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Development and Evaluation of a Degree of Hybridisation Identification Strategy for a Fuel Cell Supercapacitor Hybrid Bus

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Abstract: Fuel cells (FC) are a clean energy source that are capable of powering a vehicle's electrical energy requirements whilst providing zero operating emissions. In this study, a full-scaled computer model FC/supercapacitor (SC) hybrid has been developed to investigate the performance of the hybrid propulsion system under real-world performance conditions. A control strategy focused on maintaining a constant FC output at a user-defined value has been developed and applied to the FC/SC hybrid model. Driving cycles collected from a practical double-decker bus have been utilised to evaluate the developed model. It has been demonstrated that the proposed control strategy is capable of maintaining a constant and stable FC output while meeting a real world dynamic load. Based on the obtained results, a general strategy to identify the degree of hybridisation between the FC and the SC in a FC hybrid system has been developed and demonstrated.

Keywords: proton exchange membrane fuel cell; super capacitor; hybrid propulsion; energy management; Simulink

1. Introduction

Proton exchange membrane fuel cells (PEMFC) are a clean energy source that are capable of generating electricity with zero harmful emission at the point of use. The fuel cells (FC) generate electrical power based on an electrochemical reaction, which is different from the combustion process of conventional internal combustion engines (ICE) [1,2]. The only waste product of the PEMFC reaction is pure water, which is usually emitted as vapour [3]. From here on the term fuel cell (FC) is to be considered to denote PEMFC. Compared with ICEs, the FC offers benefits of high efficiency and zero operating greenhouse gas emissions. The FC also offers additional benefits such as simplicity, flexible modular construction, low noise, small size and small weight as a consequence of the simple electrochemical process. On the other hand, the FC has drawbacks such as low power density, is still a developing technology, slow reaction rate, short lifetimes and expensive purchase cost [4]. Important advances for the PEMFC have been achieved such as reducing the platinum catalyst loading from 25 mg/cm^2 to 0.05 mg/cm^2 [5]. The cost of the PEMFC has dropped significantly since 2000, which makes the PEMFC a viable solution for applications such as for city bus transportation [6].

Due to the inability to cover transient power demands and the current high capital cost of FCs, it is not an effective solution to use the FC as the sole power source [7–9]. Hybridising with an energy storage system, such as batteries or supercapacitors (SC), with FCs can potentially mitigate the transient power demand and cost issues. To investigate the performance of an FC hybrid propulsion system for city bus applications, a 10% scaled FC/SC hybrid propulsion system was developed to represent a scaled power system of an FC hybrid bus on paper and used to validate the Simulink computational model [10]. A control strategy focused on keeping the FC output stabilised and user-controlled has been developed and proven to work as expected under both static and dynamic conditions. A set of basic dynamic load tests have been used to demonstrate that the controller is capable of managing the power between the FC, the SC and the load while keeping the FC output controlled and stable. The developed computer model has also been scaled to the power level of a practical bus to enable practical driving cycle evaluations. Details of the scaled system and controller development can be found in References [10,11].

The degree of hybridisation between the FC and energy storage system has an important role in component sizing and system optimisation in terms of the configuration and performance of a hybrid system [12]. Previous studies suggested there is a minimum FC and battery size in the hybrid configuration to be determined by the maximum vehicle speed and acceleration requirements [13,14]. It has been concluded that an optimum degree of hybridisation range can be found for an FC hybrid vehicle depending on the application requirements and the size of the FC stack plays a vital role in cost optimisation [14]. Whilst an SC energy storage system will operate differently to a battery system, the principle of minimum energy storage size is equally applicable to all energy storage technologies in a hybrid system. Similar work has also been carried out in Reference [15] where the authors demonstrated two prototype buses with different FC/energy storage power source size combinations using both theoretical calculation and on-road experiments. It has been found that the bus with a smaller FC and larger energy storage actually surpassed the other bus for most of the degree of hybridisation optimising factors. It has been shown in References [16–19] that the degree of hybridisation is heavily dependent on the expected duty cycle. In References [8,20,21], it has been found that when selecting the energy storage for the FC hybrid system, SCs are much more effective in shielding batteries from high current loads and can respond quicker to dynamic load when compared with batteries. In order to minimise hydrogen consumption, the FC can be turned off during bus operation and use the energy storage to meet the load demand [22]. However, it has been reported that repeatedly turning the FC on and off or demanding fast transient response could potentially degrade the FC and reduce the FC life [23]. In References [8,21], a direct parallel structure of FC/battery/SC has been constructed with the results indicating that the FC needs to have a narrow power distribution during a dynamic cycle to satisfy the slow dynamic power variations. The battery pack power output is also relatively slow when responding to dynamic loads. The SC bank met the fast-dynamic load requirements well. Owing to the high energy density of the FCs, the determining factor to select the energy storage option to be hybridised with the FC is the power density, which makes SCs more suitable in this case [24,25]. In this research, the fast transient response capabilities of SCs are combined with the good energy storage densities of a PEMFC to assess the degree of hybridisation required for a full-scale bus under a real-dynamic load profile.

The literature presented has considered, to an extent, the sizing and operation of FC hybrid systems; however, such systems and their design are highly susceptible to the technologies used and the operating environment. The approach taken in References [13,14] considers the sizing of the FC and battery based on the maximum speed and acceleration requirements is a logical approach; however, it places a conservative restriction on the component sizing. In a transient system, the need for the FC to provide all of the power requirements at full speed is very conservative and limits the potential for downsizing of the FC. Furthermore, it should be noted that for an SC energy storage system, the power requirements are less of a concern owing to the high power densities of SCs. As such, the sizing of a SC based on the acceleration power requirements is not an appropriate method when considering SCs; instead, sizing for the energy storage capacity to meet the energy requirements required to level the load demands is of greater importance. The work presented in References [16–19] also considers batteries as the energy storage system, although there are similarities between the role of SCs and batteries in a hybrid system the considerations necessary for sizing these components substantially different. In References [8,20,21], FC/SC/battery hybrid systems are proposed, where the implementation of three different systems changes the dynamics of the control strategy and will impact upon the system design and control strategy. An FC/SC hybrid system is proposed in Reference [22], in the proposed control strategy the FC is turned on and off during operation and impacts the potential for the downsizing of the FC. In this research, the fast transient response capabilities of SCs are combined with the good energy storage densities of a PEM FC to assess the degree of hybridisation required for a full-scale bus under a real-dynamic load profile. The strategy implemented for this assessment focusses on maintaining a stable FC output during operation and using the SC to meet the transient power requirements.

This paper follows on from the work presented in References [10,11] and is part of a series of work carried out at University College London (UCL). The work in Reference [10] presents the development of a laboratory test rig and the control strategy implemented to provide balance of power in the system. The work in Reference [11] presents the development of computational models that were validated against the laboratory test rig. The process of scaling the system to voltage and power levels expected in a real bus was also detailed. The present paper reports on the developed control strategy and system configuration that has actually been assessed against real-world load profiles. This has allowed for the development of the methodology used to identify the degree of hybridisation between the fuel cell and supercapacitor in the system. Furthermore, the limitations of the control strategy are highlighted with potential improvements suggested. This research aims to further evaluate the developed stabilised FC output control strategy against significantly more dynamic loads, such as frequent acceleration and deceleration, that are expected to occur for a city driving bus. The purpose of this is to reduce the degradation of the fuel cell that results from transient operation. Driving cycles have been collected from a diesel electric hybrid bus operating in central London. These profiles are used to evaluate the FC/SC hybrid model developed and validated in Reference [11]. This model can be tested with real world collected bus data, which effectively offers a solution for the FC/SC hybrid bus from a power system engineering point of view. This research will evaluate the performance of the FC/SC hybrid system under dynamic conditions. The novel contribution of this work is to demonstrate the stabilised FC control strategy against a real-world double-decker bus profile and develop a general strategy to identify the degree of hybridisation between constituent power sources in the hybrid propulsion system.

2. FC/SC Hybrid Model Configuration

The system configuration of the FC/SC hybrid model consists of three parts: the FC and boost converter as the primary power source, the SC and buck/boost converter as the energy storage system, and the variable resistor and controlled source as the load simulation system, as seen in Figure 1. The system can be operated in three modes. First, the SC discharges to supplement the FC to meet high load demands. This occurs when the bus is accelerating or climbing a gradient. Second, the FC powers the load whilst using the excess power to charge the SC. This occurs when the FC is providing more power than the load demands, i.e., low speed operation or when the bus is at rest. Third, the FC output power and energy from regenerative braking are both used to charge the SC, which only occurs during regenerative braking.

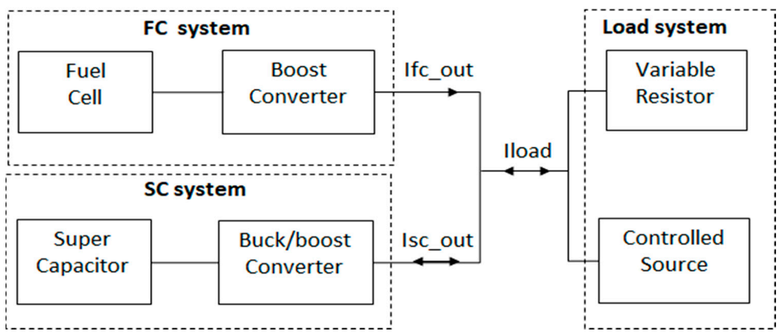

Figure 1. System configuration of the computational model.

3. Practical Bus Profile Simulation

3.1. Driving Cycle Collection

A bus, shown in Figure 2, operating on route 388 in Central London was used to collect the driving cycles for this research. The use of driving cycle data from a typical London double-decker bus can be used to further assess the performance of the FC/SC hybrid system and explore the practicality of a diesel hybrid bus replacement.

Figure 2. UCL diesel electric hybrid bus for data collection.

The bus is an Enviro 400H double decker diesel engine/lithium battery series hybrid bus that is part of the London hybrid bus fleet. Although the diesel/battery hybrid configuration is different from that of the FC/SC model proposed in this research, the purpose of the driving cycle evaluation is to use the Mathworks Matlab Simulink 2014a model to assess the performance of the FC/SC hybrid propulsion system against actual driving cycles. As a result, the most important parameter for this research is the traction motor power. The traction motor power parameter provides detailed information on all of the motoring power requirements of the vehicle and the recovered power available through regenerative braking. The power losses associated with the mechanical braking are not included in this research because the bus braking characteristics were not available.

3.2. Driving Cycle Simulation

A load simulation system was used to simulate the traction motor power profile for the FC/SC hybrid model. The load simulation system consists of a controlled variable resistor and a current source. Since the DC voltage in the hybrid system (after converters) is 630 V, the power profile can be simulated by matching the current to and from the load. When the power is positive (propelling the bus), the variable resistor will be used to dissipate the required amount of power calculated using:

$$R_{variable} = \frac{630^2}{P_{positive}}. \quad (1)$$

When the power is negative (slowing the bus), the current source will be used to provide a controlled current, which is calculated using:

$$I_{source} = \frac{P_{negative}}{630}. \quad (2)$$

The system can determine the required resistance and current depending on the power requirement and thus provides a representative simulation of the buses power profile in the FC/SC hybrid model. The load simulation system has been tested and shown to provide a nearly identical power profile to the actual bus profile.

4. FC/SC Hybrid Model Performance

4.1. Complete FC/SC Hybrid Model

With the integration of a load simulation system, the FC/SC hybrid model could be tested with the recorded power profiles. The control system had previously been tested in References [10,11] and shown to be capable of operating with a stable and controlled FC output under static and dynamic load conditions. However, to understand the implications to the sizing of system components in real-world operation, long runs of a full scale representation were required, which were more achievable with the computer model. The complete computer model is shown in Figure 3.

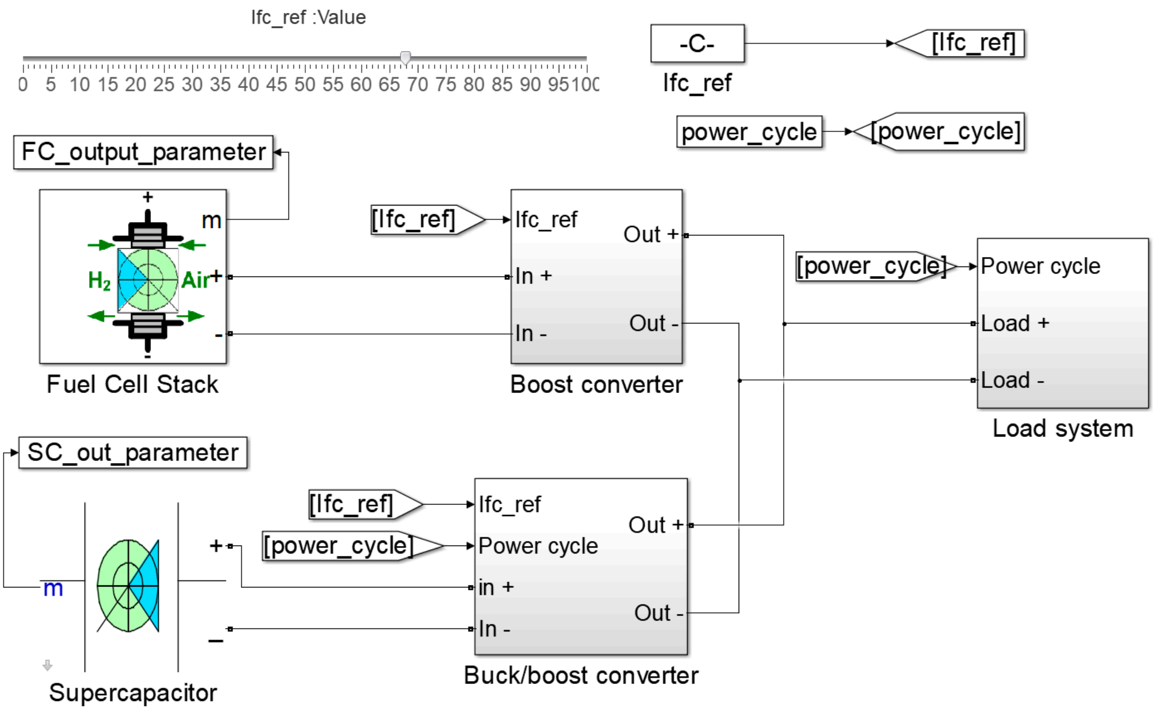

Figure 3. Simulink complete FC hybrid model for driving cycle test.

The model consisted of an FC, boost converter, SC, buck/boost converter, and load simulation system. The three parameters that the user is required to define are as follows:

1. FC and boost converter current output reference (Ifc_ref workspace).
2. Driving cycle power profile (power_cycle workspace).
3. SC initial state-of-charge (SoC) (defined within the supercapacitor block).

4.2. Driving Cycle Selection

Bus driving cycle data was collected over a 24-h operating period at 2 s intervals (approximately 19 h of bus operation and 5 h of bus powered down), and is summarised in Table 1.

Table 1. Route 388 bus data logging information.

Route Statistics		
Bus route	388	
Length	12.83 km	
Stops	37	
First stop	Elephant & Castle	
Last stop	Stratford City Bus Station	
Bus Data Logging		
Date	04/08/2014 (Monday)	
Time of first bus	05:40:00	
Time of last bus	23:50:00	
Completed journey (inbound and outbound)	20	
Speed Profile Information		
Highest speed of the day	35.7 miles/h (57.5 km/h)	
Average speed of entire day	7.68 miles/h (12.4 km/h)	
Average speed of entire day(exclusive of bus long stops due to driver break)	8.57 miles/h (13.8 km/h)	
Power Profile Information		
Peak power (positive)	202 kW	
Peak regenerative power (negative)	−169 kW	
Average power of entire day	8.31 kW	
Average power of entire day (exclusive of bus long stops due to driver break)	9.45 kW	
Outbound Journey		
Time	Duration (min)	Average power (kW)
05:40–06:20	40	9.18
07:13–07:50	37	8.31
08:45–09:17	32	9.49
10:12–10:49	37	9.45
12:49–13:37	48	5.49
14:49–15:40	51	5.67
16:54–17:40	46	6.27
19:00–19:50	50	5.65
21:12–22:02	50	6.08
23:25–00:14	49	5.97
Inbound Journey		
06:38–07:10	32	16.03
07:56–08:30	34	11.12
09:26–10:01	25	11.01
10:55–11:36	41	12.27
13:47–14:35	48	10.57
15:47–16:34	47	9.41
17:54–18:44	50	10.19
19:57–20:49	52	9.40
22:13–23:09	56	10.38
00:23–01:13	50	9.64

As Table 1 shows, the power demand varied significantly during each journey and also varied depending upon the time of operation. Due to the length of the profile and limitations of the computer processing power, the performance of the FC/SC hybrid model were investigated using segments of the power profile selected from the 24-h data set to get an initial understanding. The chosen duty cycles were selected with consideration of the power level, vehicle speed and traffic conditions as some of the more representative power cycles. The first profile selected for this research was a 360 s segment covering the period 06:55 to 07:01 when the highest peak power occurred. This included both the highest peak power (202 kW) and highest average power (26.1 kW) requirements and is denoted as the peak power profile. The traction motor power requirement and speed of the bus during the peak power profile are shown in Figure 4.

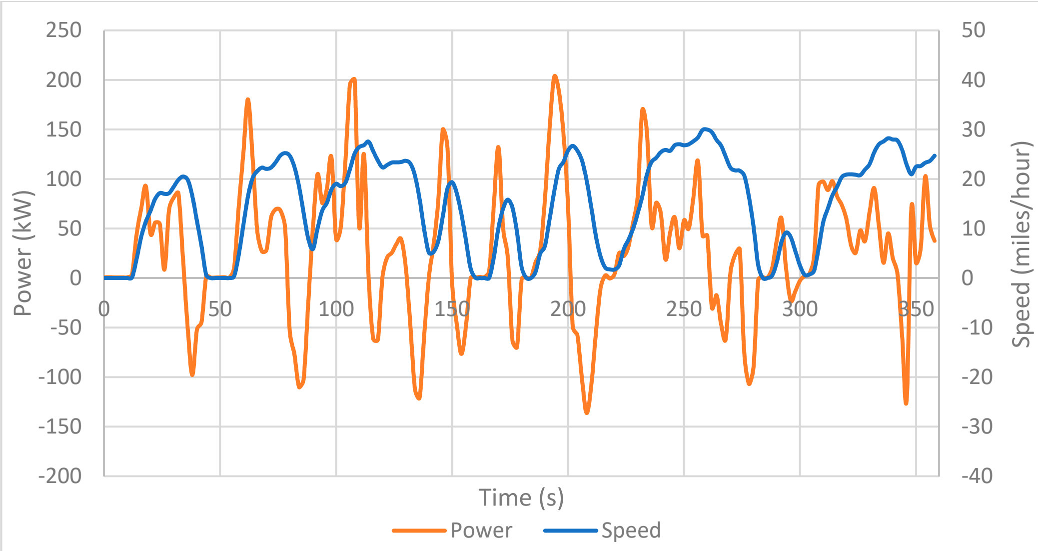

Figure 4. Power and speed traces of the peak power profile.

4.3. FC/SC Hybrid Model Operation

Analysis of the performance of the FC/SC hybrid model was carried out using the power profile from Figure 4. The results from an initial test where, Ifc_ref = 40 A and SC SoC = 80%, in terms of the power balancing and SoC change are plotted in Figure 5.

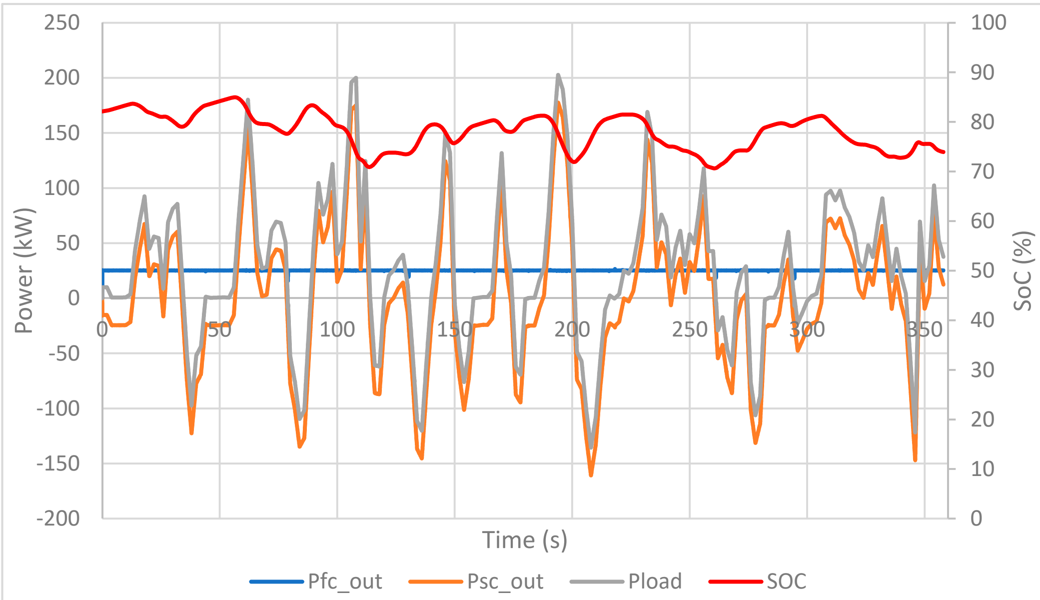

Figure 5. Power balancing and SoC change of the hybrid system for the peak power profile.

As Figure 5 shows, the Pfc_out was constant at around 25.2 kW with the initial 40 A reference value and 630 V bus bar voltage. The Psc_out was used to supplement the varying power demands. The load power was always the algebraic sum of Pfc_out and Psc_out. The converter efficiencies were calculated based on the total energy delivery. The efficiency of the boost converter (for the FC) was found to be averaged at 90%. The discharge efficiency of the buck/boost converter (for the SC) averaged at 91.1%, while the charge efficiency averaged at 91.2%. From Figure 5, it can be seen that the SoC decreased when the power profile was positive (discharging) and increased when the power profile was negative (charging). Over the test, the SC discharged from 82% (initial SoC) to 74% (final

SoC). It has been shown that the FC/SC hybrid system functioned as expected in terms of controlling the FC output and meeting the dynamic load.

5. Degree of Hybridisation Identification

This section investigates how modifying the degree of hybridisation affected the system and its ability to meet the performance requirements of the bus, and outlines the methodology of determining the required degree of hybridisation of the FC/SC hybrid propulsion system.

5.1. FC and Boost Converter Output Identification

The same peak power profile was used to allow clear comparison when the boost converter reference values (Ifc_out) were varied. The SC energy capacity (83 F) and initial SoC (82%) were also both kept the same. The same peak power profile was tested with FC and boost converter reference currents of 20 A, 30 A, 40 A, and 50 A. Additionally, a 41.5 A Ifc_ref value was tested. This was based on the average power requirement of the traction motor, where the average total algebraic power of the peak power profile was 26.1 kW, giving a 41.5 A reference current. It was found that the boost converter output was able to regulate to the user requested reference values. Since the power profile of these tests were the same, the Psc_out value followed the same trend as the initial test, but with a different offset from Pload. The SoC of the SC throughout the peak power profile with different FC and boost converter output reference values are plotted in Figure 6.

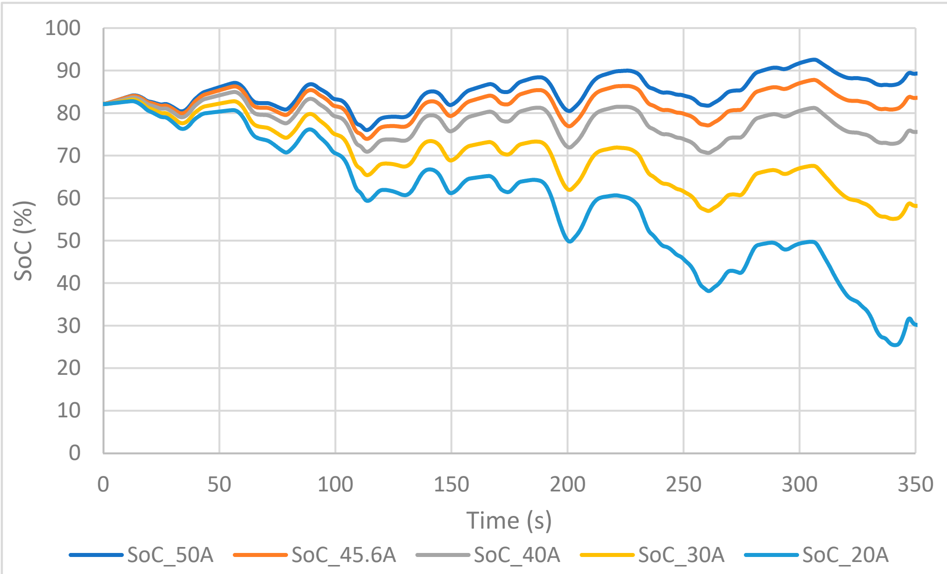

Figure 6. SoC change with reference variation of the peak power profile.

As Figure 6 shows, the smaller the FC output is, the lower the final SC SoC was. The final SC SoC was lower that the initial value when the reference was 20 A, 30 A, 40 A, and 41.5 A, but a higher final SoC was achieved when the reference was 50 A. The SC will be discharged if subjected to a driving cycle with an average power higher than the FC and boost converter output. On the other hand, the SC will be charged in this driving cycle if the average power of the power profile is lower than the FC and boost power. If the average total algebraic power of the driving cycle is close to the FC and boost converter power, the SC should end up with nearly the same final SoC as the initial SoC. However, it was found that this was not the case for a 41.5 A reference value, where the SoC dropped from an initial value 82.2% to a final value of 76.2%. The reason for this was the buck/boost converter efficiency. In this test, it was found that the average discharge efficiency was 94.3% and the average charge efficiency was 91.2%. This indicates that the SC needed to provide 5.7% more energy to the converter during discharge operations to provide the net output from the converter to the load.

While the SC received 8.8% less energy from the gross regeneration (from both regenerative braking and FC) output during charge operations. As a result, the final SoC was lower than the initial SoC. The final SoC can only be exactly the same as the initial SoC if the buck/boost converter has no losses, which is not practical.

As such, an increased FC and boost converter output power is required to compensate for the converter losses during charging and discharging. As a result, a constant 10% increase in the FC and boost converter reference output power was added to the average power calculated from the driving cycle to keep the final SoC reasonably close to the initial SoC. The peak power profile was tested again with a 10% increase in the FC and boost converter reference output power above the average power plotted as 45.6 A curve in Figure 6. The results showed that the final SoC was now 82.3%, which is reasonably close to the 82.2% initial SoC. Therefore, the required FC and boost converter output reference can be identified by using 1.1 times the selected driving cycle average power.

5.2. SC Size Identification

To determine the required SC size, it needs to be sized from two perspectives: power density and energy density. The power density determines the peak power that can be provided by the SC while the energy density determines the energy storage capacity of the SC. One of the most important advantages of the SC is its high power density. The Maxwell 48 V SC used in the laboratory test bench only has an energy storage capacity of 26.56 Wh but can achieve a peak power of 56 kW according to the data sheet. Since the peak power required from the bus was 200 kW, it is reasonable to make the assumption that a suitably sized SC can satisfy the peak power requirement for bus operation. Hence this research will focus on the energy capacity sizing of the SC for the hybrid system. Detailed justification of system scaling can be found in References [10,11].

In the previous tests, the SC capacitance was set to be 83 F, which had an energy capacity of 2.656 kWh. The same peak power profile with the same boost converter output reference (41.5 $\times$ 1.1 A) was tested with a number of different sized SCs. Five tests at SC capacitance values of 83 F, 60 F, 40 F, 20 F, and 10 F were performed. The SC SoC change throughout the peak power profile are plotted in Figure 7.

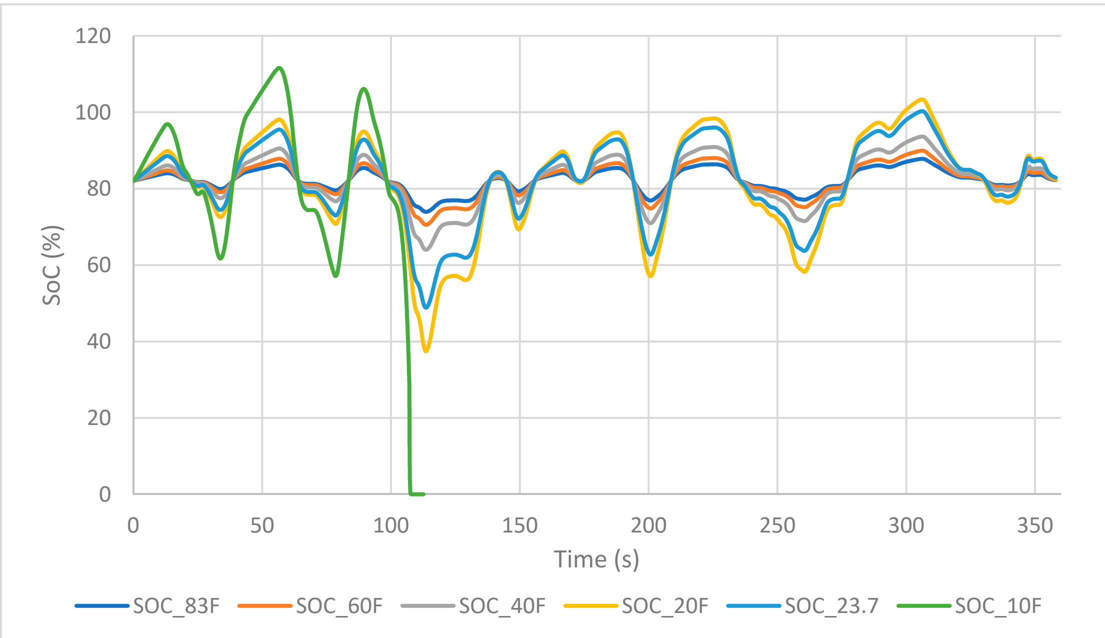

Figure 7. SoC change with different SC size of the peak power profile.

It can be seen that different sized SC end up with the same final SoC when 1.1 times the driving cycle average power was used as the FC and boost converter reference output. The main difference was the distribution of SC SoC, where a smaller SC had a wider range of SoC over the driving cycle. In the case of a 10 F SC, the simulation terminated when the SoC fell to 0%. Even for the 20 F SC, the SC overcharged, reaching a peak of 102.6%. It should be noted that the initial SoC will impact this; however, it highlights the principle of SC sizing since it is desirable to minimise the size of the SC to reduce the cost, mass and volume of the energy storage system. However, the energy storage capacity must be large enough to avoid over and under charge. From the test carried out, the most appropriate SC capacitance was therefore 40 F. However, such a trial and error approach is an inefficient means of determining the required SC size. As such, an alternative approach based on ensuring there is sufficient remaining energy to satisfy peak power demand and to ensure there is sufficient capacity left to store additional energy. As a result, the SC can be sized if the energy going in and out of the SC can be predetermined.

In order to calculate the required energy from and to the SC, a power relationship for the FC hybrid system based on current balancing and voltage regulation can be formulated as:

$$P_{fc\_out} + P_{sc\_out} = P_{load} \tag{3}$$

The equation indicates that the FC (and boost converter) and SC (and buck/boost converter) will always work together to meet the power demand for the driving cycle. The control strategy is to have the FC and boost converter output user-controlled, which means the Pfc_out is user-defined and maintained at a constant value. The load power is obtained from the traction motor power profile of the driving cycle. The required SC power can be calculated by subtracting the FC power from the power trace of the driving profile. As a result, the energy going in/out of the SC each sample can be calculated by multiplying the Psc_out by the duration of each sample (1×10^{-5} s). This allowed the cumulative energy required from or delivered to the SC to be calculated. The total cumulative energy required from the SC throughout the peak power profile is plotted in Figure 8.

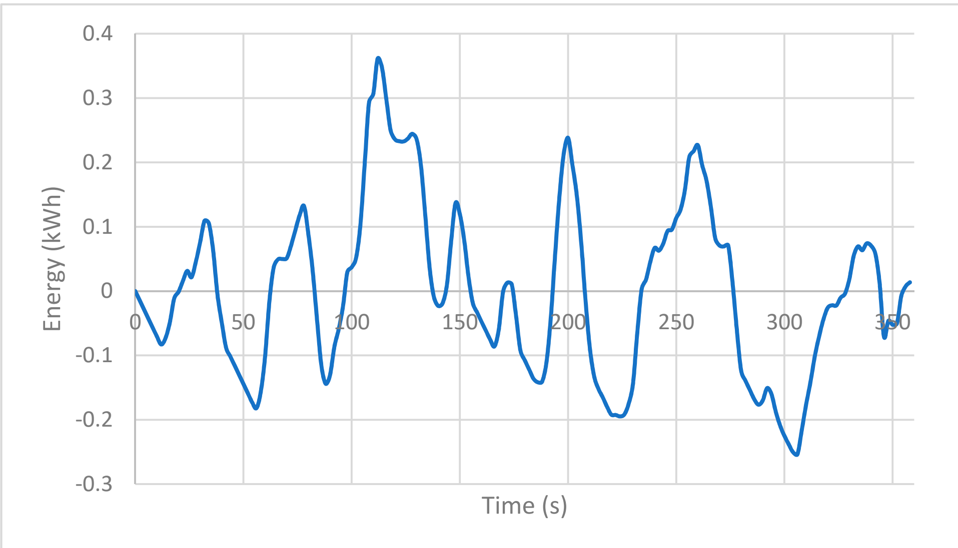

Figure 8. Cumulative energy required from the SC throughout the peak power profile.

In Figure 8, positive is when the cumulative energy balance of the SC was positive, i.e., the SC SoC was higher than the initial value. Negative is when the cumulative energy balance was negative, i.e., the SoC was less than the initial value. The difference between the highest and lowest values indicates the minimum energy storage capacity the SC can have. This will, however, be dependent on the initial SoC, where the positive peak energy indicates how much storage is required to be available from the initial SoC (0.371 kWh at 112 s) and the negative peak indicates how much energy the SC needs to store at the initial SoC (−0.263 kWh at 306 s). As a result, the SC energy storage capacity needs to be at least 0.634 kWh to deliver or absorb the required energy throughout the peak power profile. Then the required capacitance can be calculated using:

$$0.634\ \text{kWh} \times 1000 \times 3600\text{s} = 0.5 \times \text{C} \times 480^2\text{C} = 19.81\text{F}$$

Although the calculation based on the power profile showed that the required SC size was 19.81 F, the simulation carried out before showed that the SC was overcharged even with a 20 F SC. This indicates the SC size calculated by the power profile was smaller than it needed to be. The reason for this is because the calculation carried out with the power profile did not take the charge/discharge efficiency into consideration and the initial SC SoC. This suggests the cumulative energy calculation needed to be increased further to account for the charge/discharge efficiency. Since the exact efficiency would be dependent on the power profile of the selected driving cycle, the SC size could only be increased as an estimated value based on empirical calculation. Since the charge and discharge efficiency averaged at around 90% as shown before, discharge efficiency will result in an increase in SC size, but charge efficiency would result in a lower charge rate, and the total SC size has been increased by 20% for efficiency compensation. A total of 20% compensation increase has been applied on the calculated SC capacitance which gives a 23.772 F for the peak power profile case (Figure 7). The peak power profile was tested again with the new calculated capacitance and it was found the SC was not overcharged throughout the driving cycle with the increased SC size. It can be seen that the SC size can be calculated by using the power profile. This can be carried out much easier because only the power profile is required. Although the model needs to be simulated with the calculated SC size for validation, the calculation method can still significantly facilitate the sizing of the SC.

5.3. Degree of Hybridisation Identification Strategy

The previous sections have carried out tests to show how the system performs for various FC outputs as well as varying SC sizes. Methods to determine the required FC and boost converter output and required SC size have been identified with the 360 s peak power profile. Based on the discussions of previous sections, the strategy to identify the FC and boost converter output and the SC size for the FC/SC hybrid model can be summarised into the following steps:

1. Collect the power profile of the driving cycle.
2. Use the average power of the profile as the FC and boost converter output references.
3. Subtract the power profile by the FC and boost converter output power to determine the power required from and to the SC.
4. Calculate the cumulative energy required from and to the SC to determine the required capacitance.
5. Increase the determined capacitance by 20% for efficiency compensation and an additional buffer.
6. Run the simulation with 1.1 times the route average power as the FC and boost converter output reference and use the increased capacitance as the SC size.
7. Verify and validate the calculated degree of hybridisation.

6. Performance with Identified Degree of Hybridisation

To further verify the degree of the hybridisation identification strategy, more driving cycle tests have been carried out using longer duration segments of the driving cycle data, as shown in Table 1.

6.1. Bus Journey with the Highest Average Power

The bus journey with the highest average power has been selected for the first test. This bus journey lasted 32 min within the period 06:38 to 07:10 in the morning. The bus at that period of time is expected to encounter less traffic but with significant passenger loading. The required degree of hybridisation can be identified via the discussed identification strategy. The FC and boost converter output current reference was calculated to be 25.44 A based on the 16.03 kW average power and a 10% increase provided a 27.99 A (17.63 kW) reference. The required SC capacitance was calculated to be 65 F (with the 20% compensation increase), which equated to a 2.08 kWh of total stored energy. Hence the proposed operating degree of hybridisation is an FC and boost converter output of 17.63 kW and a 2.08 kWh SC. The power balancing and SoC change are plotted in Figure 9 for the proposed degree of hybridisation.

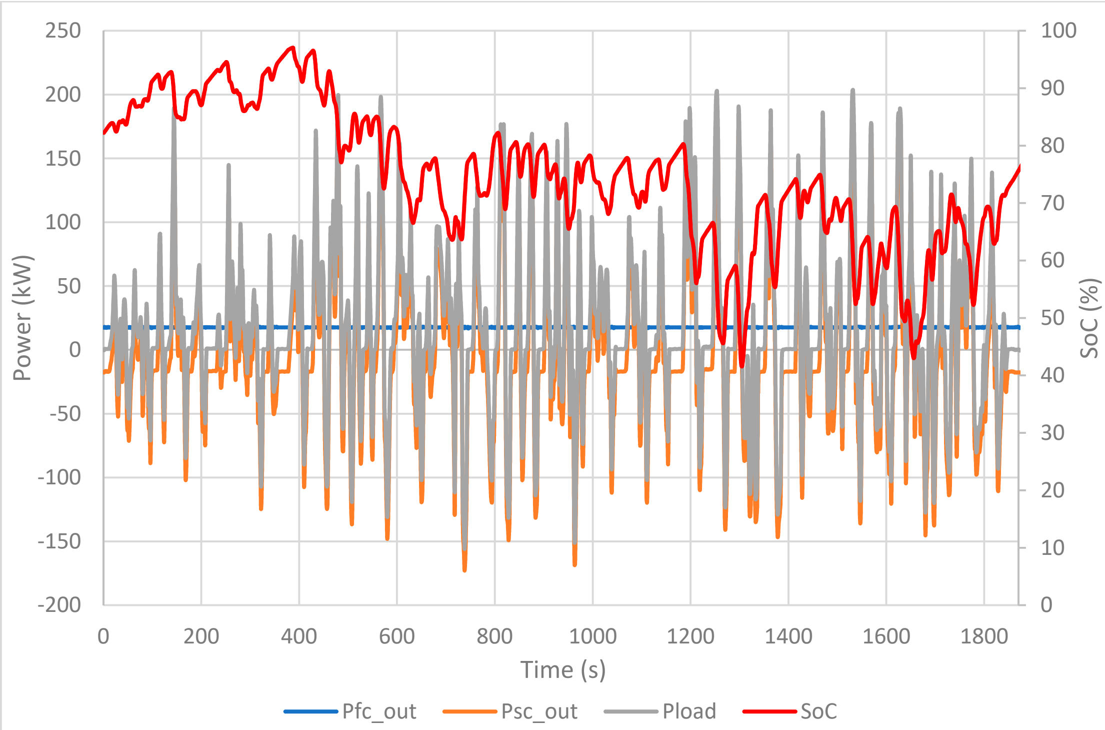

Figure 9. Power balancing and SoC change of the bus journey with the highest average power.

It can be seen that the balance of power operated as expected, with a constant FC output of 17.63 kW. The same offset between the SC power (orange) and load power (grey) was always met by the FC power (blue). The SC SoC was maintained within the earlier defined limits, reaching a maximum of 95.6% and a minimum of 41.1%; however, the final SoC of 74.8% was 7.4% lower than the initial SoC. This indicates that the efficiency of buck/boost converter operation during this bus journey was lower than during the peak power profile tests. The 10% increase of the FC and boost converter output reference could not fully compensate the efficiency loss. Calculations showed the efficiency during discharge averaged 93.3%, while the efficiency during the SC charge averaged 87.6% throughout the bus journey with the highest average power. It can be seen that the charge efficiency was lower than expected, meaning less power was absorbed by the SC during regeneration.

6.2. Bus Journey with the Lowest Average Power

The bus route completed with the lowest average power was found to be the bus journey within the period 19:00 to 19:50 in the evening, lasting around 50 min. This journey occurred during the evening rush hour where significantly more frequent stops due to traffic density are expected to occur, which is the reason the journey with the lowest average power takes longer to complete than the one with highest average power. For this journey, the FC and boost converter output current reference in the model was calculated to be 9.87 A (6.22 kW). The required SC capacitance was calculated to be 44 F (with the 20% compensation increase), which equates to a 1.41 kWh energy storage capacity.

Hence the proposed operating degree of hybridisation for this journey with the lowest average power was 6.22 kW FC and boost converter output and a 1.41 kWh SC. The power balancing and SoC change are plotted in Figure 10 for the proposed degree of hybridisation.

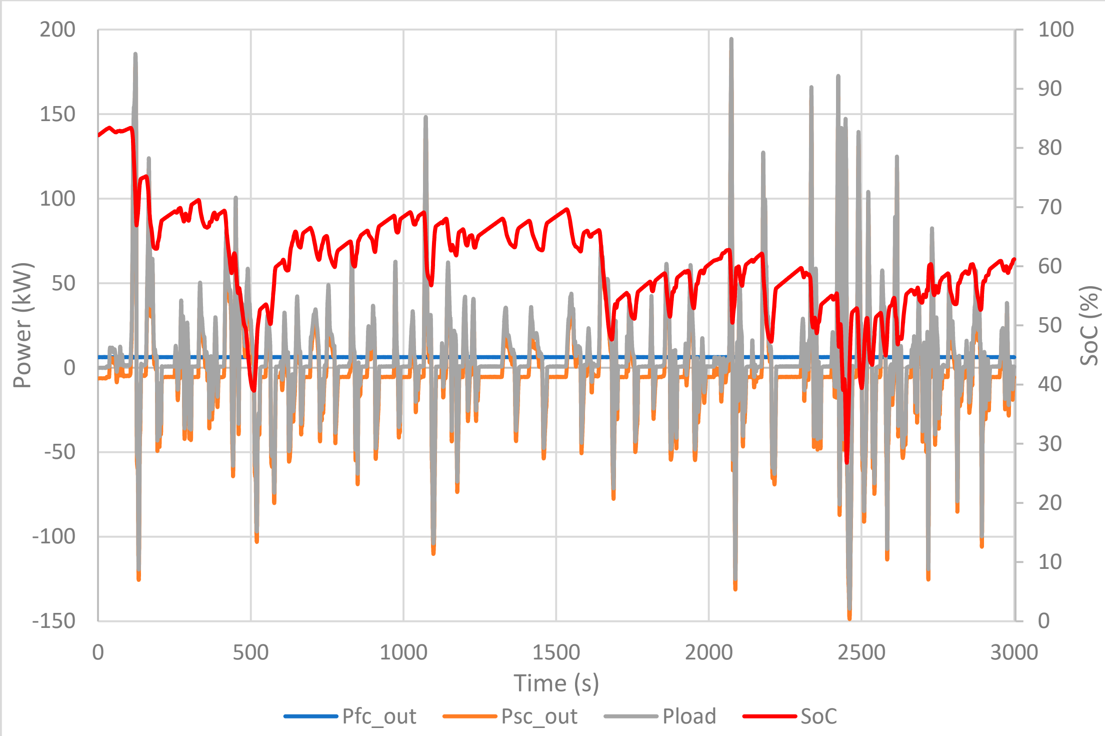

Figure 10. Power balancing and SoC change of the bus journey with the lowest average power.

As expected, the SC was used to meet any difference between the FC power and the load power demand. The lowest average power duty cycle also had a longer duration due to the frequent traffic stops. The SC attained a maximum SoC of 82.7% and a minimum SoC of 26.8%. It was also found that the final SoC was 61.2%, indicating the SC discharged by 21% throughout this driving cycle. By aligning the SoC change and power change, it can be seen that the SoC increased whenever the bus was stationary. This was because the output from the FC and boost converter was being used to charge the SC when the bus was stationary. The average discharge efficiency was calculated to be 90.3%. The average charge efficiency was found to be 78.2%. It can be seen that the bus journey with the lowest average power had an overall lower charge and discharge efficiency, particularly for charging operations.

6.3. Multiple Journey

It has been demonstrated that the proposed operating degrees of hybridisation for the journey with highest average power and lowest average power showed very different results. It was found the power profile played an important role in determining the required degree of hybridisation of a selected driving cycle. The identified degree of hybridisation can only be considered as an appropriate degree for the specific driving cycle. One consideration would be to use the entire power profile to determine the required degree of hybridisation following the same procedure. Thus, the simulation was carried out using the power profile of the first 135 min (within the period 05:40–07:55) of the 24-h bus data. The reason for selecting the first 135 min of the profile is because it included three completed bus journeys with various power ranges. The parameters of the selected profiles are summarised in Table 2.

Table 2. First 135 min of route 388 24-h bus profile parameters.

Bus Journey	Frist Journey	Second Journey	Third Journey	All Three Journeys
Time	05:40–06:20	06:38–07:10	07:13–07:55	05:40–07:55
Duration	40 min	32 min	42 min	135 min
Driving condition	Minimum traffic and light load	Light traffic and heavy load	Heavy traffic and heavy load	Overall
Average power	9.23 kW	16.03 kW	7.94 kW	10.70 kW
Required FC and boost converter output power	10.15 kW	17.63 kW	8.73 kW	11.77 kW
Required SC size	52 F (1.66 kWh)	65 F (2.08 kWh)	50 F (1.6 kWh)	124 F (3.97 kWh)
Proposed operating degree of hybridisation	10.15 kW FC and boost converter/1.66 kWh SC	17.63 kW FC and boost converter/2.08 kWh SC	8.73 kW FC and boost converter/1.6 kWh SC	11.77 kW FC and boost converter/3.97 kWh

As Table 2 shows, the SC size was significantly increased in order to run all three bus journeys. The 135-min power profile was tested with the proposed overall degree of hybridisation. Please note the driver break time between each completed bus journey was excluded from the power profile used for simulation because the bus is normally powered down in those periods. This is the reason the simulation duration was 6500 s instead of 8100 s (135 min). The FC/SC hybrid model simulation results in terms of power balancing and the SoC change throughout the driving cycle are plotted in Figure 11.

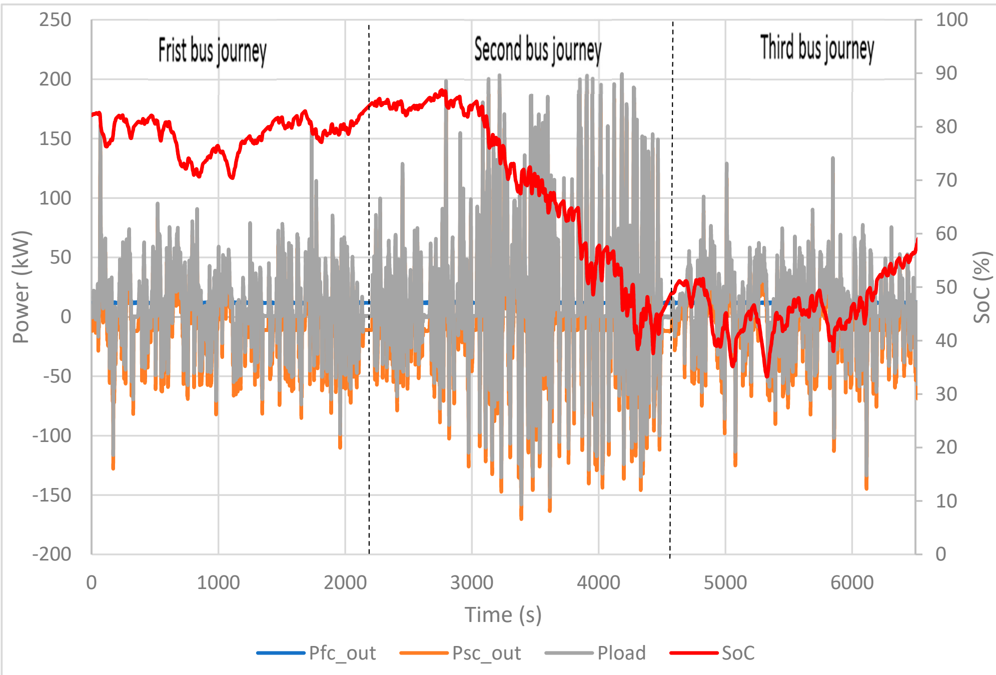

Figure 11. Power balancing and SoC change of 135-min bus profile.

As Figure 11 shows, the FC/SC hybrid mode managed to meet the 135-min bus power profile while keeping the FC output constant. The power balancing functioned as expected where the same offset was met by the FC power. The SC SoC discharged from 82% to 55.6% after the 135-min driving cycle. The SoC dropped significantly during the second bus journey because it was the most power demanding section of the day. It can be seen that different duty cycles had a significant impact on the SOC change throughout the journey.

6.4. Discussion on Stabilised FC Output Control

The previous sections showed the operation of an FC/SC hybrid propulsion system against actual driving cycles using computational modelling. The stabilised FC output control strategy showed the FC output can be maintained at a near constant value while using the SC to satisfy the dynamic load demands. A strategy to identify the FC and boost converter output power and required SC size has been proposed and has been shown to perform as expected. In principle, the FC and boost converter output only needs to provide constant output power equal to the average power of the driving cycle. It was found this can only be true if the SC charge and discharge efficiency was 100%, which is physically impossible. As a result, an estimated 10% increase to the FC and boost converter output was applied to compensate for the charge and discharge losses. The 10% increase in FC and boost converter output reference could only partially compensate for the efficiency losses. The exact percentage increase to the FC and boost converter output reference was, however, dependent on the power profile of the driving cycle because the charge and discharge efficiency varies with power.

Figure 12 shows a 200 s segment of the driving cycle from the 135-min test. The buck/boost converter efficiency varied with the power profile, where the efficiency was lower when the load power was low and vice versa. This explains why the buck/boost converter efficiency in the bus journey with the lowest average power was lower than the efficiency in the bus journey with the highest average power. To further investigate this relationship, the results obtained from the previous driving cycle tests are summarised in Table 3.

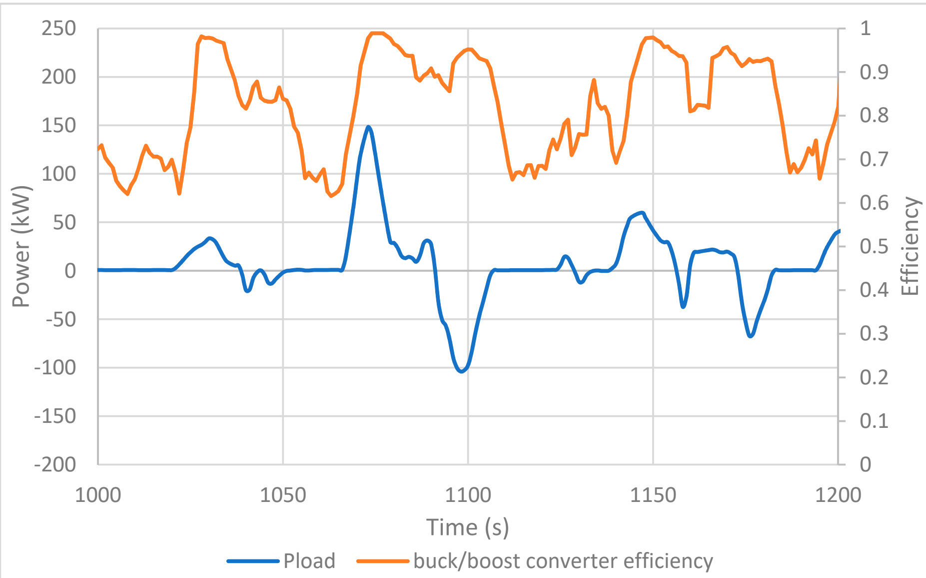

Figure 12. Relationship between load power and buck/boost converter efficiency.

Table 3. Parameter summary of different bus journey tests.

Driving Cycle	Highest Average Power Journey	Lowest Average Power Journey	Three Completed Combined Journeys
Duration	31 min	50 min	135 min
Route average power	16.03 kW	5.65 kW	10.7 kW
Initial SoC	82.2%	82.2%	82.2%
Final SoC	74.8%	61.2 %	55.6%
Discharged	7.4%	21 %	26.6%
Average charge efficiency	87.6%	78.2 %	86.6%
Average discharge efficiency	93.3%	90.3%	90.8%
Total energy provided by FC	37,907,368 J	22,168,597 J	78,254,199 J
Total energy provided by SC	502,410 J (discharge)	2,251,418 J (discharge)	7,754,859 J (discharge)
Extra reference increase (in addition to the 10% increase)	1.32%	10.2%	9.91%

As Table 3 shows, the longer the driving cycle is, the lower the final SoC. The SoC kept decreasing throughout the driving cycle, which is why it became more significant in longer runs. The total energy provided by the FC and the SC were also calculated and presented in the table. In order to keep the final SoC the same as the initial SoC, the net energy delivered by the SC should be zero. As a result, the energy provided by the SC showed in the table is the additional energy that needs to be provided by the FC. This suggests a further increase to the FC and boost converter output reference is required. The extra reference increase shown in the table indicates the magnitude of the additional increase required from the reference. As can be seen, they differ depending on the driving cycle. A further increase in the FC output by 1% will not be able to keep the SoC the same for the lowest average power journey and the three completed journeys. A further increase in the FC output by 10% will approximately keep the SoC the same for the lowest average power journey and the three completed journeys, but consequently, will overcharge the SC for the highest average power journey. This also highlights the limitation of the stabilised control strategy. In addition to the SC energy calculation, the buck/boost converter efficiency also had a significant impact on the charge/discharge efficiency and it varied with the power cycle. An improvement to the control strategy whereby the FC output can slowly vary depending on the SoC of the SC would offer protection against overcharge and undercharge, and decrease the importance of maintaining the SC SoC.

7. Conclusions

In conclusion the work presented in this paper advances the knowledge and understanding of the work previously published in References [10,11] to describe the approach taken to determine the degree of hybridisation using real-world data collected from a bus operating in London.

This research shows the operation of an FC/SC hybrid propulsion system against actual city bus driving cycles using the computer model. The computer model was scaled to the power level of a full-scale bus and evaluated with driving cycles collected from a practical bus. The results demonstrated the stabilised FC output control strategy is capable of keeping the FC output constant at the user defined value while using the SC to satisfy the dynamic power demands. It was also shown that the control strategy functioned as expected under real world dynamic loads.

The variation of the FC output and SC size was investigated to gain a better understanding of the effect of the degree of hybridisation in the bus model. The FC hybrid system was tested with different FC and boost converter current output references. The model showed it was capable of adjusting the FC and boost converter output based on the user-defined reference. It was found that varying the FC and boost converter reference only affected the SC input and output power, which changed the rate of change of the SC SoC. The method to determine a required FC output was identified to be 1.1 times that of the average power of the driving cycle, which would deliver an FC/SC hybrid system with a downsized FC. With regard to the method to identify the SC size, it was found that varying the SC size only affected the SoC change throughout the driving cycle. A number of criteria have been addressed to determine an appropriate SC size based on the results obtained. It was found that the method to identify the SC size would require the entire selected driving cycle to be simulated in the model, which is not an effective method. As a result, a method to estimate the required SC size for a certain driving cycle was identified based on the cumulative energy calculation throughout the power profile. The calculation method was validated with the computer model and it was shown to be capable of providing a reasonable estimation of the required SC size.

Based on the discussion, a method to identify the required degree of hybridisation was summarised in a number of steps. The proposed method was further evaluated with a series of driving cycles. It was demonstrated that the proposed stabilised FC control strategy was capable of managing the power balancing under dynamic conditions. The proposed method can be performed as a general strategy to identify the required degree of hybridisation for FC/SC hybrid buses with different degrees of hybridisation and under different load requirements.

Advantages and limitation of the control strategy have been investigated and analysed. Limitations of this control strategy were addressed as being the requirement of power data in advance, the requirement of an oversized energy storage and the lack of flexibility. Future improvements that can be carried out to improve the control strategy were also identified to implement an additional control algorithm that is capable of adjusting the FC output dependent on the SC SoC. A controllable FC output could potentially eliminate the requirement of duty cycle data in advance, reduce the requirement of a large SC onboard and brings more flexibility to the bus. This should be the focus of future research direction based on work presented in this paper.

Author Contributions: This work was carried out in collaboration between all authors. Author W.W. proposed the study concept, designed the control strategy, developed the corresponding software and wrote this paper. Authors W.W. and J.P. carried out software validation, data analysis and investigation. Authors J.P. and R.B. reviewed and provided supervision for this work and this paper.

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Nomenclature

I_{fc_in}	Current output from the fuel cell
I_{fc_out}	Current output from the boost converter on the common busbar
I_{fc_ref}	Reference value for the boost converter current output on the common busbar
I_{load}	Current to/from the traction motor
I_{SC_in}	Current to/from the supercapacitor
I_{SC_out}	Current to/from the buck/boost converter on the common busbar
V_{fc_in}	Voltage across the fuel cell
V_{fc_out}	Voltage across the boost converter on the busbar
V_{load}	Voltage across the traction motor controller on the busbar
V_{SC_in}	Voltage across the supercapacitor
V_{SC_out}	Voltage across the buck/boost converter on the busbar
P_{load}	Power from the load on the busbar
P_{FC_out}	Power from the FC and the boost converter
P_{SC_out}	Power from the SC and the buck/boost converter

References

1. Hayre, R.O.; Cha, S.W.; Colella, W.; Prinz, F.B. *Fuel Cell Fundamentals*; Wiley: Hoboken, NJ, USA, 2016.
2. Barbir, F. *PEM Fuel Cells Theory and Practice*; Elsevier Academic Press: Cambridge, MA, USA, 2005.
3. Murugesan, K.; Senniappan, V. Investigation of water management dynamics on the performance of a Ballard mark-V proton exchange membrane fuel cell stack system. *Int. J. Electrochem. Sci.* **2013**, *8*, 7885.
4. Wu, W.; Bucknall, R. Conceptual evaluation of a fuel-cell-hybrid powered bus. *Proc. Univ. Power Eng. Conf.* **2013**. [CrossRef]
5. Moreno, N.G.; Molina, M.C.; Gervasio, D.; Robles, J.F. Approaches to polymer electrolyte membrane fuel cells (PENFCs) and their cost. *Renew. Sustain. Energy Rev.* **2015**, *52*, 897–906. [CrossRef]
6. Eberle, U.; Müller, B.; Von Helmolt, R. Fuel cell electric vehicles and hydrogen infrastructure: Status 2012. *Energy Environ. Sci.* **2012**, *5*, 8780. [CrossRef]
7. Wu, B.; Parkes, M.A.; Yufit, V.; De Benedetti, L.; Veismann, S.; Wirsching, C.; Vesper, F.; Martinez-Botas, R.F.; Marquis, A.J.; Offer, G.J.; et al. Design and testing of a 9.5 kW proton exchange membrane fuel cell supercapacitor passive hybrid system. *Int. J. Hydrog. Energy* **2014**, *39*, 7885. [CrossRef]

8. Odeim, F.; Roes, J.; Heinzel, A. Power management optimization of an experimental fuel cell/battery/supercapacitor hybrid system. *Energies* **2015**, *8*, 6302–6327. [CrossRef]
9. Wu, W.; Partridge, J.; Bucknall, R. Development and modelling of a lab scaled PEMFC drive system for city driving application. In Proceedings of the UPEC 2016, Coimbra, Portugal, 6–9 September 2016; Volume 3.
10. Wu, W.; Partridge, J.S.; Bucknall, R.W.G. Stabilised control strategy for PEM fuel cell and supercapacitor propulsion system for a city bus. *Int. J. Hydrog. Energy* **2018**, *43*. [CrossRef]
11. Wu, W.; Partridge, J.S.; Bucknall, R.W.G. Simulation of a stabilised control strategy for PEM fuel cell and supercapacitor propulsion system for a city bus. *Int. J. Hydrog. Energy* **2018**, *43*, 19763–19777. [CrossRef]
12. Chan, C.C. The state of the art of electric, hybrid, and fuel cell vehicles. *Proc. IEEE* **2007**, *95*, 704–718. [CrossRef]
13. Zheng, C.; Xu, G.; Jeong, J.; Cha, S.W.; Park, Y.; Lim, W. Power source sizing of fuel cell hybrid vehicles considering vehicle performance and cost. *Int. J. Precis. Eng. Manuf.* **2014**, *15*, 527–533. [CrossRef]
14. Liu, C.; Liu, L. Optimal power source sizing of fuel cell hybrid vehicles based on Pontryagin's minimum principle. *Int. J. Hydrog. Energy* **2015**, *40*, 8454–8464. [CrossRef]
15. Xu, L.; Ouyang, M.; Li, J.; Yang, F.; Lu, L.; Hua, J. Optimal sizing of plug-in fuel cell electric vehicles using models of vehicle performance and system cost. *Appl. Energy* **2013**, *103*, 477–487. [CrossRef]
16. Melo, P.; Ribau, J.; Silva, C. Urban Bus Fleet Conversion to Hybrid Fuel Cell Optimal Powertrains. *Procedia-Soc. Behav. Sci.* **2014**, *111*, 692–701. [CrossRef]
17. Ribau, J.; Viegas, R.; Angelino, A.; Moutinho, A.; Silva, C. A new offline optimization approach for designing a fuel cell hybrid bus. *Transp. Res. Part C Emerg. Technol.* **2014**, *42*, 14–27. [CrossRef]
18. Ribau, J.P.; Silva, C.M.; Sousa, J.M.C. Efficiency, cost and life cycle CO_2 optimization of fuel cell hybrid and plug-in hybrid urban buses. *Appl. Energy* **2014**, *129*, 320–335. [CrossRef]
19. Lee, C.M.; Lin, W.S. Stochastic self-optimizing power management for fuel cell hybrid scooters of different sized components. *Int. J. Hydrog. Energy* **2015**, *40*, 5197–5209. [CrossRef]
20. Bubna, P.; Advani, S.G.; Prasad, A.K. Integration of batteries with ultracapacitors for a fuel cell hybrid transit bus. *J. Power Sources* **2012**, *199*, 360–366. [CrossRef]
21. Xie, C.; Xu, X.; Bujlo, P.; Shen, D.; Zhao, H.; Quan, S. Fuel cell and lithium iron phosphate battery hybrid powertrain with an ultracapacitor bank using direct parallel structure. *J. Power Sources* **2015**, *279*, 487–494. [CrossRef]
22. Yuan, J.; Yang, L.; Chen, Q. Intelligent energy management strategy based on hierarchical approximate global optimization for plug-in fuel cell hybrid electric vehicles. *Int. J. Hydrog. Energy* **2018**, *43*, 8063–8078. [CrossRef]
23. Marx, N.; Hissel, D.; Gustin, F.; Boulon, L.; Agbossou, K. On the sizing and energy management of an hybrid multistack fuel cell—Battery system for automotive applications. *Int. J. Hydrog. Energy* **2017**, *42*, 1518–1526. [CrossRef]
24. Burke, A.; Zhao, H. Applications of Supercapacitors in Electric and Hybrid Vehicles. In Proceedings of the 5th European Symposium on Supercapacitor and Hybrid Solutions (ESSCAP), Brasov, Romania, 23–25 April 2015.
25. Atmaja, T.D.; Amin, A. PEMFC Optimization Strategy with Auxiliary Power Source in Fuel Cell Hybrid Vehicle. *IPTEK J. Technol. Sci.* **2012**, *23*. [CrossRef]