ELECTRONIC CONVERTERS FOR THE FUEL CELL APPLICATIONS IN VEHICLE DRIVELINE

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Abstract

Technologies and possible applications of electronic power inverters for the use in electrical vehicles are presented in the paper. The presentation focuses on the activities in the area of fuel cell technologies. FP6 EU project HySYS (HySYS Fuel Cell Hybrid Vehicle System Component Development, http://www.hysys.de) is presented in brief.

Fuel cell can be applied in the vehicles as a main or auxiliary source of energy. Currently most interesting systems use hydrogen as fuel. The dynamic properties of the fuel cell system power supply can be improved, in order to enhance the dynamic response of the drivetrain. Due to this the additional components have to be applied as are batteries. The battery allows also the storage of brake energy and hence can help to extend the range of the vehicle.

Basic power supply architectures are presented, together with drivetrain control requirements. Also the limitations of applications are presented.

1 Introduction

The most of technology required for the use in electrical vehicle drivelines is already well established in the industrial practice. Most of the problems concerning control and supervision of components have been successfully solved in other applications, and can be easily transferred. Even more, efficiency is improved and cost reduced for the electric vehicles compared to the ones using inner combustion motors (ICE vehicles). The only problem, which has proven to be the key obstacle to the extensive use of electric motors in vehicle drivelines, is the problem of electrical energy storage. Batteries used for that purpose are especially problematic regarding the time of charging, which is simply too long. Additionally, battery weight is still too high for a pure battery electric vehicle. The specific energy of the batteries is small if compared to the one of the fossil fuels. The best currently available batteries (Li-ion) have a specific energy not higher than 120-150 Wh/kg, whereas gasoline is at 11.8 kWh/kg and diesel arrives to 13.3-13.7 kWh/kg. Even considering the different efficiency of electric vehicles (from battery to wheels it is around 80% on reference cycle) and of ICE vehicles (from ICE to wheels around 15-20% on reference cycle), there is no way to have electrical vehicles with same or similar weight, performance and range of conventional ICE vehicles. Furthermore, battery lifetime is still not long enough.

Therefore an alternative source of electrical energy has to be introduced. A good candidate for this is a fuel cell [1].

PEM (Proton Exchange Membrane) fuel cell is an electrochemical device that uses hydrogen and oxygen, with the aid of electro catalysts to generate electricity and thermal energy. It is one of the most innovative energy sources used for the propulsion of electric vehicles. PEM fuel cell power modules have many unique features as compared with other fuel cell types, such as relatively low operating temperature, high power density, and high modularity. They can be tailored to different applications, in particular for mobile applications and small-scale power generation [1], [2], [3], [4], [5].

One of the main obstacles hindering a widespread deployment of fuel cells is their high cost, combined with the high cost of required additional equipment, which includes subsystems to manage air, water, thermal energy, and power [1], [5]. However, currently fuel cell production costs are decreasing. To further assist the reduction of cost, the price of the inverter portion of the fuel cell system must also decrease, while at the same time increasing efficiency and reliability, and maintaining suitable power quality levels.

The mobile, portable power systems consist of two major power categories, continuous power and pulse power. Problems of a fuel cell power system without energy storage are [2]:

- fuel cells do not have electrical storage capability;
- dynamics is slower without a battery;
- output voltage fluctuates with loads.

These problems can be solved by employing energy storage equipment into the system. High power density ultra-capacitors and battery in power system to load level can significantly reduce the peak power requirement for the fuel cell. Such hybrid power system is composed of fuel cell, accumulator (battery or ultra capacitor), power converters (DC/DC, DC/AC, bidirectional and unidirectional), battery management system, load, and energy management system. Energy storage with the energy management system enables optimum energy usage control, start-up control and load transient control [2].

A high efficiency of energy consumption is assured primarily with the optimization of the electrical drive operation, but also with the effective energy flow control. Thus the energy can be saved into the batteries in braking and used later for the accelerating.

In the paper the HySYS project will be presented in brief. Afterwards power architecture will be discussed and some solutions will be presented.

2 HySYS project

In order to make a fuel cell hybrid electrical vehicle an interesting alternative, the cost of the system has to be significantly reduced. This goal can be reached by the reduction of costs and mass production of components used in the system. In order to support a car industry's development in this direction, EU commission is funding the research activities by the means of Framework Programmes' Projects. One of them, bringing together a great number of European car producers, is HySYS (coordinated by DaimlerChrysler), where also our team at the University of Maribor, Faculty of Electrical Engineering and Computer Science, is involved.

The goals of HySYS are [6]:

- improvement of fuel cell system components for market readiness;
- improvement of electric drive train components (Synergies FC and ICE-hybrids) for market readiness;
- optimization of system architecture for low energy consumption, high performance, high durability and reliability;
- optimization of energy management;
- development of low cost components for mass production;
- validation of component and system performance on FC vehicles.

The project is carried out in close cooperation of car industry with supplier industry, supported by institutes and universities. It focuses on most important FC and electric propulsion system components. Improved FC-system and e-drive components could be mass-produced and delivered by the suppliers to the automotive industry, providing competitive FC vehicles. The results of HySYS will be one step further towards the hydrogen economy and also a basis for future European research activities.

2.1 HySYS Vehicles

Two major companies involved into the HySYS project, Daimler Chrysler (DC) and PSA Peugeot Citroen (PSA) will build fuel cell vehicles, which will undergo a testing under operation conditions. Both vehicles have the same maximal velocity and range, but due to the different sizes the installed power is different. The DC vehicle has a high power fuel cell as the main energy source while the PSA vehicle has a high power battery with a low power fuel cell as a range extender.

In spite of this the fuel cell components, batteries, power electronics component (with different power electronics architectures) and motor structure are the same in order to reduce the development and manufacturing costs.

2.2 FC hybrid vehicle power architectures

Several possible architectures of power systems were described in [7]-[11]. Two of them were considered for the FC hybrid vehicles. Each of them has its advantages and disadvantages.

In the case of battery sided DC/DC converter as presented in Figure 1, the voltage of the fuel cell is not conditioned by a power converter [7], [8]. The voltage on the DC/AC inverter DC-link is changing in a relatively wide range, depending on the load, which has to be considered in the PWM algorithm of DC/AC converter. In the case when the number of cells in fuel cell system doesn't satisfy the minimum voltage requirement of the DC/AC converter and driveline, the additional voltage booster has to be applied between the FC system and DC link (Figure 2).

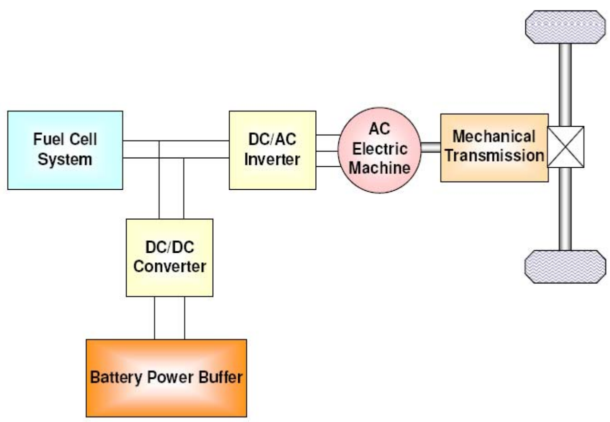

Figure 1: Architecture with Battery sided DC/DC converter

The DC/AC converter for the electric machine and DC/DC converter for the battery power buffer have to be bidirectional (Figure 1). The DC/DC converter for the fuel cell system is not required, which increases the power efficiency of the fuel cell system. At this point it is important to note that a fuel cell is a primary source of electric energy in the vehicle, whereas the battery is only a supporting power buffer, applied in the transient conditions. Therefore the power into the system is provided only by the fuel cell and the efficiency of the transfer of this power to the driveline should be maximized. Even in this case a fuel cell system can be turned off for a short time during the driving, since the fuel cell can not store the energy.

In the case of the fuel cell sided DC/DC converter [2], [9], [10], [11] as shown in Figure 2, the DC link voltage of the DC/AC inverter for the electric machine is also changing, resulting in the additional computation requirements by the PWM algorithm. The fuel cell DC/DC converter is only operating in one direction, since the fuel cell can not store the energy. In the case of low number of cells in the fuel cell stack voltage can be increased by the use of bust converter, thereby reducing the current. The battery does not require a designated power converter; since it is a completely bidirectional system and can store the energy without the conditioning. Thus this architecture is less practical for the power conditioning, since the power flow into and out of the battery can only be controlled indirectly. The architecture should have the lowest production costs, but would be more practical if a super-capacitor would be used instead of battery.

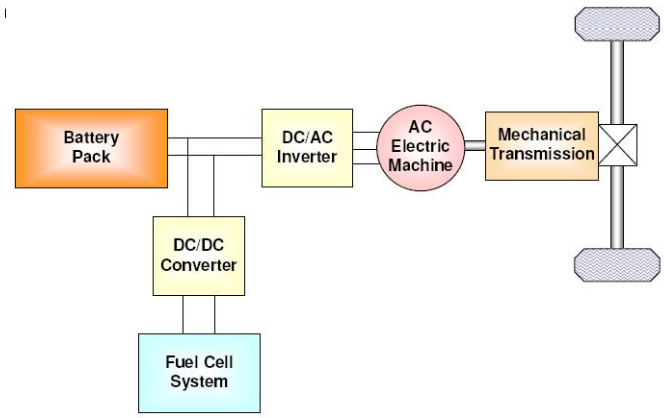

Figure 2: Architecture with FC sided DC/DC converter

The choice of the power architecture depends on many aspects. If the number of cells is relatively high (100 or more) and the efficiency is the most important issue, the power architecture with battery sided DC/DC inverter is a good solution. In case of low number of fuel cells in the stack DC/DC converter should be used in the fuel cell system.

In the case of electric vehicles architecture with battery sided DC/DC converter (Figure 1) is suitable for full power and performance vehicles. The architecture with FC sided DC/DC converter (Figure 2) is only convenient for the limited performance vehicles, where the performance is reduced in order to drastically reduce the costs of the system. Such a vehicle can be applied for the urban use, but the range at high speed (and power) depends on the battery pack energy.

Several subsystems have to be developed. First of them is a DC/DC $14V_{DC}$ converter, which has to provide electric power to the classical 14V systems in the vehicle. An important component is also the one-quadrant chopper with electric resistance, which transforms electric power in thermal power (on an external liquid cooled resistor) during the very long braking phases, when the battery is no longer able to store the energy from the electric motor operating in the regenerative phase.

2.3 Electric motor control

Interior permanent magnet synchronous motor (IPMSM) has been designed for the driveline. The permanent magnet synchronous motor model is a non-linear system even in the case when the parameters are considered constant. In order to satisfy the demands regarding the driving comfort of the vehicle, electric motor has to be controlled with high precision. From this reason it has to be controlled using non-linear approaches, if the desired dynamics should be high enough. Even more, there are several effects, which further complicate the model, like saturation, cross saturation, cogging torque, and presence of higher harmonics in the rotor flux [12], [13], [14], [15], [16], [17]. In saturation IPMSM control could become unstable. Even if this is not the case, the response dynamics are reduced [12], [13]. Next issue is the cogging torque. The ways to reduce its impact to the control quality are presented in [14], [17]. Finally, the effects of harmonics in the permanent magnet flux introduce pulsating into the produced torque [14].

A controlled electric drive developed for industrial application purposes can have a dynamic behavior faster than the one needed for an automotive application. However, the torque ripple is an important issue. In case of the fixed speed transmissions applied (without the use of conventional gearbox clutch) it is very important that it is correctly managed in order to avoid drivability problems which could occur due to the presence of low frequency harmonics at low speed.

In order to reduce the DC/AC converter losses as much as possible, maximal torque has to be obtained with the minimal stator current. This is possible by the appropriate control of IPMSM, because the reluctance torque can be used. The way of maximizing the torque with the minimal stator current is by the optimal distribution of the current among d- and q-axis [15], [16], [18].

Operating in the nonlinear modulation range, or in more common terms, the over-modulation, introduces several problems into the system, like: large amounts of subcarrier frequency harmonic currents are generated; the fundamental component voltage gain significantly decreases; and the switching device gate pulses are abruptly dropped. In PWM controlled motor drives, operation in this range results in poor performance, and frequent over-current fault conditions occur. Full inverter voltage utilization is important from cost and power density improvement perspectives. Also, a drive with high-performance over-modulation range operating capability is less sensitive to DC/AC converter dc-bus voltage sag, which often occurs in diode-rectifier front-end-type drives due to ac line voltage sag or fault conditions, hence, increased drive reliability [19].

Hill-holding operation of vehicle is an important issue in the control of driveline. However, there are some solutions presented for it in the literature. Basically, the maximal torque per ampere has to be reached. This is made possible by the algorithms calculating the minimal current producing the desired torque and the switching loss optimization algorithms [19], [20].

3 Conclusions

Basic issues regarding the power electronics system and electric motor drive are presented in the paper. Some possible power system architectures are shown and discussed.

Also the main issues of the applied electric motor drive control are presented, regarding the demands for the driving comfort, precision and reliability. In the case of more complex systems, where besides the DC/AC converter for the driveline also another loads are connected, the power architecture with battery and fuel cell sided converters should be used, since it is the only one which can satisfy the power conditioning and transfer requirements, additionally providing a relatively constant DC voltage, thus reducing the cost of additional components.

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