State of the Art of Structures and Main Components of Hybrid and Electric Vehicles

Gergana I. Vacheva, Nikolay L. Hinov

The main objective in this paper is to review the most widely used structural schemes of hybrid and electric vehicles and their basics blocks. The various sources of energy are consistently presented - fuel cells, batteries and supercapacitors which are described with their equivalent circuits and models. In the examined electric transport vehicles there are several options for control energy flows and methods for their effective implementation of various types of control impacts. Different configurations for the transmission of energy from the source through electronic converters and engine in startup and breaking mode of the vehicle are described. Comparison between the different types of engines, with applications in electric transport is made. The result is that, it becomes possible to make an optimal choice of the particular structure and its elements according to the use of the vehicle.

Преглед на структури и основни съставни елементи на електрически транспортни средства (Гергана И. Вачева, Николай Л. Хинов). *В работата са разгледани най-използваните структурни схеми на хибридни и електрически транспортни средства и техните основни блокове. Последователно са представени различните източници на енергия – горивни клетки, батерии и суперкондензатори, описани с техните еквивалентни схеми и модели. Показани са няколко варианта за управление на енергийните потоци в разглежданите транспортни средства, а също и методите за тяхната ефективна реализация с различни типове управляващи въздействия. Описани са различни конфигурации за предаването на енергия от източника, през електронните преобразуватели и двигателите в режим на потегляне и спиране на транспортното средство. Направено е сравнение между отделните видове двигатели, с приложение в електротранспорта. В резултат на това става възможно да се направи оптимален избор на конкретна структура и нейните елементи в зависимост от предназначението на транспортното средство.*

Introduction

The modern society is characterized by its mobility. In the current development and state of the economy, the movement of people and commodities is vital for the existence of human civilization. This leads to a constant increase in the number of different types of vehicles for transportation which on the other hand creates a series of serious environmental problems. There is a predominance of transport vehicles powered by engines with internal combustion. The depletion of the stocks of oil and the need to protect the environment, suggests the demand of other alternative sources of energy. In this aspect electrical transport vehicles are one solution that allows the development of the economy and the preservation of the standard of living, in compliance with the environmental requirements.

Different architectures of hybrid and electrical vehicles are observed, sources of energy and elements for its storage (fuel cells, supercapacitors and batteries), power converter for the control of energy flows and methods for their optimization are presented in this paper. The purpose is to consider the different options and to describe their advantages and disadvantages.

Sources of Energy and elements for its storage

Several major sources of energy: rechargeable batteries, fuel cells and supercapacitors are used in the electrical transport vehicles and hybrids. Depending on the concept of the means of transport may be used only one of the listed types or a combination of them. The most frequently used versions of the sources of energy are addressed below.

In figure 1 is shown the most common structure of the source of energy in transport. It contains all three types of sources of energy described above. They will be enumerated consistently, together with their mathematical descriptions which are used for the purposes of the modeling.

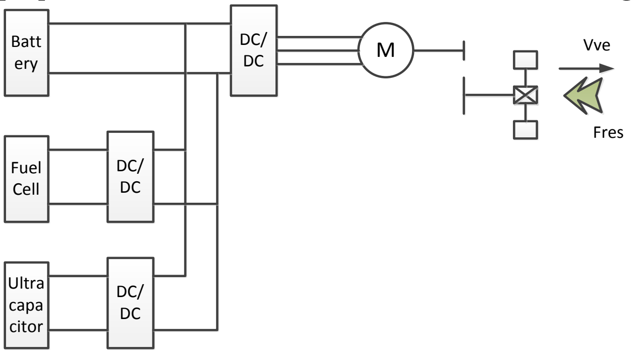

Fig.1. Fuel cell-battery-supercapacitor hybrid electric vehicle

System with fuel cell

Fuel cells incorporate stack, which are responsible for power and several auxiliary systems such as compressor cooling systems and others [2, 3]. There are a wide range of possibilities for the modeling of fuel cells. Equivalent models obtained by impedance allow easy interaction with other electric models. The output voltage can be described by the following equation:

$$U_{fc}(V) = E - R.I_{fc} - \left(I_{fc} - C_1 \frac{d}{dt} U_{C1}\right) R_1 \qquad (1)$$

where voltage E is dependent on the temperature of the pile, constant Faraday, hydrogen, oxygen, water pressure and standard voltage in the fuel cell. R is the resistance represented in ohms and C_1 is the capacitance of the capacitor.

The fuel cell is connected to the rest of the system through the inductance to adjustment the peak current and DC-DC converter. Equations system are presented:

$$u_{fc}(t) - u_{ind_{fc}}(t) = L \frac{d}{dt} i_{fc}(t) + R i_{fc}(t) \qquad (2)$$

$$\begin{Bmatrix} i_{chop\_fc}(t) = m_2(t) i_{fc}(t) \\ u_{ind\_fc}(t) = m_2 u_{bat}(t) \end{Bmatrix} \qquad (3)$$

Batteries

Electrochemical batteries known only as "batteries" are electrochemical devices that convert electrical energy into potential chemical energy during charging and vice versa during the discharge. The battery is composed of several cells together [8,9]. Basically, cell battery consists of three elements: two electrodes (positive and negative) submerged in an electrolyte.

Manufacturers of batteries usually categorize them with coulometric capacity (ampere-hour), which is defined as the number of ampere-hours earned at discharge from state to fully charged. An important parameter of the battery is state of charge (SOC). It is defined as a relation to the remaining capacity on a fully charged one. Changing the charging status at a given time interval *dt*, with discharge and charge current *i* can be expressed by the following equation:

$$\Delta SOC = \frac{idt}{Q(i)}, \qquad (4)$$

Where $Q(i)$ is the ampere-hour capacity of the battery at a given current i. Upon discharge the current is positive, while negative during charge. In this case, the battery status can be expressed by:

$$SOC = SOC_0 - \int \frac{idt}{Q(i)}, \qquad (5)$$

where SOC_0 is initial value of SOC.

Electric and hybrid electric vehicles energy capacity is considered the most important because it is directly linked to the operation mode. In this case, the energy supplied by the battery can be expressed by:

$$EC = \int_0^t V(i, SOC) i(t) dt, \qquad (6)$$

where $V(i, SOC)$ is the voltage across the battery terminal, which in its current and charging status.

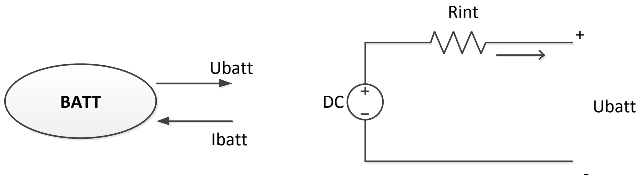

Fig.2. Battery (left) and equivalent circuit (right)

Modelling the battery is thoroughly studied in various conditions held in the short- and long-term operation of the vehicle. Widely accepted procedure for modeling of the battery is an electrochemical analysis. Fig. 2. shows the battery output voltage and input current.

To properly calculate the battery is necessary to access the state of charge (SoC). This can be a complex task, especially in the batteries in which the acid concentration in the electrolyte cannot be measured accurately. In this article was chosen a method that determines the efficiency considering the current hour. This method is described in the following equation:

$$SoC_t(\%) = SoC_{t-1}(\%) - \frac{100\eta}{C_n}\int i(t)dt \qquad (7)$$

Supercapacitor

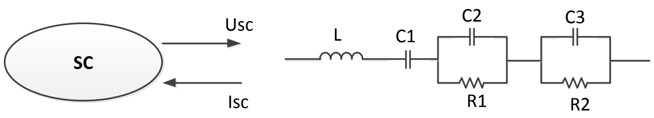

Fig.3. Supercapacitor (left) and equivalent circuit (right)

The supercapacitors enable high power supply, which is a good characteristic for use in electricity transport vehicles. The modeling of supercapacitors can be delivered through a variety of equivalent circuits [4]. Fig. 3. represents one that can be described with the following equation:

$$u_{uc}(t) = u_L(t) + \int \frac{1}{C_1} i_{uc}(t)dt + \int \frac{1}{C_2}\left(i_{uc}(t) - \frac{u_{C2}(t)}{R_2}\right)dt + \int \frac{1}{C_3}\left(i_{uc}(t) - \frac{u_{C3}(t)}{R_3}\right)dt \qquad (8)$$

Supercapacitors are related to DC bus through inductance and boost converter.

$$u_{sc}(t) - u_{ind\_fc}(t) = L\frac{d}{dt} i_{sc}(t) + R i_{sc}(t) \qquad (9)$$

$$\begin{Bmatrix} i_{chop\_sc}(t) = m_3(t) i_{sc}(t) \\ u_{ind\_sc}(t) = m_3 u_{bat}(t) \end{Bmatrix} \qquad 10)$$

Parallel coupling

The DC bus voltage will be utilized with a battery while the currents will be distributed in parallel nodes. The parallel connection is divided into two to facilitate the control system. It is described by the following equation:

$$\begin{Bmatrix} i_{load}(t) = i_{bat}(t) + i_1(t) \\ i_1(t) = i_{chop\_fc}(t) + i_{chop\_sc}(t) \end{Bmatrix} \qquad (11)$$

A comparison is made between different sources used for energy storage.

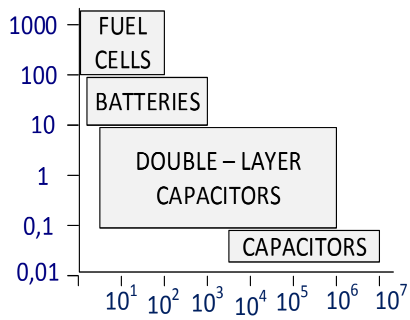

Fig.4. Comparison between capacitors, supercapacitors, batteries and fuel cell

Classification of the architectures for the drive mechanism

The basic method for classification of hybrid electrical vehicle is driving mechanism. There are three types - serial, parallel and series-parallel. The block diagrams are presented in the Fig.5,6,7.

Series hybrid system

In Fig. 5. is shown a configuration of electrical vehicle powered by an electric motor which is powered by a storage system or generator[23]. Also included is a small internal combustion engine to generate electric power. During recharge, the electric motor is a standby generator absorbing the braking power and charges the storage system. One of the advantages of the series hybrid system is that the control system is relatively simple. Also the operation is very similar to the one of the electric vehicles.

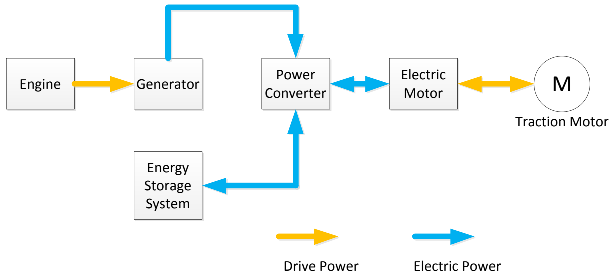

Fig.5 .Series hybrid system configuration

Parallel hybrid system

The configuration of a parallel hybrid system is shown in Fig. 6. Both motors provide adhesion for the wheels, which means that the hybrid power is collected in a mechanical junction of the vehicle. In this case, the motor is supplied by a battery to drive the wheels and also operates like a generator to power it. The control of parallel hybrid system is more complex than the series system, due to the mechanical connection between the engine and the wheel drive.

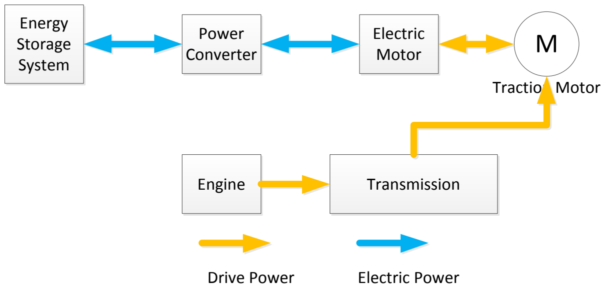

Fig.6 . Parallel hybrid system configuration

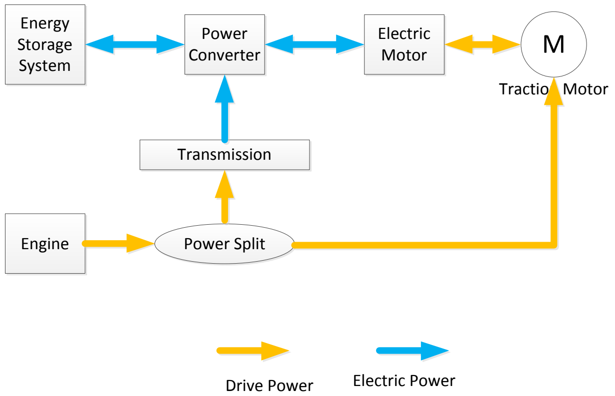

Fig.7 . Series-parallel hybrid system configuration

Series-parallel hybrid system

In Fig. 7. is shown the series-parallel hybrid system where the vehicles have characteristic of series and parallel system. This design depends on the presence of the motor / generator and the connection between them, which may be electrical and mechanical. The basic principle of this system is the separation of power from the engine to the gas / gasoline power set by the controller. The battery is charged by regenerative braking or with surplus power from the engine. The biggest advantage in this type of system is greater energy efficiency and the possibility for higher speeds.

Control of the hybrid sources based on FC, SCs and batteries

Structures of the hybrid power sources

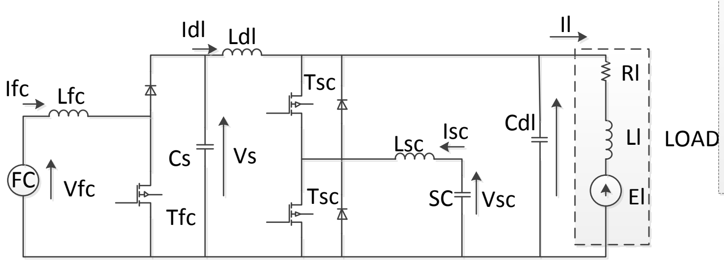

Fig.8. Structure of the first hybrid source

Fig. 8. shows the power schematic of irreversible DC converter powered by a fuel cell including storage device for energy - supercapacitor.

Fig. 9. shows the power circuit, powered by batteries, fuel cell connected to boost converter and storage device connected via reverse currents to a DC converter [7, 8].

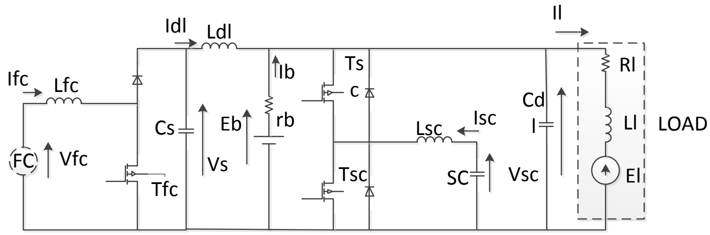

Fig.9. Structure of the second hybrid source

The role of the fuel cell and the battery is to provide power to the load while the supercapacitors are used as a source of energy. The storage system controls the power peaks in the load during acceleration and braking of the electric vehicle.

Both proposed topologies are supplied from a DC power source and connected to a DC motor. This machine is used as a load and acts as a motor or generator in braking mode. Mainly two methods are proposed for control of hybrid sources. The management is based on a sliding mode control. In the first case (Fig. 16.) is used a voltage controller and in the second case (Fig. 17.) a current controller. The second objective is to maintain a constant flow of energy from the fuel cell without significant peaks of power. Energy is supplied by supercapacitors during the transients. Another goal is energy recovery during charging of supercapacitors.

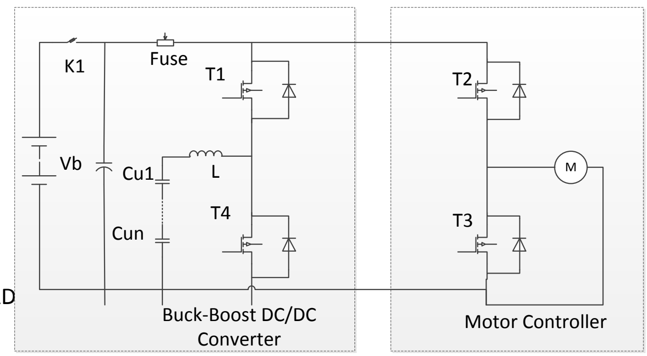

Fig.10. Hybrid power source system

The Fig. 10. shows a power schematic of hybrid system. The batteries are major source of power and the ultracapacitors are the secondary energy system. They are connected to DC bus through the load. The bidirectional buck-boost converter is composed of two power transistors (T1, T4) and inductance *L*. In the proposed schematic the supercapacitor is an additional source of energy and it is due to the ability to work with a large instantaneous power at the input and the output. It satisfies both conditions – stationary and dynamical.

Motors

Brushed DC motors

The electrical transport vehicles may use wide range of electrical motor types. The simplest form of the engine are brushed electric motors [20]. They are a good starting point because they can be easily controlled. The classical brushed DC motor with permanent magnets is shown in Fig. 11. The simplified model has a coil and currents passing through the wire close to the magnetic field. The operation of the commutator ensures that the current through the coil supports the change of direction so that the power is in the same direction. It is clear that it has many improvements compared to a real DC motor. Fig. 11. shows most important features which are:

• The rotatable wire of the coil is often called the armature, encases the circle around a piece of iron so that the magnetic field of the magnets do not cross air gap which will weaken the magnetic field.

• More than one coil is used so that the conductive wires are close to the magnets for most of the time. This means that the commutator does not consists of two halved rings, and in the two segments for each coil.

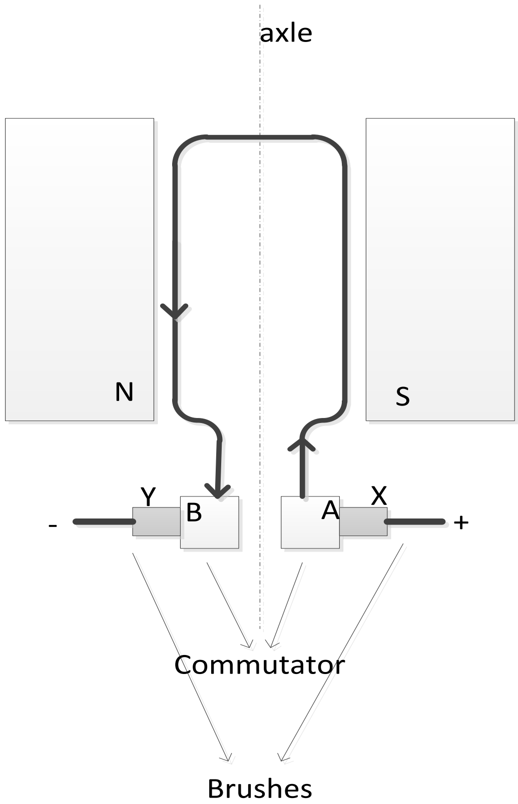

Fig. 11. Operation of the simple permanent magnet DC motor

The current I might be expressed by the following equation:

$$I = \frac{V}{R_a} = \frac{E_s - E_b}{R_a} = \frac{E_s}{R_a} - \frac{K_m \Phi}{R_a}\omega \qquad (12)$$

where E_s is supply voltage, E_b is generated voltage, K_m is a constant, ω is angular speed, Φ is magnetic flux. This equation proves that the current decreases when the angular speed increases. The following equation describes the connection between the torque and the speed of rotation:

$$T = \frac{K_m \Phi E_s}{R_a} - \frac{(K_m \Phi)^2}{R_a}\omega \qquad (13)$$

where T is the torque. This indicates that this type of engine has a maximum value at zero speed and drops continuously with the speed increase. This is shown in Fig. 12.

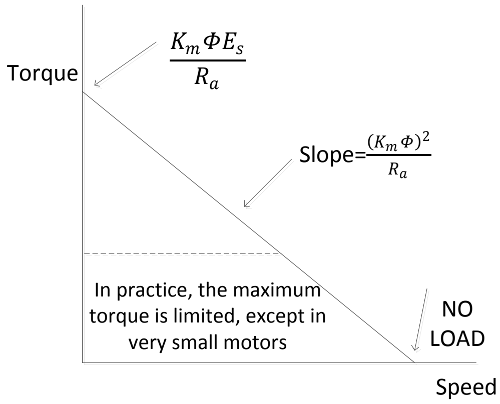

Fig. 12. Torque/speed graph for a brushed DC motor

Brushless DC motors

More frequently are used brushless DC motors (BLDC) [19]. The basic principle of the motor is shown in Fig. 13. The switches control the DC source through the coil of the stator. In the rotor is consist permanent magnet. In the course of the current in the direction of the magnetism of the stator, the rotor begins to rotate in a clockwise direction.

It is obvious that the flow of the current must be synchronized with the position of the rotor. This is accomplished with the aid of the sensors. They are often sensors of Hall, which use valve stack of the rotor to determine its position. It is possible to also use optical sensors.

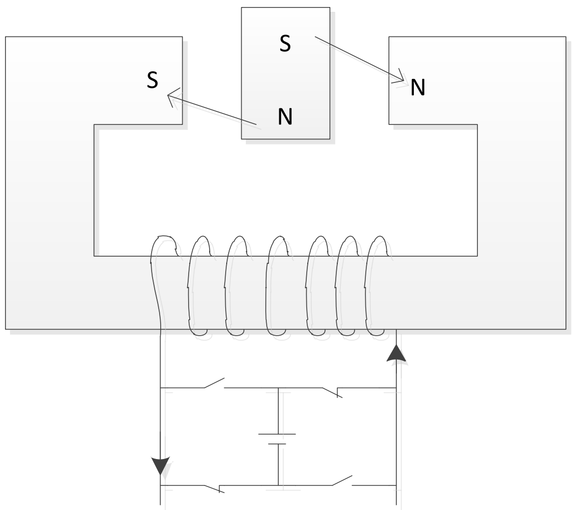

Fig. 13. The basis of operation of the brushless DC motor

Switched reluctance motors

However that has only recently entered in wide use switched reluctance motor (SRM), its principle is very simple. The main operation is shown in Fig. 14. where iron stator and rotor are magnetized by the current through the coil of the stator. Because the rotor does not rotate synchronous with the magnetic field, torque will be established to reduce the air gap and to make the magnetic field symmetrical.

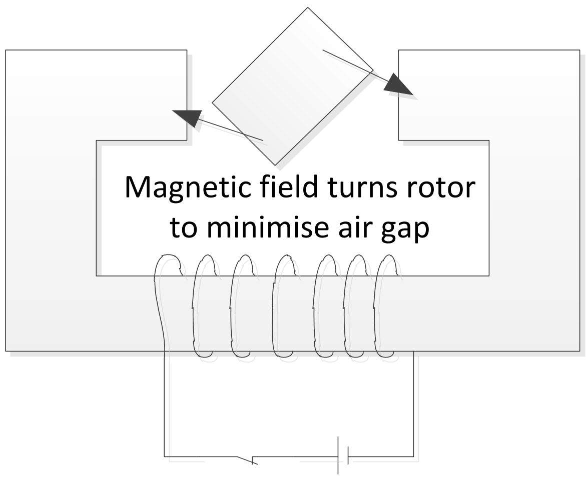

Fig. 14.The principle of operation of the switched reluctance motor

The induction motor

Induction motor is widely used in industrial machinery of all types [15]. They require a alternating voltage, which may make them unsuitable for power supply of DC sources such as batteries and fuel cells. However it is used as to the schematic shall be added the inverter. The principle of operation of the three-phase induction machine is shown in Fig. 15 . The three coils are wounded on the outer side of the motor, known as stator. The rotor usually consists of copper or aluminum wire which are electrically connected in the ends, forming the cage. Although it seems hollow inside the rotor is usually construct by sheet iron [19].

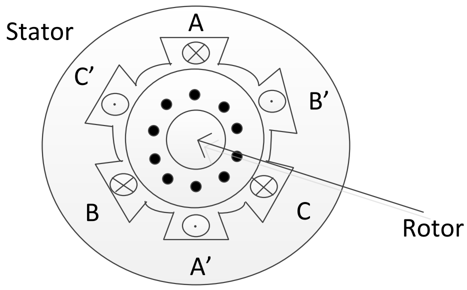

Fig. 15. The stator and rotor of an induction motor

DC-DC boost FC converter control principle

On Fig. 16. is represented graphically the control of hybrid fuel cell [16]. The reference currents are generated by the PI regulator which is controlled by voltage. Currents can be described by the following equation:

$$I_{FC}^{*} = k_{PF1}(V_{DL}^{*} - V_{DL}) + k_{IF1}\int_0^t (V_{DL}^{*} - V_{DL})\,dt, \quad (14)$$

where k_{PF1} and k_{IF1} are proportional and integral gains.

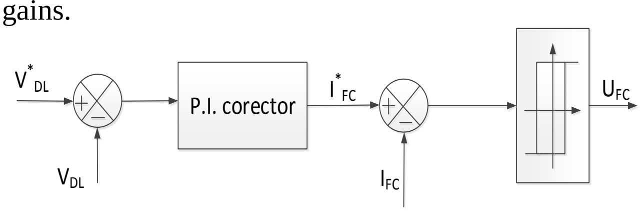

Fig. 16. Control of the FC converter

In Fig. 17. are represented the currents of the fuel cell generated by the PI regulator is controlled by current. Load current and switching device are controlled by the hysteresis comparator and they are expressed by:

$$I_{FC}^{*} = k_{PF2}(I_L - I_{DL}) + k_{IF2}\int_0^t (I_L - I_{DL})\,dt, \quad (15)$$

where k_{PF2} are k_{IF2} are proportional and integral gains.

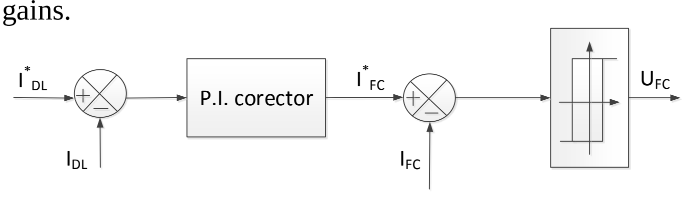

Fig. 17. Control of the FC converter

Fuzzy Logic Global Power Management Strategy

Electrical variable transmission based on the hybrid electric vehicles is very complex, particularly from the point of view of non-linearity, functionality and switching structure [25]. It is also necessary to be controlled by the intelligent controller to ensure stability and security in the dimensioning of the components. The Fig. 18. shows a proposed system with fuzzy logic for the control of energy flows.

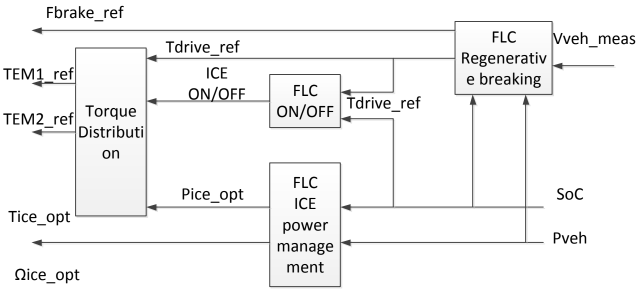

Fig. 18. Diagram for the global FLC strategy

The system with fuzzy logic is described with the following equation:

$$F_{trans\_ref} = C(t)\left(v_{veh_{ref}} - v_{veh_{mes}}\right) + F_{res\_mes} \quad (16)$$

where the total reference force F_{trans_ref} is estimated by speed reference $v_{veh_{ref}}$ and main forces F_{res_mes} with speed controller $C(t)$.

In the output of the controller can be examined with the following equation:

$$F_{mot\_ref} = K_d F_{trans\_ref} \quad (17)$$

$$F_{brake\_ref} = (1 - K_d) F_{trans\_ref} \quad (18)$$

where K_d is factor of regenerative breaking, F_{mot_ref} is force of regenerative breaking , F_{brake_ref} is brake friction force.

Through the use of fuzzy logic for the control of hybrid system is increased the generated energy. At the same time is ensured the charging of the battery with the necessary energy and the state of charge maintained.

The Artificial Neural Network

Neural networks are a computational method of biological brains. While each neuron is functionally simple, a plurality of them are interconnected and adjustable by directed links. In automation neural network consists of artificial neurons [24]. Artificial neurons are computing elements. First is performed weight sum of all inputs (Fig. 19.). This amount is responsible for the activation of neurons.

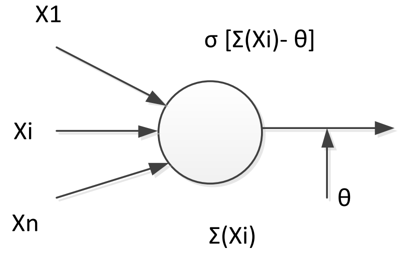

Fig. 19. The artifition neuron

The neural network consists of layers of the arrangement of neurons that are interconnected by weight connections. In Fig. 20. is shown a three-layer structure. The input layer has neurons are each input to the system and also the output layer. Among them is a hidden layer, which handles the process. These weight functions are represented by matrices [W1] and [W2] are adjustable.

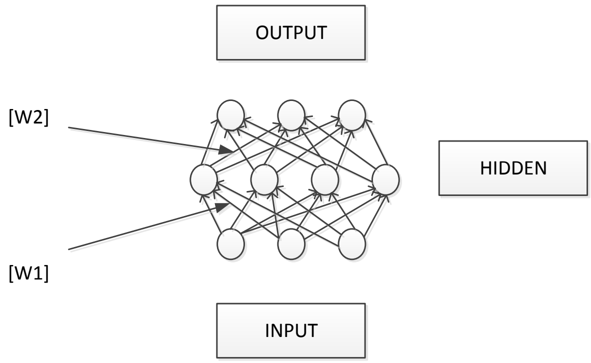

Fig. 20. An artificial neural network

This system can be described by the following mathematical function:

$$\underline{Y} = F\left(\Sigma_{hiddens}\underline{\underline{W}}^{(2)}.\left(\Sigma_{outputs}\underline{\underline{W}}^{(1)}.\underline{I}\right)\right) \quad (19)$$

where $\underline{I}$ is vector with the input data, $\underline{\underline{W}}$ is matrix of the hidden layer with weight function, $\underline{Y}$ is vector with the output data. The power of artificial neural networks lies in the theorem which says that with enough hidden neurons functions presented by artificial neural network can make an approximation of each function as nonlinear and for arbitrary precision in the final field.

Conclusion

The basic source of energy is reviewed in this paper, which is used in the electrical transport vehicles. A different structural schemes is presented, including the hybrid vehicles. Many different design solutions are examined, load characteristics and capabilities of different types of motors and methods for control of the energy flows in hybrid electric vehicles.

As a result the main tendencies and conclusions in the development of the electric vehicles are pointed out:

- The possibilities for a recuperative accumulation of energy while braking depends of the mass of the vehicle and the movement cycle. It must be taken in hand that the use of such a system augments the price of the vehicle and complicates the control, so the usage is not always reasonable;
- Because of the current market prices of the constructive elements the hybrid vehicles are widely more available compared to vehicles solely powered by electricity;
- To ensure a good dynamic of the electric vehicle the collaboration between a battery and a supercapacitor is a must;
- The contactless and accelerated battery charging including during a stay in an urban environment will be used increasingly in electrical vehicles [26, 27];
- The extended mileage with a single recharge is provided by the utilization of the hybrid technology.

The possibility for a selection of an optimal solution according to the specific applications and requirements for a vehicle are provided by the current review.

Acknowledgements

The funding's for the scientific researches and outcome data that are represented in the current work are provided by the Internal contest of Technical University of Sofia – 2016, with project No: 162ПД0006-03. The authors would like to thank all the reviewers for their advices and suggestions on improving this paper.

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Eng. Gergana I. Vacheva *is from the Department of Power Electronics at the Technical University of Sofia. Main fields of interest: Hybrid and electric vehicle, Bidirectional converters, DC-DC electronic converters of energy, industrial technologies.*

tel.: 02/9652569 e-mail:gergana_vacheva@tu-sofia.bg

Assoc. Prof. Dr. Nikolay L. Hinov *- Technical University of Sofia, Department of Power Electronics, graduated in 1995 in TUS, fields of interest: resonant converters, induction heating, soft commutation, analysis of power converters, modeling and simulation.*

tel.: 02/9652569 e-mail: hinov@tu-sofia.bg