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Theoretical Analysis of Energy Management Strategies for Fuel Cell Electric Vehicle with respect to fuel cell and battery aging

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Abstract

As the dependency on the non-renewable energy sources is increased and the environmental concerns are illuminated, research on zero emission energy sources such as PEM fuel cell has been intensified. One of the main hurdle to commercialize PEM Fuel cell as a main energy source in automobile application is the degradation (Aging) of the fuel cell. In order to reduce fuel consumption and fuel cell degradation in Fuel Cell Electric Vehicles, effective distribution of power demand between Fuel Cell and Battery is required. The energy management strategies can improve fuel economy and or fuel cell aging by meeting power demand efficiently. Concerning development and or evaluation of energy management strategies, ultimate limits of improvement of the fuel cell stack aging for the given drive cycle needs to be known. There are several methods researched to calculate ultimate limit of fuel cell stack aging reduction for given drive cycle.[1] Here in this paper 'Dynamic Programming' approach for calculating ultimate limit for improvement of fuel cell stack aging has been applied. The influence of maximum power of the battery on fuel cell stack aging and battery aging, using dynamic programming as optimizer has been evaluated. The Economic advantage while using different size of battery and fuel cell stack has been calculated in this paper.

Keywords: Fuel cell stack aging, Li-Ion Battery aging, Dynamic Programming, Economic Analysis

1 Introduction

As the dependency on the non-renewable energy sources is increased and the environmental concerns are illuminated, research on zero emission energy sources such as PEM fuel cell has been intensified. Fuel Cell Electric Vehicles still have enormous potential in terms of costs reduction and durability improvement. Normally in Fuel Cell Electric Vehicle, battery is used in addition to the fuel cell. Battery supports start-up, cold start, sudden peak power and energy storage during electric braking. Splitting of power demand between battery and fuel cell helps significantly to improve stack durability, efficiency and transient response [1]. Energy management strategies (hybrid strategies) describe the way of splitting electric motor power between battery and fuel cell. One of the earlier works on energy management strategies is simple conditions based strategy presented by Jin-Hwan Jung and Young-Kook Lee [2] where the hybrid controller is a function of demanded power from the electric motor and state of charge (SOC) of the battery. Li and Xu [3-6] developed fuzzy control based strategy for Fuel Cell hybrid vehicle where demanded power and state of charge of battery are taken as inputs for fuzzy controller and estimated optimal load on Fuel Cell. Paganelli and Guezennec [4] developed equivalent consumption minimization strategy (ECMS) and compared results with SOC-proportional control based strategy. In order to use the different energy management strategies for the improvement of fuel cell aging and battery aging, ultimate limit calculation has been utilized in this paper. There are several methods, can be used to find the maximum limit for the drive cycle. [1].Here Dynamic Programming has been applied in order to find the ultimate limit for improvement of fuel cell stack aging for Hyway and FUDS drive cycle for different battery maximum power. Impact of battery maximum power on the fuel consumption has been described by Akula et al[1]The aging mechanism of the fuel cell stack and the battery are very complex and it is very well described along with their stress factors by Herb [7]. The electric current dynamics of fuel cell and battery is one of the stress factors that influence fuel cell and battery aging [7]. The energy management strategies have influence on the current dynamic of the fuel cell and the battery. For example, voltage cycle which is the blue print of the current dynamic, degrade the carbon particles (carbon corrosion) in the fuel cell and end in power losses [5]. Similarly, current dynamics of the battery have a strong correlation with the depth of discharge (DOD). High DOD causes faster capacity loss [6] and inner resistance growth of the battery. The stress factors current dynamics of fuel cell and current dynamics of battery are influenced by the energy management strategy. If current dynamics of the fuel cell is decreased, current dynamics of the battery is increased. This is a contradiction between fuel cell aging and battery aging (see Figure 1). The only way to solve this contradiction is to analyse and optimize strategies by using aging simulations and need to find optimised strategy which is beneficial for fuel cell aging, battery aging and fuel consumption. Therefore aging models are developed for Fuel cell Stack & Lithium ion battery by Herb [7, 8]. In order to find the optimized strategy, knowledge of the ultimate limit of improvement of the fuel cell aging, battery aging and fuel consumption for the particular drive cycle should be helpful. The Influence of battery maximum power on the fuel stack aging model has been simulated using the backward vehicle model. The Backward vehicle model doesn't require driver model to control the speed of the vehicle. It means that in the backward model required velocity and actual velocity of the vehicle are assumed to be same. The traction forces at wheel are calculated directly from the velocity and gradient profiles. The backward vehicle model is comparatively faster in simulation than Forward vehicle model (where driver model to controls speed). The detailed difference between Forward and Backward vehicle model is well described by Akula et al [1]. In this paper brief descriptions of Dynamic programming, fuel cell stack degradation model and battery degradation model have been described. Influence (ultimate limit) of battery maximum power on the fuel cell stack aging and battery aging using Dynamic Programming has been illustrated. At the end Economic advantage of different Powertrain (Fuel cell stack+battery) has been calculated.

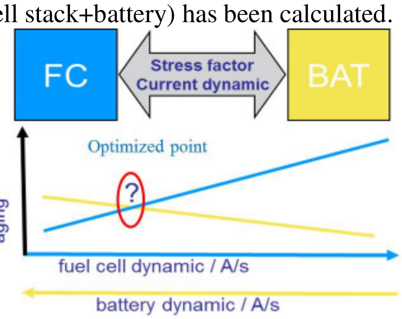

Figure 1 Aging stress factor between fuel cell and battery [7]

2 Objective

The main objective of this work is to find ultimate limit for improvement of fuel cell stack degradation for the given cycle. The knowledge of these limits can be applied as a reference to evaluate and or to develop different hybrid strategies in order to reduce fuel cell stack degradation. It can also help to calculate economic influence of different size of battery and fuel cell on the Fuel cell Electric Vehicle.

3 Dynamic Programming

The Dynamic Programming (DP) is a global optimization method can be used for solving optimal control problems. DP can be used to find optimal trajectories of state variables for minimizing objective function. These optimal trajectories of state variables can be obtained only when future disturbances and reference inputs are

known. This optimal solution can be used as benchmark studies for sizing of powertrain components particularly hybrid powertrains.
Many excellent text books are published on subject of DP theory among them [13] and [14].An overview of history and development of DP is described in [15]. Sundstrom developed generic Matlab function for DP [16]

4 Influence of battery max. Power on powertrain degradation

In favour of finding influence of battery max power on powertrain degradation, it is advisable to have knowledge about basics of fuel cell stack aging and battery aging model, how they are behaving and which optimisation parameters utilized in order to calculate the influence of battery maximum power.

4.1 PEM fuel cell stack degradation model

Fuel cell stack degradation can be determined mainly by two phenomenon: loss of performance of the fuel cell stack over operating hours and leakage of the hydrogen through membrane [7]. The approach of loss of performance over operating hours has been applied to estimate effect of different hybrid strategies on the fuel cell stack degradation. Moreover stack degrades at different rate during normal drive cycle and during start up- shutdown cycle. However stack degradation during drive cycle is analysed. As it is well known that fuel cell stack aging mechanism is very complex and not much research data available for model building of PEM fuel cell, two models are utilized to predict the fuel cell stack degradation. These models are named as ‘Model A’ and ‘Model B’. The Model A includes current dynamics, coolant temperature, relative humidity and idle current as main stress factors of the fuel cell stack aging. It has been developed from the measurement data which includes the influence of the above stated stress factors on the fuel cell stack aging. The Model A is a semi empirical model [7]. The Model B is based on the Kinetic modelling of Platinum dissolution in PEMFCs by Darling and Meyers [9]. The loss of platinum as a source of fuel cell stack performance loss during the drive cycle has been considered in the Model B. There are two ways by which platinum can be lost in the solution, one is by electrochemical dissolution and the other is by chemical dissolution [9]. The Model B is based on the loss of platinum due to chemical dissolution of platinum. The reduction in the Platinum oxide film is calibrated to the loss of performance in the fuel cell stack degradation model. The degradation rate is also dependent on the type of MEA. The detailed information about the fuel cell stack degradation modelling due to platinum dissolution is well described by Darling et al [9]. Model A is developed on the basis of measurement of stack aging while Model B is based on the stack degradation due to platinum dissolution which means that Model A includes all the stack aging mechanism while Model B includes only the stack degradation due to platinum dissolution. For analysing prediction of both models about fuel cell stack degradation, three different strategy named as ‘Reference’, ‘Strategy A’ and ‘Strategy B’ are utilized and simulated for the Real drive cycle. The results of the simulation have been shown in the Table 1. Here the negative sign means improvement in the stack degradation as compared to the Reference strategy. It has been presented in the Table 1 that Model A and Model B predicts the similar trends for Strategy B. The difference in the prediction for the Strategy A might be due to Model A has included all aging mechanisms that affects the fuel cell stack degradation and Model B has predicted only the aging due to platinum dissolution. However it can be seen that both Model A and Model B gave nearly same prediction about stack degradation. The Model B contains only one optimizing parameter while Model A contains several. In order to reduce complexity during optimization by dynamic programming Fuel cell stack aging Model B has been adopted for the further analysis.

Table 1: Prediction of the stack aging by Model A and Model B

Hybrid strategy	Model A prediction on FC stack aging	Model B prediction on FC stack aging
Reference	Reference	Reference
Strategy A	-14%	-10%
Strategy B	-13%	-13%

Here to find optimized stack degradation during the drive cycle, platinum oxide reduction has been taken as optimising parameter from the Model B. Optimisation of platinum oxide reduction can optimize fuel cell stack degradation for the drive cycle. Here dynamic programming has been utilized to find optimum path of SOC of the battery in order to find the optimum value of integrated platinum oxide reduction for the drive cycle.

4.2 Li-ion battery degradation model

The goal of the battery aging model is to find the influence of the different hybrid strategies on the battery aging. In the aging model the change in the model parameter due to aging is found by connecting it to the effect of different stress factors. The aging model contains temperature, depth of discharge (DOD), state of charge (SOC) and current dynamics as stress factors for the battery aging. The battery model consists of "Terminal voltage model" and "Thermal model". The influence of temperature on the SOC of the battery is modelled in the battery model. The aging model with the use of stress factors (inputs) SOC, DOD, Temperature and current dynamics calculates the Terminal model parameters such as Resistance and Capacitance at each time step and these values are supplied to the Terminal voltage model to find the actual Terminal voltage at each time step. The influence of stress factors on the battery parameters inner Resistance and Capacitance is gathered from the test results [7]. The detailed description of the Battery model and Battery aging mechanism is explained by Herb [7].In order to find the relationship between Battery Energy amount and Battery degradation, simulation of the Battery aging model for different energy management strategies named as 'Reference', 'Strategy A' and 'Strategy B' on Real Drive cycle has been performed and results of the same have been illustrated in the Table 2. Here the battery energy amount is calculated by adding battery discharge energy to battery charge energy. The battery aging is percentage change of the battery inner resistance up to 1000h while using Real Drive cycle.

Table 2: Relationship of Battery Energy amount with Battery Degradation

Hybrid strategy	Battery Energy amount	Battery Degradation (Model prediction)
Reference	Reference	Reference
Strategy A	24% more	20% more
Strategy B	15% more	15% more

The linear relationship has been found between battery energy amount and battery degradation in the Table 2. Higher the battery energy amount, higher battery degradation. Energy amount of battery for different battery maximum power has been calculated in order to find influence of battery size on battery degradation.

4.3 Influence of battery maximum power on Fuel cell powertrain degradation

Dynamic Programming method described in the section 3 has been applied to find the influence of battery maximum power on fuel cell stack degradation and battery degradation for FUDS and Hyway. DP is applied to find optimal trajectory of battery state of charge (SOC) to minimize platinum oxide reduction with constraints of battery SOC, battery power, fuel cell power and drivability as it has been illustrated in the following equations.

$$\min . J = \int_0^T Pt0_{reduction} \, dt \qquad (1)$$

Such that

$$SOC_l < SOC(t) < SOC_h$$

$$SOC(T) = SOC(0)$$

$$Pmaxch < Pbat(t) < Pmaxdisch$$

$$0 < Pfc(t) < Pfcmax$$

The Daimler Fuel cell Electric Vehicle with following specifications (see Table 3) utilised in the Backward Vehicle simulation model.

Table 3: Fuel cell Electric Vehicle Specifications [1][11]

Peak Power output of drive	100kW/136 hp
Continuous power output of drive	70 kW
Max. torque of drive	290 Nm
PEM Fuel cell Max Power	80 kW
Lithium –Ion Battery Max power	30kW
Battery Capacity	1.4kWh, 6.8Ah
Curb weight	1809 kg
Total weight of vehicle	2084 kg

Considering finding influence of battery maximum power on the fuel cell powertrain degradation, two scenarios of the powertrain have been considered. As it has been illustrated in the Figure 2, for scenario 1, there have three kinds of powertrains been analysed. There has 80kW of FCS power been adopted for all three powertrains during scenario 1, while battery maximum power has been varied from 30kW (powertrain A), 40kW (powertrain B) and 20kW (powertrain C).

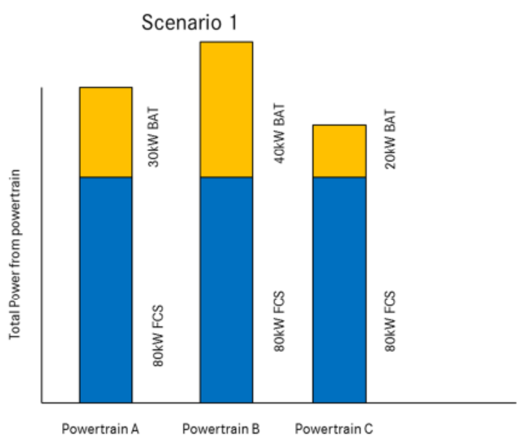

Figure 2: Powertrain comparison Scenario1

Likewise as it has been presented the scenario 2 in the Figure 3 where the total maximum power from the powertrain has been kept constant as per the Table 3and FCS maximum power and battery maximum power have been varied accordingly.

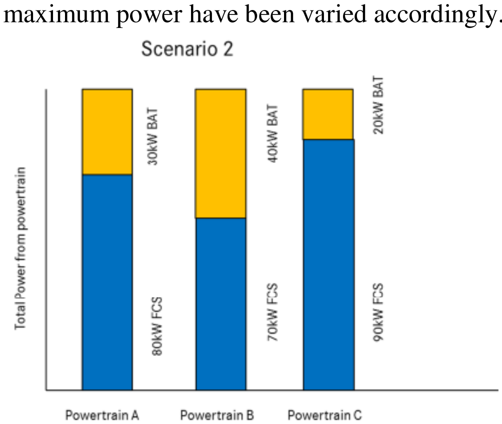

Figure 3: Powertrain comparison Scenario2

In that sense 80kw FCS and 30kW battery has been considered for powertrain A (Table 3), 70kW FCS and 40kW battery power has been adopted for powertrain B and 90kW FCS and 20kW battery power has been applied in powertrain C for the scenario 2. In the both scenarios powertrain A has been utilized as reference powertrain.

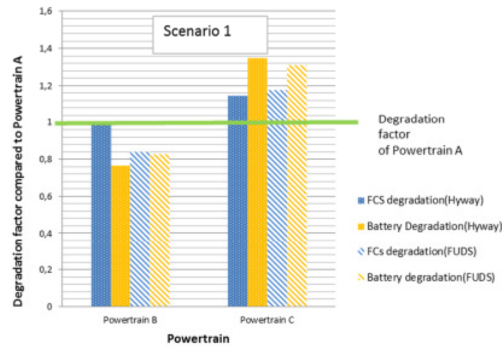

Figure 4: Influence of different powertrain on FCS and battery degradation for scenario1

Influence of different powertrain of Scenario 1 (see Figure 2) on fuel cell stack degradation and battery degradation has been illustrated in the Figure 4. The fuel cell stack degradation and battery degradation of the powertrain B and powertrain C has been compared with the powertrain A of the Figure 2. Here the FCS and Battery degradation have been calculated for two driving cycle named 'Hyway' and 'FUDS'. FUDS cycle is US –city drive cycle while US-Highway drive has been consisted in Hyway cycle. It can be seen from the Figure 4 that FCS and Battery of powertrain B have been degraded 0.99 times and 0.77 times respectively during Hyway cycle and 0.84 times and 0.83 times respectively during FUDS cycle compared to the FCS and Battery of powertrain A. However FCS and Battery of powertrain C has been degraded more than FCS and Battery of powertrain A for the Hyway cycle as well as for the FUDS cycle. In this case it can be concluded that 40kW Battery variant has lowest powertrain degradation (FCS deg and Battery deg) as compared to the 30kW Battery variant of powertrain A for the scenario 1.

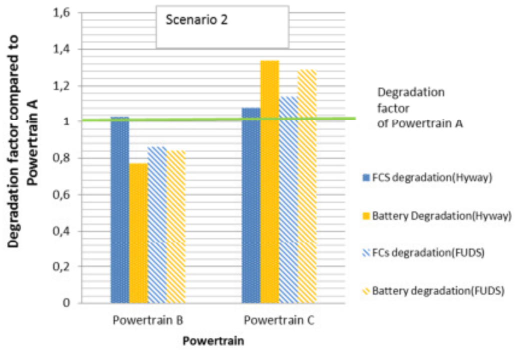

Figure 5: Influence of different powertrain on FCS and battery degradation for Scenario2

Influence of different powertrain of scenario 2 (see Figure 3) on FCS and battery degradation has been presented in Figure 5. It can be analysed from the Figure 5 that FCS and Battery of powertrain C have been degraded around 1.08 and 1.34 times respectively for Hyway cycle and 1.18 and 1.31times respectively for FUDS cycle as compared to the FCS and Battery included in powertrain A. However FCS and Battery of powertrain B has been degraded 20 to 30% less for Hyway and FUDS cycle as compared to the powertrain A of the Scenario 2 of the Figure 3. That means for the degradation perspective 70 kW FCS and 40kW Battery variant (powertrain B) has lowest FCS and battery degradation as compared to the powertrain A and powertrain C of Scenario 2.

The comparison of powertrain of Scenario 1 and Scenario 2 on the impact of FCS and battery degradation concluded that going from 30kW battery variant to 40kW battery variant lowers the battery degradation up to 20 to 30% and FCS degradation up to 5to 15% depending on the drive cycle. However decreasing battery maximum power from 30kW to 20kW boosts the battery degradation 35-40% and FCs degradation up to 15% depending on drive cycle. Depending on the results shown in the Figure 4 and Figure 5, Economic advantage of the different powertrain has been calculated in the section 5.

5 Economic advantage of Fuel cell powertrain

In the section 4.3 influence of battery power on the fuel cell stack degradation and battery degradation has been compared with 30kW battery and 80kW FCS powertrain (powertrain A). However what it means in terms of cost has been presented in this section.

Here in order to calculate the cost benefits, the cost prediction included by Thomas Mayer et al [10] is taken as reference costs for PEM fuel cell and Lithium -Ion battery. The Economic advantage has been calculated for Hyway and FUDS cycle of Scenario 1(see Figure 2) and has been shown in the Figure 6

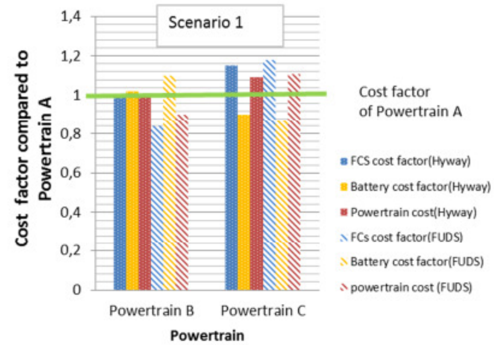

Figure 6: Cost calculation for different powertrain for Scenario 1

Basic idea behind the economic calculation is that end of life performance for all the powertrain has to be equal powertrain A. The cost calculation has been illustrated in the Figure 6 and Figure 7 has been calculated in following manner. For example if the results presented in the Figure 4 are taking in to account than, while using 40kW battery in powertrain B, FCS will degrades 0.99 times for Hyway cycle as compared to the degradation of FCS included in powertrain A, which means if end of life performance has to be matched with powertrain A, the FCS of powertrain B needs to be sized as 0.99 times the FCS of powertrain A for the Hyway cycle, In this way it will costs 0.99 times the FCS used in powertrain A. Similarly for battery will have 10kW more power however if Battery goes from 30kW to 40kW it will degrades 0.77 time the Battery degraded in powertrain A, that means in order to match the end of life criteria with battery used in powertrain A, Instead of 40kW battery, 30.8 kW(40x0.77) battery is needed .That means that 30.8 kW battery will costs 1.08 times of battery used in the powertrain A. In this way total costs of the powertrain will be 0.99((0.99xFCS cost of powertrain A+1.08xbattery cost of powertrain A=0.99xPowertrain A cost) times the cost of powertrain A.

The cost for different powertrain of scenario 1 has been illustrated in the Figure 6. It can be seen from Figure 6 that the powertrain B costs nearly the same as powertrain A for the Hyway cycle , however estimated costs for the powertrain B for FUDS cycle is 10% lower than powertrain A of scenario 1. However powertrain C has been cost 9 to 10% more as compared to the powertrain A of scenario 1depending on the drive cycle.

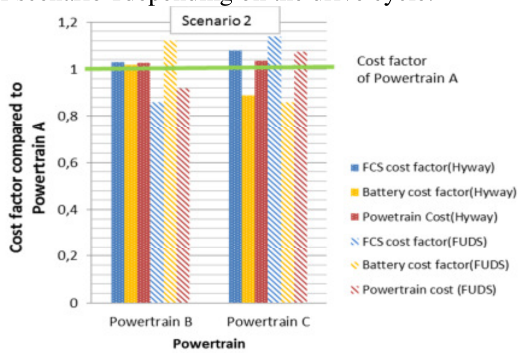

Figure 7: Cost calculation of different powertrain for Scenario 2

Likewise in the Figure 7 cost calculation of different powertrain for Scenario 2 (see Figure 3) has been presented. It can be analysed that for the Hyway cycle powertrain B costs around 2% more than powertrain A, however it costs 8% lower for FUDS cycle as compared to the powertrain A. Similarly powertrain C costs around 3 to 7% more as compared to powertrain C depending on drive cycle.
By analysing Figure 6 and Figure 7, It can be seen that for the Hyway cycle cost of the powertrain b is nearly same as of powertrain A for the both Scenarios However for the FUDS cycle cost of total powertrain has been reduced to 8 to 10% with the use of powertrain B as compared to powertrain A for the both Scenarios. From this result, it can be concluded during Highway drive condition going Battery maximum power from 30kW to 40Kw (powertrain A to powertrain B) doesn't have much cost impact however can save up to 10% during the city drive conditions. In this way 40kW battery maximum power, is the best solution found in the both Scenario 1 and 2.

6 Conclusion and Recommendation

In this paper brief description of dynamic programming is given. The influence of different powertrain on the fuel cell stack aging and battery aging are described for the two scenarios. The FCS maximum power has been fixed for the all three powertrain and only Battery Maximum power has been varied while for the Scenario 2 maximum output power of the whole powertrain (FCS +Battery) has been fixed . However not a significant difference between scenarios in terms of degradation and cost have been found. Cost analysis for the different powertrain concluded that for the Highway driving conditions 30kw battery maximum power and 40kW battery maximum power have the same costs however battery with 40kW maximum power can save up to 10% of the powertrain costs during city driving condition.
The following works should improve the quality of the analyses.
The knowledge of maximum limit of improvement of fuel cell stack aging should be utilized to develop and or evaluate Energy management strategies. The developed strategies should be tested on short fuel cell stacks to validate the stack aging prediction from the model. The same approach should also be done with the battery. Finally after component aging validation on powertrain level and vehicle level further optimization of the strategy can be done.

Nomenclatures

BAT	Battery	
DOD	Depth of Discharge	
DP	Dynamic Programming	
FC	Fuel Cell	
FCS	Fuel Cell Stack	
FUDS	Federal Urban Driving Cycle (City Drive)	
PEM	Proton Electrolyte Membrane	
Pbat	Battery Power	[kW]
Pmaxch	Maximum charge power	[kW]
Pmaxdisch	Maximum discharge power	[kW]
Pfc	Fuel cell power	[kW]
PtO	Platinum oxide	
SOC	State Of Charge	

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Kavin Trivedi , currently working as a System developer with ISS Innovative Software Services GmbH. His current project is to develop and validate the fuel cell stack aging model for the Fuel cell powered Electric Vehicle with Daimler AG fuel cell department. He is also working as Project controller/ coordinator for different projects within Daimler AG. He received Master of Science in Mechatronics from FH-Aachen in 2008 and Master of Business Administration from Steinbeis Hochschule Berlin in 2012. He has worked during his previous jobs on modelling and simulation of hybrid vehicle and internal combustion engine vehicle. He plays Cricket as professional cricket player for Baden Wurttemberg and NRW cricket clubs.

Prasada Rao Akula works in fuel cell power train simulation and optimization of hybrid strategies at Mercedes-Benz R&D India in Electrical and Electronics department. He received his Masters of Technology degree in Electronics and communication engineering with specialization of control and guidance in 2006 from Indian Institute of Technology (IIT), Roorkee, India. During his academics, he involved in projects related to industrial automation and control for chemical production plants. These projects helped him to learn about operation of various controllers, actuators and sensors related to process industries. With his classmates, he developed and implemented controller for effective load distribution (load shedding) among electric generators for a captive power plant of a chemical industry. He started his career in Patni computers systems (Now it is IGate) as software engineer, involved in software development and testing of driver assistance systems like forward collision alert (FCA), collision preparation system (CPS) and Electronic stability controller (ESC).Later he joined in Mercedes-Benz R&D India, involved in various research projects related to vehicle dynamics and controls. Presently he is working on powertrain optimization of fuel cell vehicles for Daimler AG, Germany.