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A HIL Comparison of Energy Management Strategies for Low Cost Supercapacitor Hybrid Vehicles

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Abstract

Four energy management controllers for use in a fuel cell, supercapacitor hybrid vehicle and are compared in a Matlab Simulink simulation. The controllers are tested on a light delivery vehicle with a maximum laden weight of 1800kg. The benefit of over sizing the energy buffer is examined for each controller. The controllers with various supercapacitor buffer sizes are compared with respect to the peak fuel cell power demand, the rate of change of power demand and the operating time of the fuel cell in the inefficient region. The NYCC and LA4 driving cycles are used to test the robustness of the controllers, which are designed using the ECE15 driving cycle. A laboratory electrical vehicle emulation is constructed to allow practical testing of the energy management controllers and validation of the Simulink simulation. The emulation has an FPGA controlled DC motor to simulate the vehicle load, this is coupled to the electric vehicle traction drive. The fuel cell is interfaced via a dual interleaved boost converter and the supercapacitors are connected directly across the DC-link of the traction drive. The emulation is used to validate the Matlab model, testing the controllers on the LA4 and ECE15 driving cycles.

Keywords: Energy Management, Supercapacitor, PEM, Fuel Cell

1 Introduction

The energy management strategy of a hybrid electric vehicle determines the power sharing between the multiple energy sources in the system. Careful consideration is required during vehicle design as the sizing of the buffer and the choice of energy management controller impact the efficiency of the vehicle and lifespan of the powertrain components. Minimising the transient loading on the fuel cell is an important objective for the power train controller in order to prolong the life of the fuel cell system [1]. The application under consideration is a small delivery vehicle designed for locations sensitive to emissions such as factories, inner city pedestrianised zones and city parks. The vehicle has a basic mass of 800kg and is capable of carrying a maximum payload of 1000kg at a top speed of 50km/h. The powertrain has the supercapacitor power buffer connected directly across the DC-link of the traction drive and the DC-link voltage is allowed to vary within predefined limits whilst a PEM fuel cell is connected via a DC-DC converter. This powertrain architecture, shown in Figure 1, is considered low cost due to the removal of the high power bidirectional DC-DC converter that is usually used to interface supercapacitors in electric vehicles [2].

2 System Model

The simulation was designed using Mathworks Simulink, allowing each component of the power train to be modelled individually and combined to form a full system. This allows individual elements to be copied into the vehicle emulation for laboratory validation, described in Section 7.

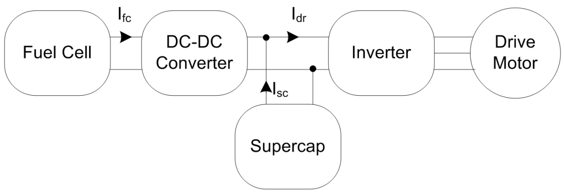

Figure 1: Vehicle powertrain

2.1 Vehicle traction drive and driver

The driver is represented by a PI controller which generates a traction drive torque reference based on the vehicle speed and a predefined driving cycle. The result is a forward facing model [3] that attempts to meet a the driving cycle, this allows testing on a variety of challenging driving cycles without exceeding the traction drive operating limits. The traction drive translates the driver torque demand into a motor torque imposing power and torque limits and applying a fixed electrical to mechanical conversion efficiency of 70%. Equation 1 and the parameters shown in Table 1 are used to determine the vehicle's velocity at the next simulation, v_{n+1} time step using current velocity, v_n and the motor torque, T_n.

Table 1: Vehicle parameters

Variable	Description	Value	Units
g	Acceleration due to gravity	9.807	m/s^2
n_t	Gear ratio	5.900	pu
η	Mechanical drive train efficiency	1.000	pu
J_w	Inertia of vehicle wheel	0.164	kgm^2
J_m	Inertia of motor	0.037	kgm^2
r_w	Wheel radius	0.274	m
d_f	Distribution factor	1.000	factor
k_r	Coefficient of rolling resistance	0.027	
ρ	Air density	1.230	kg/m^3
C_d	Drag coefficient	0.310	
A_f	Frontal area of vehicle	1.750	m^2
m	Base vehicle mass Fully laden vehicle mass	800 1800	kg
θ	Gradient of road surface	0.000	radians

$$v_{n+1} = \frac{T_n - \left(\frac{d_f r_w}{n_t \eta_t}\right)\left[\left(k_r \cos\theta + \sin\theta\right)mg + \frac{1}{2}\rho C_d A_f v_n^2\right]_n}{\left[\left(\frac{\left(n_t J_m\right)}{r_w}\right) + \left(\frac{J_w}{n_t \eta_t r_w}\right) + \left(\frac{d_f r_w m}{n_t \eta_t}\right)\right]} dt + v_n \qquad (1)$$

2.2 DC-DC converter

The unidirectional DC-DC converter interfaces the fuel cell with the supercapacitor buffer which is connected directly across the DC link of the traction drive. A fixed efficiency of 95% is used to represent the losses in the converter.

2.3 Supercapacitor power buffer

The supercapacitor power buffer is modelled by an ideal capacitor with a fixed resistance to represent internal losses. The model is based on Maxwell 2.7V 3000F cells which are connected in series to provide the energy buffer for the simulation.

2.4 System controller

The system controller implements the control methods described in Section 4. The controller has measured voltage and velocity inputs, and generates the DC-DC converter current reference. This allows the controller to be implemented directly in the hardware emulation, without any modifications, for validation and further testing.

2.5 Source

The source component in the simulation is a PEM fuel cell. A typical PEM fuel cell efficiency curve, gained from experimental results [4], is shown in Figure 2. To achieve maximum efficiency the system should be operated at as low a power as possible above the high polarization loss region, above 1.5kW in this study.

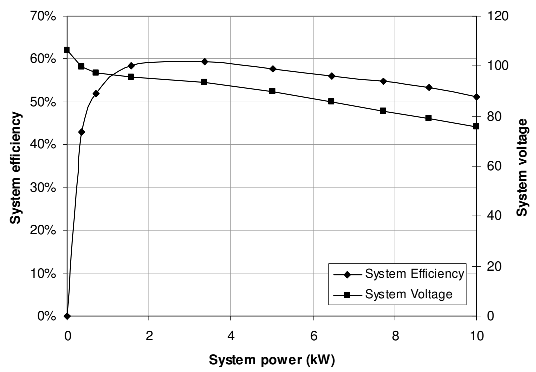

Figure 2: Typical PEM characteristics

2.6 Test cycles

To analyse the controller performance under realistic conditions the simulations are run over three different driving cycles. The controllers were initially designed using four repetitions of the ECE15 driving cycle shown in Figure 3. The New York City Cycle (NYCC) and the Urban Dynamometer Driving Schedule for light duty vehicles (UDDS), also known as the LA4 and FTP72 [5], were then chosen as alternative test cycles. The UDDS driving cycle has been modified to limit its maximum velocity to 13m/s, which is the maximum velocity of the test vehicle. The UDDS cycle, shown in Figure 4, is a more challenging cycle than the ECE15 design cycle to test the controller's limits, whilst the NYCC, shown in Figure 5, is a low speed cycle to simulate light use of the vehicle.

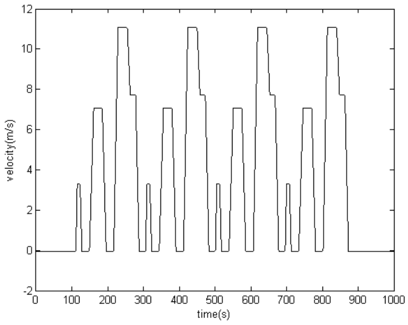

Figure 3: 4x ECE 15 driving cycle

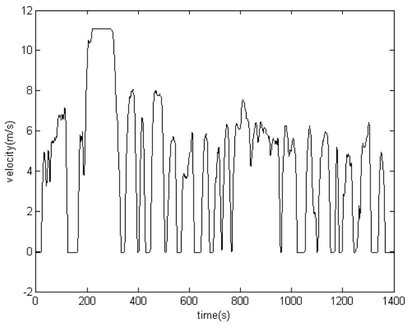

Figure 4: UDDS driving cycle

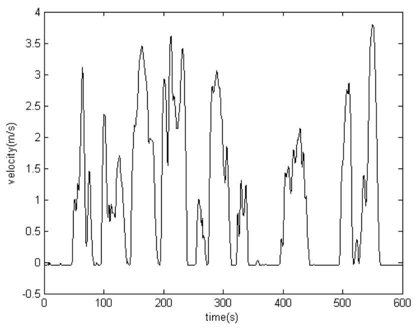

Figure 5: Low velocity test (NYCC driving cycle)

3 Supercapacitor Buffer Sizing

The ideal operation of an electric hybrid vehicle power train with an energy buffer allows the power rating of the source to be reduced to supply only the constant velocity demands of the system. The source power rating therefore corresponds either to maximum cruising velocity or maximum hill climbing. The buffer is utilised only during periods of acceleration and regenerative braking to smooth the source power demand.

Separating the vehicle drive power equation, Equation 2, into a constant velocity and acceleration term produces Equations 3 and 4. The velocity dependent power, $P_{vel,}$ is then supplied by the fuel cell and the supercapacitor energy buffer supplies P_{accel}. The resulting component specifications for the unladen (800kg) and fully laden (1800kg) vehicles are shown in Table 2.

$$P_{dr} = v\left[\left(\frac{(n_t J_m)}{r_w}\right) + \left(\frac{J_w}{n_t \eta_t r_w}\right) + \left(\frac{d_f r_w m}{n_t \eta_t}\right)\right]\frac{dv}{dt} + \left(\frac{d_f r_w}{n_t \eta_t}\right)\left[(k_r \cos\vartheta + \sin\vartheta)mg + \tfrac{1}{2}\rho C_d A_f v^3\right] \quad (2)$$

$$P_{vel} = \left(\frac{d_f r_w}{n_t \eta_t}\right)\left[(k_r \cos\vartheta + \sin\vartheta)mg + \tfrac{1}{2}\rho C_d A_f v^2\right]v \quad (3)$$

$$P_{accel} = \left(\left[\left(\frac{(n_t J_m)}{r_w}\right) + \left(\frac{J_w}{n_t \eta_t r_w}\right) + \left(\frac{d_f r_w m}{n_t \eta_t}\right)\right]\frac{dv}{dt}\right)v \quad (4)$$

Table 2: Minimum supercapacitor buffer size data

Weight (kg)	800	1800
Peak drive power (kW)	21.4	30.0
Mean drive power (kW)	1.3	2.7
Cruise Power (kW)	3.9	8.1
Energy Used (MJ)	1.3	2.7
Buffer Energy (kJ)	75.4	164.0
Buffer Power (kW)	17.5	23

To ensure that a vehicle has sufficient energy storage capacity for all operating duties that may arise over its lifetime the energy buffer storage needs to be greater than 164kJ. Buffer sizes of 164kJ, 328kJ, 492kJ and 656kJ have been simulated to assess the impact on controller effectiveness.

4 Controller Description

This section describes the objectives and the design of the four energy management controllers.

4.1 Control objectives

The key objectives of the energy management strategy are to improve efficiency and extend vehicle life whilst keeping within the operating constraints of individual components. This requires:

- Maintaining the supercapacitor energy levels within maximum and minimum SOC
- Maximising recovered energy through regenerative braking
- Maximising fuel cell efficiency
- Minimising energy source transients to extend operating life

In order to maximise the efficiency and operating life of the fuel cell, the objective is to achieve a smooth and constant power demand whilst avoiding the low efficiency region below 1.5kW.

4.2 Fixed reference

The fixed reference controller loosely controls the voltage level of the supercapacitor buffer. The target voltage level is set at the buffer's maximum voltage and a simple proportional gain is used. The minimum gain is chosen through trials to give the widest allowable variation in supercapacitor energy level (SOC) resulting in the smoothest possible source demand.

4.3 Velocity varying

The velocity varying controller loosely controls the voltage level of the supercapacitor buffer using a reference that decreases with increasing vehicle velocity. This ensures all regenerative braking energy can be absorbed by the power buffer. The reference is tracked by a proportional controller that is chosen by trial to give the maximum allowable SOC variation. This should result in the lowest rate of change of fuel cell power and the smoothest fuel cell power demand.

4.4 Average

Using the fuel cell to supply the average drive power cannot be implemented in a practical system without a priori knowledge of the driving cycle and an accurate vehicle model. In real time a controller based on measured previous drive power demands can be implemented. Drive power values for the previous 60 seconds are averaged to provide the source power demand reference.

4.5 Fuzzy logic

The fuzzy logic controller determines the output power drawn by the DC-DC converter from the fuel cell based on a set of fuzzy rules which operate on the vehicle velocity and supercapacitor state of charge (SOC). The fuzzy rules were designed with the aim of varying the SOC with velocity whilst avoiding rapid changes in fuel cell power and avoiding the low efficiency operating region. Figure 6 and Figure 7 show the surface plots of the controller output against inputs, which were obtained from a simulation of the controller.

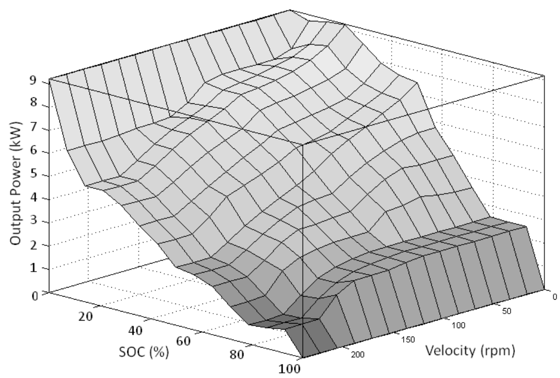

Figure 6: Fuzzy logic output: SOC vs. velocity

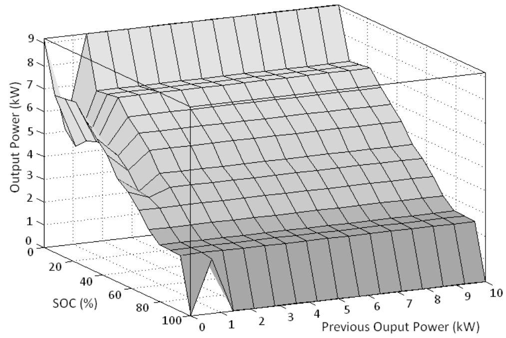

Figure 7: Fuzzy logic output: SOC vs. previous source power

5 Varying Buffer Size

Figures 8-12 show the initial testing of the controllers over the calibration driving cycle, 4xECE15. Figure 3 shows the drive cycle velocity whilst Figure 8 shows the drive power demand. Table 3 compares the controller's performance on the 4xECE15 driving cycle for each supercapacitor buffer size. The average and fuzzy logic controllers both failed to operate within 100% and 0% SOC with the 164kJ buffer and the remaining controllers produced peak source demands in excess of 21kW. Section 9 discusses the test results along with alternative driving cycle and vehicle emulation results.

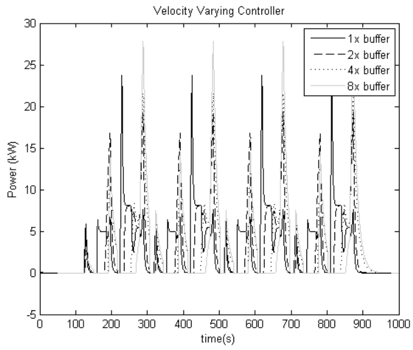

Figure 10: Source powers for velocity varying controller

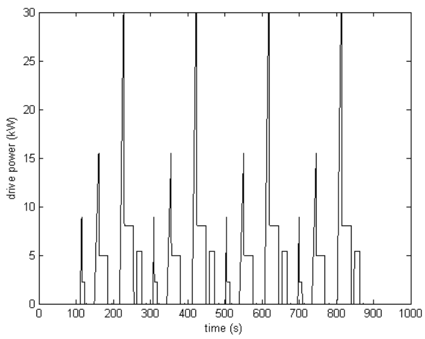

Figure 8: 4xECE15 drive power demand

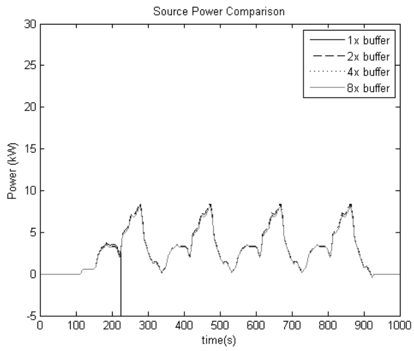

Figure 11: Source powers for average power controller

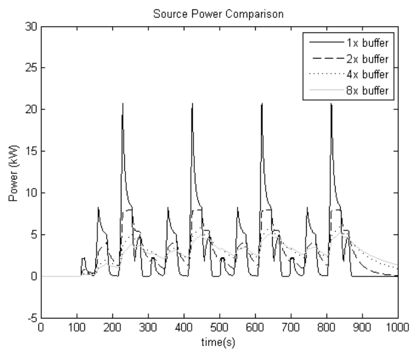

Figure 9: Source powers for fixed reference controller

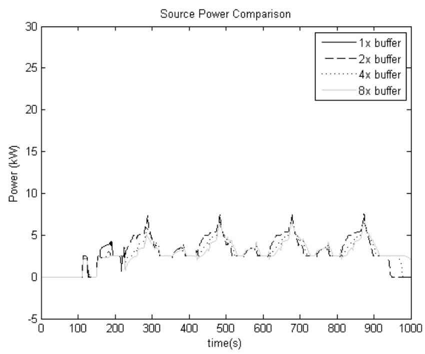

Figure 12: Source powers for fuzzy logic controller

Table 3: Controller performance with varying buffer size

Buffer Size:	164kJ		328kJ				492kJ				659kJ			
	Fixed Ref	Velocity Varying	Fixed Ref	Velocity Varying	Average	Fuzzy Logic	Fixed Ref	Velocity Varying	Average	Fuzzy Logic	Fixed Ref	Velocity Varying	Average	Fuzzy Logic
Peak Source Power (kW)	21	22	7.9	20	8.5	7.5	5.1	24	8.2	6.5	3.8	28	8.1	6.1
Minimum SOC (%)	38	27	46	31	36	18	29	32	58	34	32	43	69	42
Maximum dP/dt (kW/s)	3	5	1	4	0.5	1.5	0.5	3	0.5	1	0.3	3.5	0.5	0.5
p<1.5kW (s)	12	7.9	25	11	18	1.1	16	8.2	19	1.7	12	6.7	19	2.9

6 Varying Driving Cycle

To accurately test the energy management strategy multiple drive cycles should be used to describe the vehicles operating profile. The UDDS driving cycle, shown in Figure 5, and NYCC, shown in Figure 4, have been selected as alternative stop start cycles suitable for small delivery vehicles.

The 1800kg vehicle was tested using the 328kJ buffer on the UDDS and NYCC driving cycles. The results are shown in Figures 13–18 and a comparison with the ECE15, calibration driving cycle, is shown in Table 4.

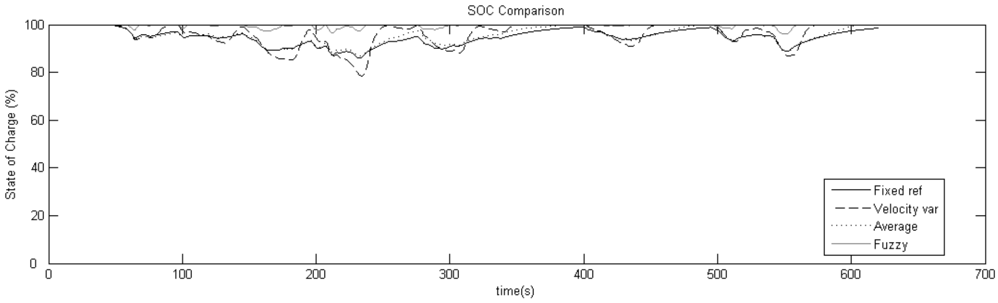

Figure 13: NYCC supercapacitor buffer SOC

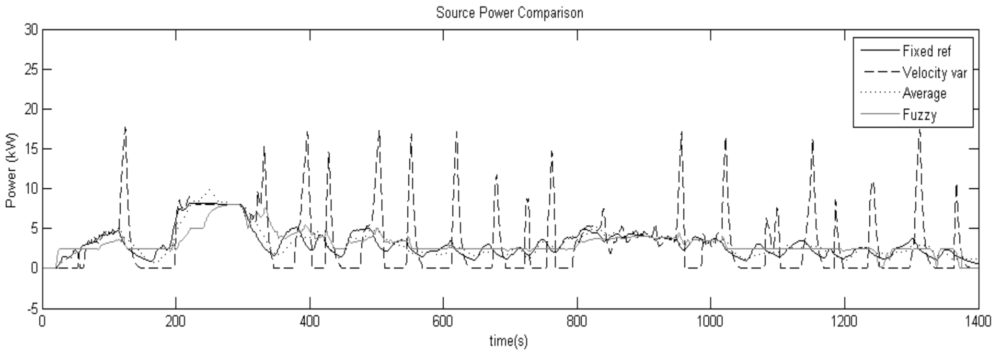

Figure 14: NYCC source power demand

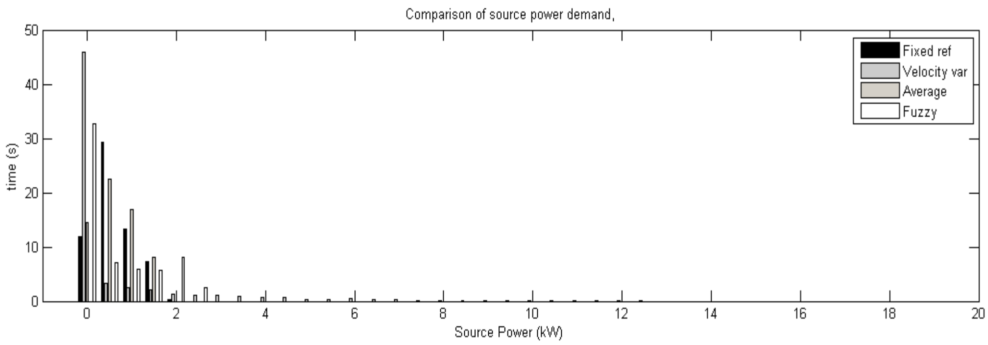

Figure 15: NYCC source power distribution

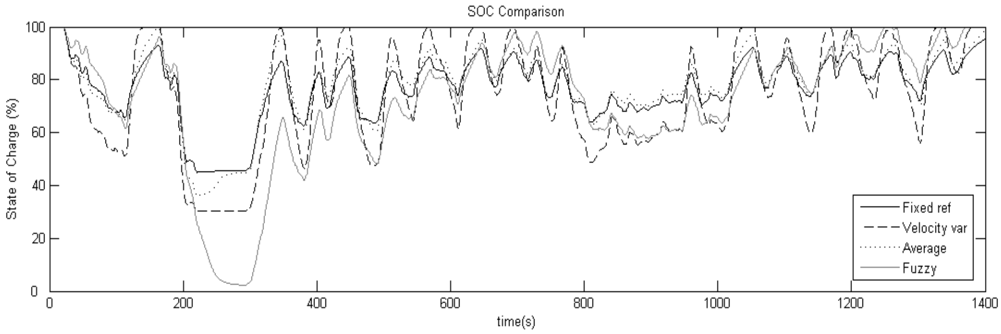

Figure 16: UDDS supercapacitor buffer SOC

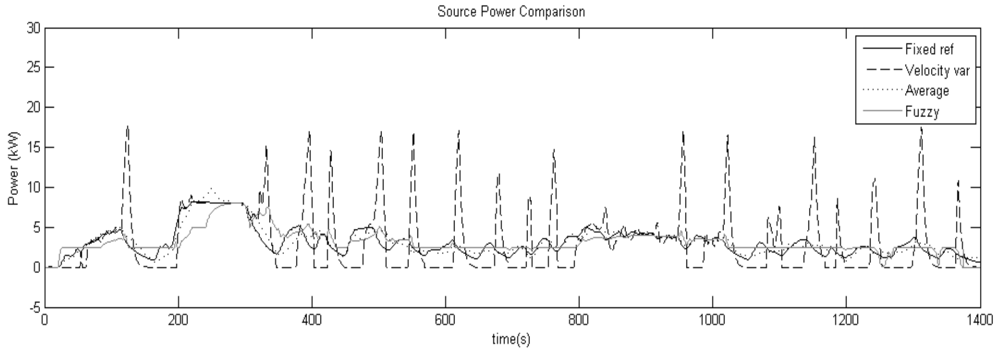

Figure 17: UDDS source power demand

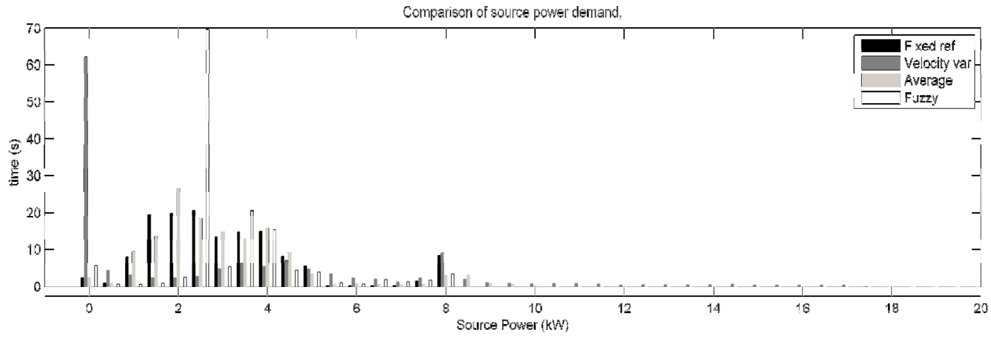

Figure 18: UDDS source power distribution

Table 4: Controller performance over different driving cycles

Driving Cycle:	ECE15				UDDS (LA4)				NYCC			
	Fixed Ref	Velocity Varying	Average	Fuzzy Logic	Fixed Ref	Velocity Varying	Average	Fuzzy Logic	Fixed Ref	Velocity Varying	Average	Fuzzy Logic
Peak Source Power (kW)	7.9	20	8.5	7.5	8.0	17.8	9.4	8.0	1.8	12.4	1.7	2.4
Minimum SOC (%)	46	31	36	18	0.45	0.3	0.36	0.1	86	78	87	96
Maximum dP/dt (kW/s)	1	4	0.5	1.5	0.5	4.5	0.5	1	0.5	3.2	0.5	1
p<1.5kW (s)	25	11	18	1.1	28.5	9.8	24.2	2.6	49.7	7.9	47.5	18.9

7 System Emulation

To validate the simulation a laboratory based electric vehicle emulation was used. The system consists of a 20kW Ansaldo electric vehicle traction drive mechanically coupled with a DC load motor. The torque of the load motor is controlled by an FPGA system to simulate the dynamic response of a pre-programmed vehicle characteristic. A Labview interface is used to allow user friendly reconfiguration of the vehicle parameters in the FPGA. The regenerative capability of the motor inverter set is limited by the manufacturer and does not allow a high regenerative capture ratio but is suitable for a comparison of the controllers.

A dual interleaved boost converter with an inter-phase transformer is utilised in the system due to its simple robust topology, small-size and the inherent cancellation of ripple currents at input and output [6]. The resultant input current ripple is reduced in amplitude compared with the ripple current in the individual inductors and is at twice the switching frequency. A similar effect is seen in the output capacitor current waveform. Current mode control is used for the cycle-by-cycle control of the converter, ensuring current sharing between the two interleaved stages, and providing a straightforward mechanism for programming the fuel cell power demand.

A dsp-based μProteus [7] development system is used for overall supervisory control of the power train. This unit is specifically intended for vehicle applications, providing 20 input / output channels and is programmed in Simulink using the Real Time Workshop and State Flow tool boxes. In addition to performing condition monitoring and sequencing the simulated energy management controllers can be implemented directly.

A PI controller is used to simulate the action of a human driver, providing a torque ref based on the error between the measured velocity and the predefined driving cycle. The velocity reference is provided from file via a National Instruments Labview system and the torque reference is generated and applied to the control input of the Ansaldo traction drive. This allows consistent repetitions of a driving cycle for controller comparison.

The supercapacitor storage buffer for the system is connected directly across the traction drive terminals. The buffer is a series connection of four 144F Maxwell supercapacitor modules, each containing eighteen 2600F 2.5V Ultracapacitors. The voltage variation of the buffer is limited by the traction drive lower operating limit, 150V, and the upper voltage limit of the capacitor modules, 180V. The available storage capacity of the system is therefore 245kJ.

The source is a DC power supply which implements the polarisation curve shown in Figure 2. This allows thorough testing of the DC-DC converter over a range of input voltages.

The emulator's transient response is limited so the unladen (800kg) vehicle parameters are used to compare the energy management controllers.

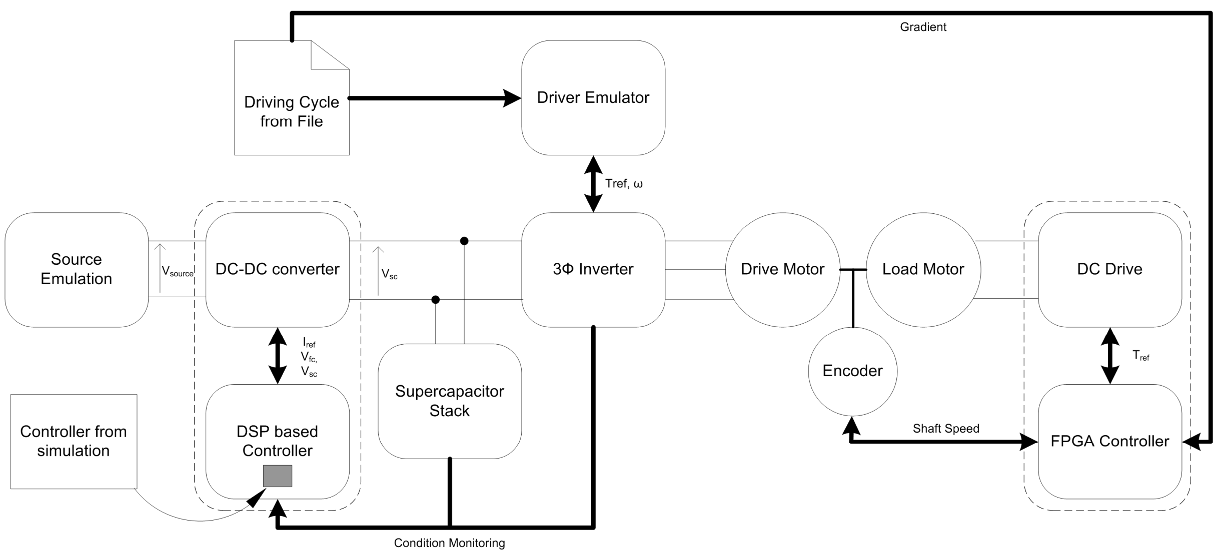

Figure 19: Vehicle emulator diagram

8 Validation Results

The controllers implemented in the Matlab simulation, described in Section 4, were implemented on the vehicle emulation described in Section 7. Figure 20 shows the emulation operation on the ECE15 driving cycle and Figure 21 shows operation on the UDDS, LA4 driving cycle. The fixed reference and velocity varying controllers both required redesign for use in the emulation to ensure that the supercapacitor voltage remained within the 150-180V limits, again the control parameters were chosen by trials. The average controller could not be implemented due to memory limitations in the emulation system.

The number of successive ECE15 cycles has been reduced, compared to the simulation, from four to two to reduce simulation time.

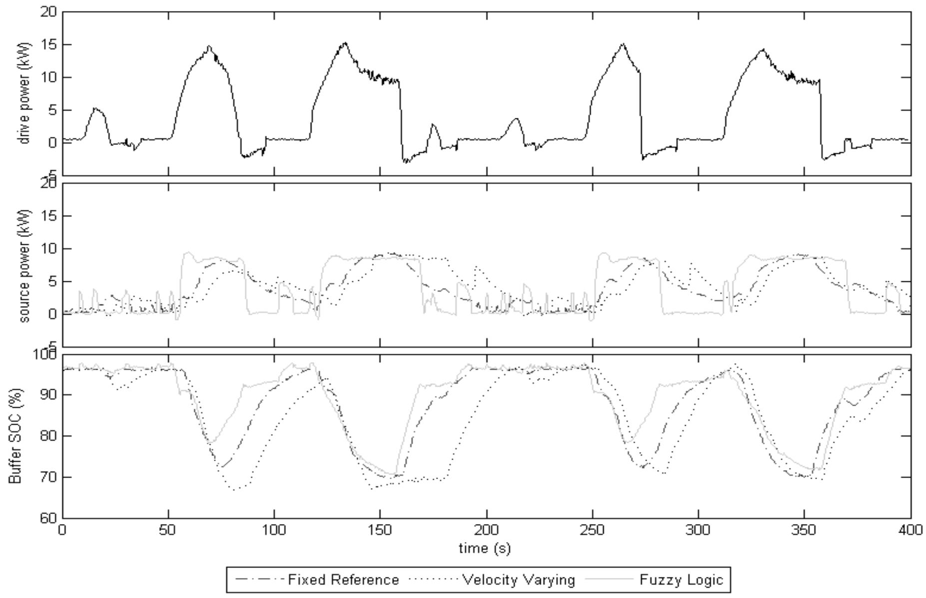

Figure 20: 2xECE15 driving cycle

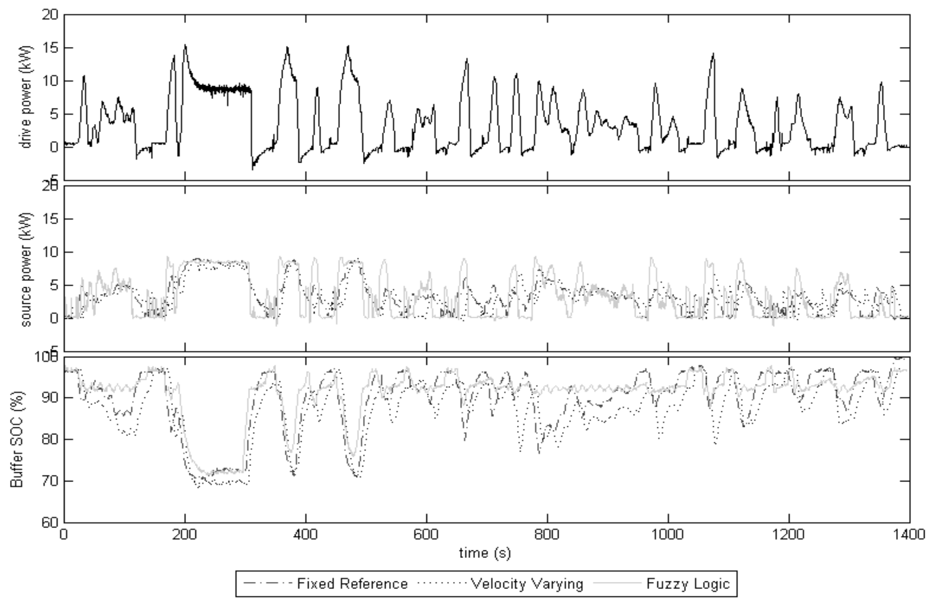

Figure 21: UDDS(LA4) driving cycle

9 Discussion of Results

The results from simulating the vehicle and varying buffer size show that it is unrealistic to implement the minimum energy buffer size and expect a smooth fuel cell power demand. Only the iteratively tuned controllers functioned on the 164kJ buffer and both only reduced the peak fuel cell power from 30kW to 21kW and 22kW respectively. Table 3 shows a comparison of the controllers with increasing buffer sizes. By increasing the buffer size the other controllers could be implemented and a further improvement in fuel cell power demand can be achieved. Restricting the peak fuel cell demand to the maximum cruising power of 8.1kW can be viewed as a successful control algorithm.

The velocity varying controller produced a poor response with all buffer sizes in comparison to the other controllers. The varying target voltage with speed meant that tighter control of the supercapacitor buffer voltage was required. This resulted in higher peak demands throughout the vehicle's operation, the fuel cell peak power demand is therefore not reduced below 20kW for any buffer size.

The fixed reference controller produced the best results over every buffer size as it was iteratively tuned to give the maximum possible voltage variation. This resulted in the lowest peak fuel cell power demands and the shallowest dP/dt rates of all the controllers. The results from the alternative driving cycles, shown in Table 4, were also favourable in respect to peak power and dP/dt. Iteratively redesigning the controller for operation in the vehicle emulation is a non trivial task and takes considerably longer than in a simulation environment. This reduces the practical applications for the controller despite its low peak power demand of 8kW and its low dP/dt rate.

From the varying buffer size simulation it is apparent that there is no benefit of increasing the buffer size for the average controller beyond that of its minimum operating level. Any extra capacity is not used as there is no SOC parameter in the controller. This is highlighted by the similar performances of source power demand in Figure 11. When operating on the alternative driving cycles the controller did not require retuning, unlike the fixed and velocity varying controllers, and produced results comparable to that of the iteratively tuned fixed reference controller. In real time applications the controller could be memory intensive and thus expensive to implement as highlighted by the emulator.

The fuzzy logic controller proved to be the best overall controller as it could manage multiple control objectives. The controller achieved a significant reduction in peak fuel cell power demand on the ECE15 and UDDS driving cycles, 7.5kW in simulation and 8kW in emulation. A low dP/dt rate was also achieved on every test whilst minimising the operating time in the low efficiency region of the fuel cell. The fuzzy logic controller also performed well in the vehicle emulation, requiring no redesign and limiting the peak demand to 8kW which is directly comparable with the specifically designed fixed reference controller.

Detailed comparison of the simulation and experimental results is not possible since the controllers implemented on the test rig required re-designing to work within the limited voltage range of the available supercapacitor bank, however the energy storage capacity of the supercapacitor bank over the working voltage range was 245kJ, comparable with those used in the simulation. Nevertheless the experimental results show similar patterns and trends to those seen in the simulations and therefore serve to validate the conclusions from the simulations.

10 Conclusion

Increasing the size of the energy buffer beyond that required for regenerative energy capture can dramatically reduce the demand requirements on the fuel cell. The larger the increase the smoother and more efficiently the source can operate. The choice of energy management strategy is critical to ensure the maximum benefit is gained from the system.

For battery systems simple controllers such as the average drive power controller produce suitable results. However for a fuel cell based system where low power operation should be avoided more advanced control is required. Fuzzy logic control allows a combination of control objectives to be achieved and reduces the need for iterative controller design. This increases the flexibility of the system allowing efficient operation in multiple vehicles and on multiple driving cycles.

Energy management strategies need to be tested over a range of challenging driving cycles to assess their performance. The simple fixed reference controller in this study outperforms other controllers on the driving cycle and vehicle it has been optimised for but needs redesigning for each application.

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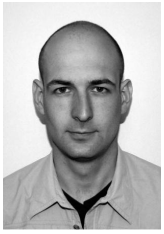

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