Design of the Experimental Setup for a Plug-in Hybrid Electric Vehicle

Shane Overington, *Member, IEEE,* Sumedha Rajakaruna, *Senior Member, IEEE,* and Syed Islam, *Senior Member, IEEE*.

***Abstract*—This paper identifies the procedure utilized to determine the required ratings of components for the experimental setup of a 2 by 2 power-split connected plug-in hybrid electric vehicle. The test vehicle considered for this project has been selected from the available small scale conventionally driven vehicles in Western Australia. The main criteria for vehicle selection required that an existing electrical network was available, with alternator and battery and that the chassis has significant space and supportable structure for the coupling of an electric motor to the driveshaft. Following the selection of the vehicle the appropriate sizing of electrical components was undertaken considering a scaled standardized drive cycle selected to be utilized for testing. This involves the estimation and selection of the electric motor size, energy storage requirement and associated ratings of power electronics for control. The ADVISOR software package has been utilized to support the calculated sizes of electrical components for this experimental setup.**

***Index Terms*— ADVISOR, energy requirements, power-split connected plug-in hybrid electric vehicle, sizing procedure.**

I. Introduction

ALTERNATIVE vehicular technologies predominantly feature as the discussion of recent research due to the ever depleting fossil energy resources and rising fuel costs. The successful transition between theoretical analysis and practical experimentation determines the feasibility of any proposed ideology. The concern for the practical side of research comes down to the availability of components and associated costs. One significant means for undertaking practical research is through the use of a scaled test-bench such that component ratings and therefore costs are reduced whilst the underlying rules and limitations of the theoretical design remain intact. The development of such a scaled test-bench in this research realises a 2 by 2 power-split plug-in hybrid electric vehicle (PS-PHEV) that will be utilised for the experimental analysis of a developed control system.

Originally the research for such an energy smart vehicle considered the use of the standard PS-PHEV due to the overwhelming support for better operational performance compared with the series and parallel counterparts [1]. The main reason for selecting the power-split topology was the benefit of having both electrical and mechanical couplings to select from to better utilise fossil energy consumed by the internal combustion engine (ICE). The power-split topology in effect allows the ICE to operate at an efficient level whilst providing flexibility in energy transfer having both the electrical and mechanical energy paths to choose from [2-4].

There are two main types of power-splitting devices the planetary gear set and the electric variable transmission (EVT) [5-9]. The difference between the two power-splitting devices is the location of the power split. In the planetary gear set the power-split occurs in the mechanical side of the powertrain, providing a direct coupling of the ICE to the final drive [9]. The EVT on the other hand relocates the power-split to the electrical side of the powertrain [9], effectively being able to decouple the ICE from the final drive as needed to act as a generator. Both types of power-split have the ability to improve the ICE operation significantly with increased complexity and cost compared with the series and parallel topologies [9, 10]. This is where the 2 by 2 PS-PHEV (or dual drive HEV [11]) system demands greater interest.

The standard PS-PHEV systems with the planetary gear set or EVT rely on propulsion power being sent to the same drive axle(s) whereby the mechanical and electrical couplings are necessary to achieve the hybrid combination. Referring to Figure 1, the 2 by 2 PS-PHEV realises a power-split technique similar in principle to that of the standard PS-PHEV without the expensive and complex power-splitting device. The system instead utilises one propulsion device on the front axle and the other propulsion device on the rear axle representing the mechanical coupling of the PS-PHEV, whilst making an electrical coupling between the two propulsion devices via a generator. Through the monitoring of speed and power requirements of the system the ICE is capable of minimising waste energy through selective operation similar to that employed by the power-splitting devices [2, 7, 12, 13]. This topology thereby identifies with the most beneficial aspect of the standard PS-PHEV topology; efficient energy utilization without the concern for the increased mechanical complexity or cost.

With the concern for sizing of the experimental setup for this 2 by 2 PS-PHEV, Section II discusses the realisation of the vehicle architecture through drive train calculation and selection, followed by energy storage and associated component requirements. Section III supports the energy storage requirement calculated in Section II with simulation, and finally Section IV summarises the work completed outlining the future expectations of the experimental setup and its usefulness.

II. Vehicle Architectures

A. Test Vehicle Selection

The criterion for the test vehicle selection considers the limitations facing hybrid electric vehicle development in Western Australia. Primarily the cost and availability of hybrid vehicle components limits the potential for a full scale design. It was decided that a conventionally driven vehicle

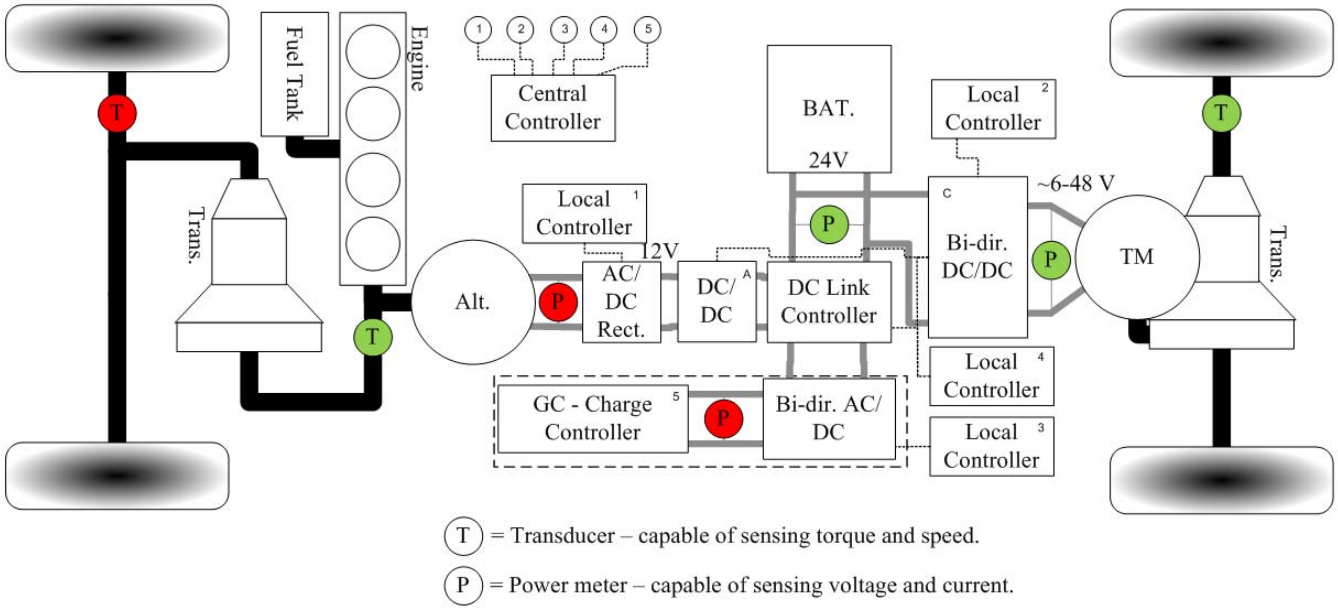


Fig. 1. Block diagram of the 2 by 2 power-split configuration for the PHEV topology.

TABLE I
ADVANTAGES OF VEHICLE SELECTED

Specification	Advantage
Automatic CVT with F/N/R	Providing flexibility for the speed of operation of the ICE with respect to the final drive.
Selectable 4WD or 2WD	Existing means to disconnect the ICE from the final drive via signal operation
Shaft driven	Accessible drivetrain to modify and integrate a traction motor
Carry Racks	Structural support for modifications such as batteries and converters
Electric Starter System	Existing electrical network with alternator connected to the ICE

would have to provide the base vehicle topology for the experimental setup due to the above reasons. Thereby the mechanical modifications made to the existing chassis and drivetrain need to be limited in order to preserve as much of the existing mechanical structure of the vehicle as well as to reduce the costs of the project. The vehicle topology therefore needs to reflect the 2 by 2 PS-PHEV topology (Figure 1) such that it has the mechanical assembly to apply propulsion to both the front and rear axle.

From initial inspection a four wheel drive (4WD) quad bike such as the one seen in Figure 2, satisfies the mechanical assembly required for the vehicle topology of Figure 1 [14]. The specifications of this system outlined in Table I determine the advantages for selecting this topology. It was deduced that the mechanical drivetrain would supply power from the ICE to the front and rear axle when in 4WD mode and would supply power to the rear axle during the 2WD mode of operation at the flick of a switch. This means that if the ICE is disconnected from the rear axle it will only supply power to the drivetrain (i.e. front axle) during 4WD mode which is the requirement for the 2 by 2 PS-PHEV. With the ICE coupled to the front axle only the traction motor (TM) can be coupled to the now disconnected rear axle to form the second drivetrain of the 2 by 2 PS-PHEV seen in Figure 1. The Automatic CVT connected to the ICE provides the potential for improved operation of the ICE since the operating speed will not be

Figure 2. All-wheel drive quad bike example vehicle selected for the base topology of the proposed experimental setup [14].

limited to one individual gear ratio but a range of gear ratios improving the flexibility for ICE operational efficiency. Finally the existence of the electric starter system allows the upgrade to more energy storage and the use of the already connected alternator (or integration of a second TM) for the electrical coupling between the front and rear axle, forming the power-split connection of the 2 by 2 PS-PHEV system. Having selected the base vehicle for the experimental setup the ICE drivetrain is catered for initiating the need to design the electrical network of the test-bench.

B. Electric Propulsion

To complement the existing ICE power rating of the selected vehicle the TM should conform to an acceptable power rating for hybrid and electric modes of operation. This involves determining the size of the TM that satisfies the drive cycle selected for testing. In addition the TM must be capable of supporting the vehicle power and torque requirements to reflect the operation of existing hybrid electric vehicle

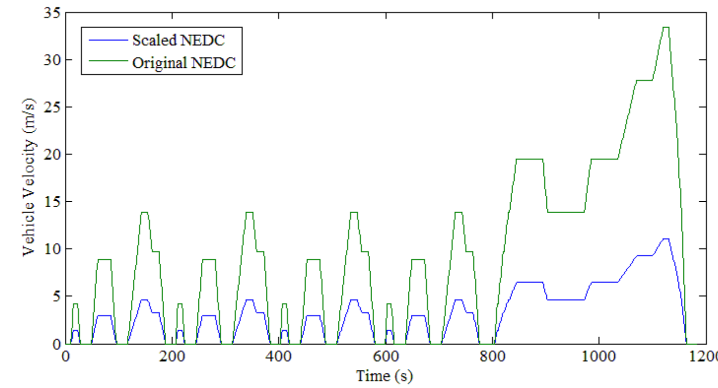
TABLE II
VEHICLE COMPONENT SPECIFICATIONS

Specification	Quantity
Internal Combustion Engine	387 cc, 20 kW, 30Nm @ 5500 rpm
Traction Motor	6 kW continuous, 12 kW peak, 48 Vdc, 0-5000 rpm, 18 Nm @ 3200 rpm
TM Efficiency	75% (worst case scenario)
Transmission/Final Drive Efficiency (η_t)	85%
Converter Efficiencies (η_{dc})	95%
Battery Coulomb Efficiency (η_c)	80%
Depth of Discharge	80% (Lithium ion @ <0.5CA)
Vehicle Mass (M)	350 kg (inc. accessories and curb weight)
Wheel Radius (r_d)	~254 mm
Vehicle Width	1112 mm
Vehicle Height	1160 mm
Aerodynamic drag coef. (C_D)	0.3
Air density (ρ)	1.2 kg/m^3
Gravitational Acceleration (g)	9.8 m/s^2
Rolling Resistance (f_r)	0.02 (gravel road- worst case)
Mass Factor (δ)	1.2 (approx.)

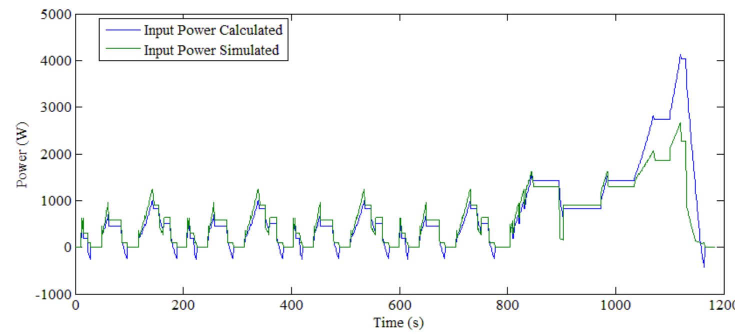
topologies. Therefore considering an electric vehicle as the rear axle drive train for the TM power rating calculation will ensure correct sizing of the secondary propulsion device. Following the realization of the TM power rating, power electronic component ratings and the energy storage requirements are determined from the selected drive cycle namely the New European Drive Cycle (NEDC). The NEDC profile was also utilized to determine the total testing time required on any given day. Relative to the choice to complete a scaled experiment for this project the test drive cycle needed to be considered at a scaled level.

The selection of the NEDC drive profile comes down to its use by other researchers in the area of vehicular technology and the potential for comparative analysis [7, 15]. For the purpose of scaling this drive cycle, acceptable speeds for a similar sized quad bike must be considered. Typical speeds exhibited by a quad bike range up to 50 km/h depending on the work completed by the user. Agriculture provides one of the main applications for such all-terrain vehicles (ATV) travelling at speeds much less than 50km/h on average (e.g. maintenance, mustering, spraying, etc.). In addition organizations such as Farmsafe Australia and HWSA identify the need to set speed restrictions on quad bikes to ensure the safe use of such vehicles in an attempt to reduce increasing fatality numbers caused by quad bikes [16, 17]. Concerns such as these indicate that the power rating for fuel consumption reduction of an ATV by a secondary propulsion device would need only to satisfy the average vehicle speed and a moderate maximum vehicle speed. The original NEDC profile of Figure 3 a) has been scaled down from 120 km/h maximum speed to 40 km/h such that the average speed has been reduced from 44.4 km/h to 11.1 km/h.

The TM power rating also relies on the hybridization factor and maximum speed of the typical drive cycle. The concern for the hybridization factor (HF) is a percentage comparison of the power rating of the TM against the total power rating of a hybrid electric vehicle (HEV) [18, 19]. The analysis completed by the authors of [19] concludes that the potential



a)



b)

Fig. 3. Comparison of simulated and calculated profiles *a)* Scaled and original NEDC drive profile *b)* Input power required from TM.

for fuel economy improvement is limited when it comes to the HF. Once the TM power rating reaches a certain percentage of total power rating the improvement for fuel economy begins to remain relatively constant leading to the concern of cost verses potential for improvement. Once the HF passes the 20% mark, the fuel economy percentage improvement up to 70% HF rises from 20.2% to 28.5% indicating that the extra cost for increased TM power may not be covered in the potential savings on fuel [19]. This realizes the inequality of equation (1).

$$\frac{P_{TM}}{P_{TM}+P_{ICE}} \geq 0.2 \quad (1)$$

Leading to;

$$P_{TM} \geq 0.25P_{ICE} \quad (2)$$

Secondly the TM power rating must be greater than the average continuous power requirement of the scaled NEDC drive cycle. Equation (3) determines the power requirement in Watts for propelling a vehicle of mass M, along a flat surface with rolling resistance coefficient f_r, aerodynamic drag coefficient C_D, vehicle frontal area A, air density ρ_a and mass factor δ at some velocity V in m/s [10].

$$P_r = V\left(Mgf_r + \frac{1}{2}\rho_a C_D A V^2 + M\delta\frac{dV}{dt}\right)\ (W) \quad (3)$$

This leads to the instantaneous power requirement (i.e. 'Input Power Calculated') of Figure 3 b) having an average power requirement of 970 W, with a peak power of ~4 kW.

TABLE III
ENERGY STORAGE REQUIREMENTS

Specification	Quantity
Drive Profile	11 x scaled NEDC
Peak Velocity	40.0 km/h
Average Velocity	11.1 km/h
Time	3 hours 53 minutes
Distance	40.07 km
Voltage	24 V
RMS Current	46.9 A
Maximum Current	180.8 A
Energy Storage	163.3 Ah
Energy Storage	3,919 Wh

Finally, the ICE power rating of the considered quad bike is 20 kW [14], with an HF of 20% the TM power rating needs to be at least 5 kW from equation (2). This 5 kW minimum also satisfies the power requirement of the NEDC drive profile if the vehicle were to operate in electric mode only. Additionally if the TM power rating of a higher magnitude is selected this has the potential for better fuel economy at increased costs per percentage improvement [19].

From those products found in Western Australia a TM with the specifications listed in Table II was selected. Having a 6 kW continuous power rating, and a 12 kW peak power rating this TM satisfies the required power of the drive cycle while adhering to the HF determined from [19]. Referring to the operating voltage of the TM and considering that there is a linear relationship between the voltage and speed of operation for the TM the current and voltage outputs of the bi-directional DC/DC converter for the TM shown in Figure 1 can be determined. The concern however falls to the gear ratios between the output of the TM and the wheels of the vehicle. From [10] we know that the vehicle speed ($V_{(m/s)}$) to wheel rotational speed (N_{wheels}) is calculated as;

$$N_{wheels} = \frac{60V_{(m/s)}}{2\pi r_d} \quad (rpm) \qquad (4)$$

Where r_d is the radius of the wheels. This leads to the comparative speed that is required from the TM considering the gear ratios linking the TM to the drive axle.

$$N_{TM} = N_{wheels} i_o i_g \quad (rpm) \qquad (5)$$

Where i_o and i_g represent the final drive and gearbox ratios respectively for the drive train. The data sheets for the TM identified in Table II indicate a linear relationship between the voltage and speed of operation with a voltage across the terminals at 48 V the operating speed is approximately constant at 3500 rpm for power levels up to 6 kW. This leads to the relationship between voltage (V_{TM}) and speed (N_{TM}) of the TM;

$$N_{TM} = \frac{3500}{48} V_{TM} \quad (rpm) \qquad (6)$$

The maximum speed of the vehicle for the NEDC drive profile at 40 km/h indicates the maximum speed that the TM

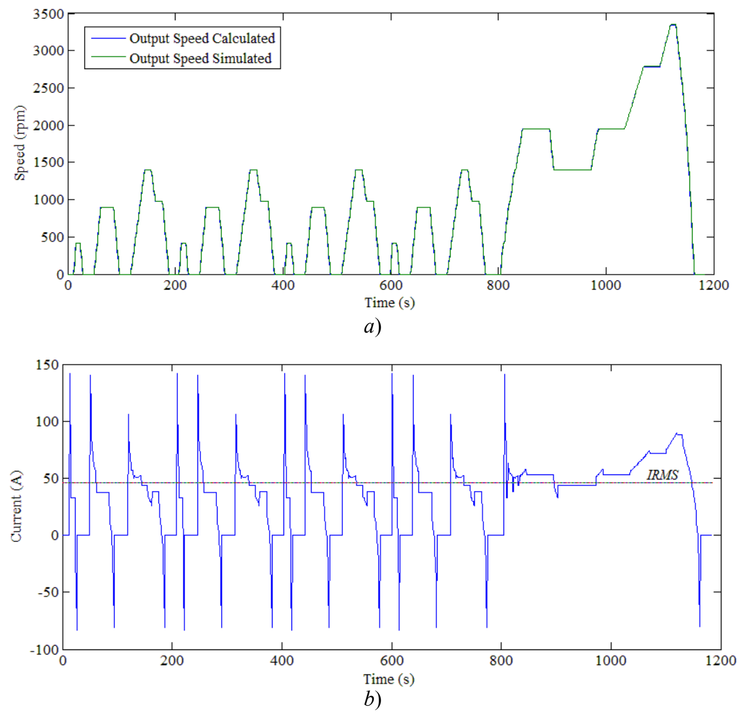


Fig. 4. Comparison of simulated and calculated profiles *a*) TM operating speed with gear ratio 8 *b*) Current drawn from the bi directional DC-DC converter connected to the TM.

needs to achieve at rated voltage. Using equations (4) – (6) the required ratio (i_{total}) between the drive axle and the TM for this condition is determined;

$$i_{total} = i_o i_g = \frac{3500 \times 2\pi r_d}{60 V_{(m/s)}} \qquad (7)$$

A ratio of 8.37 between the TM and drive axle will suffice, for the specifications listed in Table II. For simplicity in calculation a ratio of 8 was selected. Referring to Figure 4 a) the TM speed for the NEDC drive profile is determined at peak speed of 3342 rpm, and the requested current shown in Figure 4 b) with peak current of 141.6 A and RMS current of 45.8 A. A concern for the control of the TM is the high current at low speed and low voltage during acceleration of the vehicle. To overcome this concern the voltage has been limited to greater than 2 V in the calculations. The input of the bidirectional DC-DC converter connected to the TM in Figure 1 has been selected at 24 V since this is a common voltage for deep cycle batteries and provides a voltage step between the alternator voltage of 12 V to the 48 V of the TM across the DC Link shown in Figure 1.

The energy storage requirement of the test vehicle relies on the above calculations to the extent of the power demanded by the road load. With the energy storage voltage set at 24 V the current drawn from the battery bank of Figure 1 can be determined from the instantaneous power requested over the duration of the drive cycle as seen in Figure 2 b). For the purposes of testing it is assumed that the electric mode of operation would consume the most energy such that the test-bench is operated as an electric vehicle for a given day of experimentation. Allowing 4 hours of operation for this vehicle in one day the NEDC cycle can be completed 11 times

TABLE IV
ADVISOR SIMULATION RESULTS

Specification	Quantity
Energy Consumed at Terminals	92.72 Ah
Energy Consumed at Terminals	2225.3 Wh
Energy Drawn From Cells	115.9 Ah
Energy Drawn From Cells	2781.6 Wh
Energy Storage Required	144.9 Ah
Energy Storage Required	3477.0 Wh
SOC using Simulated Coulomb Energy	20 % (3477 Wh Total)
SOC using Calculated Coulomb Energy	29.0 % (3919 Wh Total)
Over Engineered by	12.7 %

under continuous operation. This would allow at least 4 hours of testing on any given day considering that the hybrid mode of operation will maintain the battery SOC longer than the calculated 4 hours and charging will occur during the night. This leads to the specifications for the energy storage requirements as listed in Table III with the efficiencies as listed in Table II. For the depth of discharge (DOD) from a lithium ion battery data sheet [20] the 80% DOD at 0.5 CA indicates that the RMS current drawn from the battery must be less than 50% of the rated battery amp-hours. This means for the battery to be discharged to 80% DOD it must have an amp-hour rating of twice the RMS current calculated in Table II at 46.9 A (i.e. 93.8 Ah). Therefore the total amp-hour energy requirement of the energy storage system with 80 % DOD at rates below 0.5CA can be selected at approximately 160 Ah which is the calculated amp-hour energy rating.

III. SIMULATION

A. *Verification and Evaluation*

In order to support the calculations completed for this research, simulations using the ADVISOR software package were undertaken. ADVISOR is based on MATLAB/Simulink which provides ease of transition between calculations completed using MATLAB into the Simulink environment for integration with existing vehicle models stored in libraries of the ADVISOR software [21, 22]. The specifications of the selected vehicle and associated electrical network were entered into ADVISOR and simulated for the same drive profile as listed in Table III. The model selected from the ADVISOR software was the electric vehicle model, as a worst case scenario (as mentioned above) and to ensure similarity with calculation.

Figure 3 b) identifies the correlation between the power requirement of simulation and the calculations completed using equation (3) for the drive train of the electric vehicle considered. The differences in the spikes for the power profile are due to ADVISOR's inclusion of the wheel slip for the vehicle operation and varying efficiencies of some of the drive train components. Additionally Figure 4 a) determines consistent correlation between the speed requested from the TM of the simulation and that of the calculations with a gear ratio of 8.

ADVISOR determines the battery energy consumed by the drive profiles for predetermined vehicle models and ideal operating conditions. Referring to Table IV the energy consumed as determined by the ADVISOR simulation came to 2225 Wh meaning 52.3 % SOC will remain from the calculated 3919 Wh. For this determined energy consumption an ideal efficiency is considered in ADVISOR at STP for the lithium-ion battery bank. If we assume that the coulomb efficiency of 80% holds from calculation on a worst case scenario the stored energy used increases to 2782 Wh. This is the energy drawn from the batteries such that it will potentially have discharged 80% of the total energy stored in the batteries (Refer to DOD of Table II). Therefore the total energy storage required as determined by ADVISOR is 3477 Wh this means that via calculation the energy storage requirement is over engineered by 12.7% and the simulation indicates that less energy is required by the drive profile, supporting the energy requirement determined in calculation for the test vehicle; 160 Ah at 24 V. This energy storage requirement of the test vehicle will thereby allow at least 4 hours of testing each day whether it is utilized as an electric vehicle or as a hybrid vehicle.

IV. CONCLUSION

The 2 by 2 PS-PHEV in principle provides the same advantages as the standard PS-PHEV, at reduced cost and complexity of the drive train. With the same principle advantages the potential for operation and control is ultimately the same. The base vehicle selected for the experimental setup satisfies the need for propulsion of the front and rear axles with the potential to disconnect the ICE from one of the axles for intermittent operation. This then allows the TM to be sized according to electric vehicle operation requirements as well as the power electronic ratings and energy storage requirements relative to the NEDC drive profile selected for testing. Having determined the experimental setup sizes in calculation, simulations were completed for support realizing the required energy storage.

Due to the similarities in principle of the standard PS-PHEV and the 2 by 2 PS-PHEV the experimental test setup has the potential to show the improved operation of a PS-PHEV with reduced cost. The determined experimental setup will therefore be utilized to show the benefits of a PS-PHEV control system designed for use on a standard PS-PHEV without the increased costs and complexity in mechanical calculation and design. In future there is also the option to integrate an ultracapacitor for extended battery life and greater dynamic behavior of the electrical network.

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