., Lim, Y., Chon, M. et al., "Effect of Air-Conditioning on Driving Range of Electric Vehicle for Various Driving Modes," SAE Technical Paper 2013-01-0040, 2013.