

Selection and Characterisation of PMSM motor for mild HEV Applications

Mohamed Awadallah¹, Peter Tawadros², Paul Walker³, Nong Zhang⁴

¹ School of Electrical, Mechanical and Mechatronic Systems, University of Technology Sydney - UTS

Mohamed.M.Awadallah@student.uts.edu.au¹, eng.m.zakaria@gmail.com¹, Peter.Tawadros@uts.edu.au²,
Paul.Walker@uts.edu.au³, Nong.Zhang@uts.edu.au⁴

Summary

This paper presents a theoretical background and real-time validation procedure for an electric propulsion system for a mild-hybrid vehicle configuration, based on a permanent magnet synchronous motor (PMSM) on the output shaft of a manual transmission. The validation technique uses the rapid prototyping technique of hardware-in-the-loop (HIL) in order to validate the characteristics of an off-the-shelf PMSM and controller by implementing them in a HIL model of the mild hybrid vehicle. The results obtained suggest that whilst the motor did not meet the manufacturer-rated specifications, it would nevertheless function acceptably for the purposes of the proposed mild hybrid vehicle architecture.

Keywords: brushless motor, data acquisition, electric drive, hardware-in-the-loop (HIL), and permanent magnet motor

1 Introduction

Mild hybridization is a compromise that minimizes conceptual changes to vehicle systems while enhancing fuel efficiency. By definition, a mild hybrid system is used to assist the internal combustion engine (ICE); driving on electrical power alone is not possible. In this paper, we discuss a mild-hybrid system in which the electric motor is inserted between the transmission output and the differential. This drive component merges four functions into one system. The primary use of the motor is for torque-hole fill-in in an automated-manual transmission (AMT)-equipped powertrain while also reducing clutch slip. The secondary uses are to supplement the ICE by supplying additional power to the drivetrain when high power is demanded, as well as to regenerate power where possible. Selecting the most appropriate electric propulsion system (EPS) for hybrid vehicles depends on many factors, including the driver's expectation, vehicle and project constraints, energy source and more. Other target requirements may include noise, vibration and harshness (NVH), drivability, or other quality characteristics. There is extensive literature in the field of designing EPS to particular constraints [1], [2], [3]. The research presented herein focuses on simplification of architecture to provide rapid prototyping and validation functions. It is part of a broader research project aimed at delivering a low-cost hybrid electric vehicle (HEV) suitable for deployment in developing regions.

This validation process covers specific implementation techniques for interfaces, and model processing in real-time with electrical hardware functionality, as well as mathematically modelling the motor for simulations. The tools and interfaces necessary for validation are also presented. These include the motor controller and dSPACE MicroAutoBox II. The validation process will also include design processes for

handling real-time control using Simulink, dSPACE RTI & Control Desk environments. Finally, physical validation will be described, based on dynamometer testing to obtain motor performance data. We discuss Rapid Controller Prototyping (RCP); our chosen method for design & development of control for our motor control problem. The design of our solution involves interfacing the MicroAutoBox II controller to the permanent magnet synchronous motor (PMSM) Controller. All interface signals are configured, and the two controllers are connected using the controller area network (CAN) protocol and relays.

Motor dynamometer test cycles were used to investigate and validate motor characteristics. The cycles are designed to test the motor at all speeds including very low-speed operation, transient speed and load testing. The PMSM was subjected to iterative cycles in the laboratory. Low-speed steady-state controllability of the dynamometer presented issues. Therefore, an investigation was undertaken to determine whether speed and current measurements could be used to predict accurately power output over a range of input voltages and voltage profiles, by understanding motor losses.

2 Traction Motor

In the initial stage of the project, an extensive design study suggested that the best motor option for a low-cost HEV is that of a PMSM, with a rated continuous mechanical power output of 10-20 kW. PMSM drive is widely used for EV and HEV applications. The major advantages of PMSM motor include high efficiency, low maintenance, good longevity and reliability, low noise emissions, and low cogging torque. Importantly, the control of a PMSM motor is also considerably cheaper than other suitable candidates (eg., induction motor (IM), and switched reluctance motor (SRM)). Table 1 is an evaluation of most commercial electric motors for vehicular propulsion systems [4], [5], [6]. The evaluation grades six major characteristics of each motor on a scale from 1 (worst performance) to 5 (best).

Table 1: Qualitative comparison of commercial electric motors

	Brushed DC Motor	IM	PMSM	SRM
Power density	2.5	3.5	5.0	3.5
Efficiency	2.5	3.5	5.0	3.5
Controllability	5.0	5.0	4.0	3.0
Reliability	3.0	5.0	4.0	5.0
Maturity	5.0	5.0	4.0	4.0
Cost	4.0	5.0	3.0	4.0
Total	22.0	27.0	25.0	23.0

2.1 Cost Analysis

Because equipment used for this project was purchased at retail cost, it is difficult to estimate manufacturing cost. [7], [8], [9] propose various methods for approximating the manufacturing cost based on physical performance. McKeever [8] gives individual equations (1), (2) for both the inverter and motor cost, however because of the technological and scale improvements in the intervening period, they cannot be considered realistic in the current term.

$$\text{Inverter cost} = \$418 + \$7.60 \times kW \text{ peak} \quad (1)$$

$$\text{Motor Cost} = \$33.33 + \$10.6 \times kW \text{ peak} \quad (2)$$

OAK RIDGE [7] proposes a near-term cost of US\$41 per rated kW for total motor and inverter cost. Wu [9] provides a compound annual growth rate (CAGR) for the capital cost of HEV components. For the motor/controller, the CAGR is -4.4%. By applying the CAGR to the figure proposed by OAK RIDGE, we arrive at a 2016 figure of US\$31.30/kW. Our motor and controller are therefore expected to add approximately US\$375.60 to the cost of the base vehicle.

2.2 Selected motor

The electric motor in our mild hybrid is designed to be mechanically connected directly to the prop shaft. An electrical input power of up to 20 kW is provided for the system. It is intended to provide acceleration

assistance but no, or highly limited all-electric driving mode [10], [11]. The motor output is mainly used for accelerating and starting. To select an appropriate electric motor, an analysis of the vehicle architecture under the New York City Dynamometer Drive Schedule (NYCDDS, NYC Cycle) was conducted [12]. The NYC cycle was selected as the most appropriate representation of the target market for our proposed vehicle architecture. The analysis used a speed trigger to determine the number of gear shift events over the course of the cycle, eliminating superfluous events by excluding shifts made within 5 seconds of another. In cases where speed decreased then increased across a speed trigger over any 5-second window, a redundant downshift was deleted. Where the speed first increased then decreased across a trigger, then a superfluous upshift is also deleted. For the total cycle length of 598 seconds, 42 gearshifts were required. Ignoring downshifts, the average power required at upshift was calculated to be 9.47 kW, with only five upshift events requiring over 10 kW (see Figure 1).

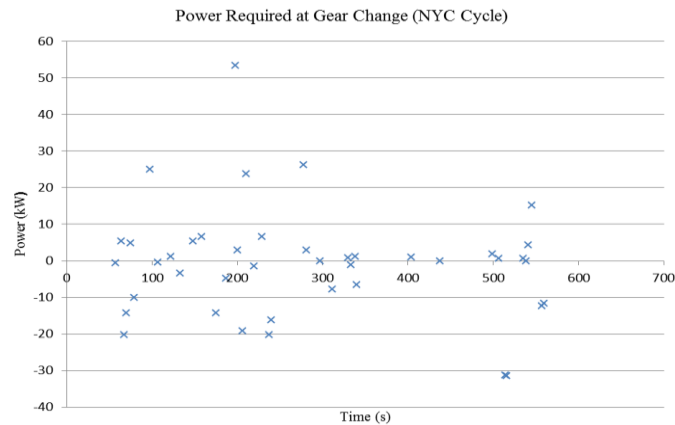


Figure 1: Power required at gear change

A similar plot for motor output torque can be produced using the target speed at each projected gear change. As the motor is placed after the first reduction ratio, it is independent of this variable, and the output torque is, therefore, a simple function of the target speed and required power. All but four gear change events are found to require less than 125 N.m output torque for torque fill-in (see Figure 2). The motor speed and torque characteristics can then be determined by plotting these variables for each gear change event.

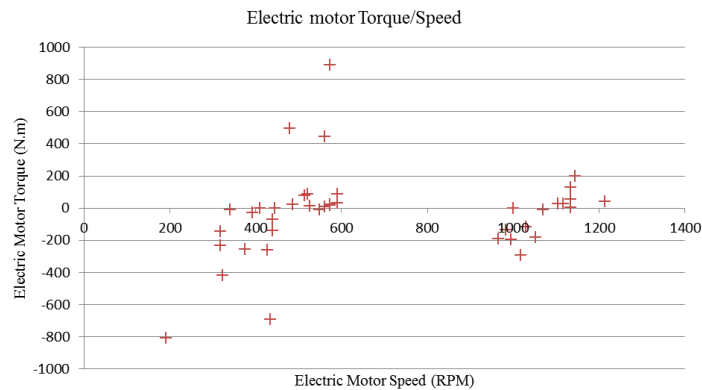


Figure 2: Electric Motor Torque speed

Based on the NYC cycle analysis, the Motenergy ME0913 (12 kW / 30 kW pk.) motor was selected as a suitable motor for initial testing. Although its peak torque is somewhat lower than ideal, it is the closest off-the-shelf solution to meet our hardware needs. Bench-testing yields characteristic curves, which are included in the Simulink program. The motor is a 3-phase, Y-connected motor with an axial air gap and 3 Hall sensors at 120 degrees electrical timing. It has two stators with a rotor in the centre and a four pole motor (8 magnets). It is rated by the manufacturer to 30 kW peak at 96 V with continuous current of 125 A of AC (180 A of DC into the motor control) [13].

2.3 Mathematical model

2.3.1 Motor modelling

To simplify the system model, a DC equivalent motor model is used to represent the prime mover. The DC equivalent model reduces the three phase PMSM to a simple two-degree-of-freedom model and allows direct control of input voltage without consideration of power electronics for these simulations. The complexity of simulating power electronics is eliminated, and the direct voltage control of the motor is now possible. The motor may be defined by two equations. Using Kirchhoff's Voltage Law, the differential equation for the electric circuit is defined in equation (3). Using Newton's second law of motion, the motor is defined in equation (4).

$$V = IR + K_m \dot{\theta} + L \frac{dI}{dt} \quad (3)$$

Where I is the line current, L is the line inductance, K_m is the back emf constant, $\dot{\theta}$ is the angular velocity, R is the line resistance, and V is line voltage.

$$T_e = K_f \dot{\theta} + J \frac{d\dot{\theta}}{dt} + T_L \quad (4)$$

Where T_e is the electrical torque, K_f is the friction constant, J is the rotor inertia, T_L is the supposed mechanical load.

A description of PM motor modelling by Laplace transfer functions and matrix representation has been previously conducted in [14], [15].

2.3.2 Plant modelling

The physical simulation models of EPS (motor and control) were established in the MathWorks' Simscape environment. Generally to reduce the computational demand for simulations, EPS models use an integrated efficiency map, requiring only a maximum output torque and the supplied battery power to determine the driving load delivered to the wheels. lookup tables may be used to find directly the output torque using this method, based on a given throttle commands and motor speed. The look-up table used in the model presented is obtained from ADVISOR and is based on the Unique Mobility 10 kW PM motor. Figure 3 shows the SIMULINK implementation of motor [16], [17]. For the EPS it is assumed that the demanded power from the controller is supplied to the motor (P_s), this is combined with motor speed and efficiency to determine the actual motor output torque. The motor torque is calculated as follows for the EPS.

$$T_{EPS} = \eta_{EPS} \frac{P_s}{\dot{\theta}} \quad (5)$$

Where P_s is the supplied power, T_{EPS} is the output torque from the motor, and η_{EPS} is the EPS efficiency. It is important to note here that the maximum torque available in the motor is limited by the rated power.

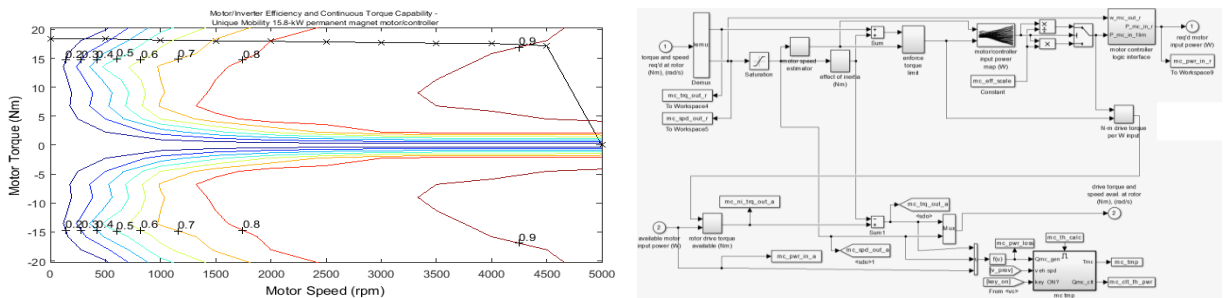


Figure 3: PM Model in SIMULINK

3 EPS Architecture

In Figure 4, a diagram of the EPS is shown. It includes six parts: the electric motor, KHB1260124 power converter, used to supply the Mars 0913 motor with electric power, and the Electronic Speed Control (ESC) to provide efficient, smooth and quiet controls [18]. The ESC manages the current supplied to each phase, polarity, the position of the rotor through Back-EMF, monitors the speed, Hall-effect position sensors and then controls the operation of the electric motor to produce the required torque and speed, according to the command from the supervisory controller through the CAN network [19]. It is also used to read the physical motor parameters speed and temperature. dSPACE MicroAutoBox II is used to provide supervisory control to the motor controller by reading information through the CAN-bus into a feedback control loop, and issuing commands to the motor controller using analog and digital signals through the interface circuitry. The interface circuitry is a custom-designed relay board and wire connections. It is the interface that combines the output ports, e.g. sensor signals, CAN bus signals and motor driver command signals. Relays control system power; throttle and brake enable, and motor direction. Other functions are controlled by analogue control signals and CAN-based feedback. For the purpose of proof-of-concept, the motor is powered by a grid-connected 157 kW variable DC power supply, due to safety issues associated with battery storage and discharge in the laboratory environment.

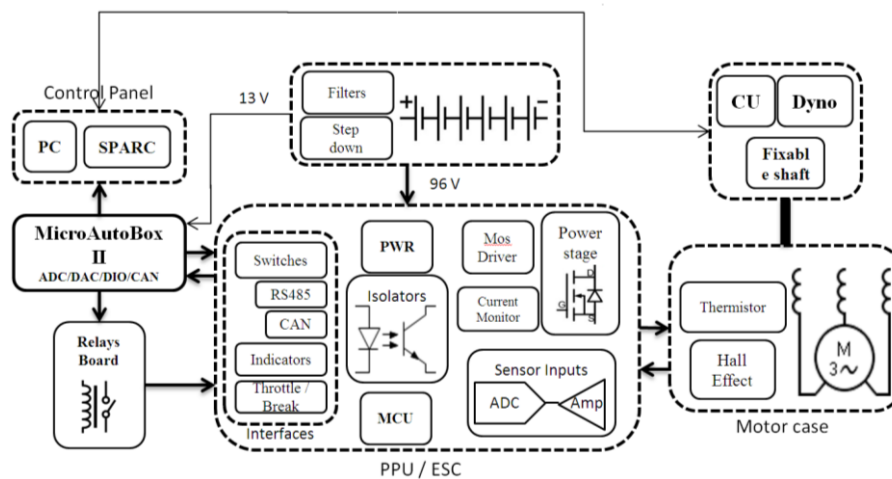


Figure 4: The functional block diagram of EPS.

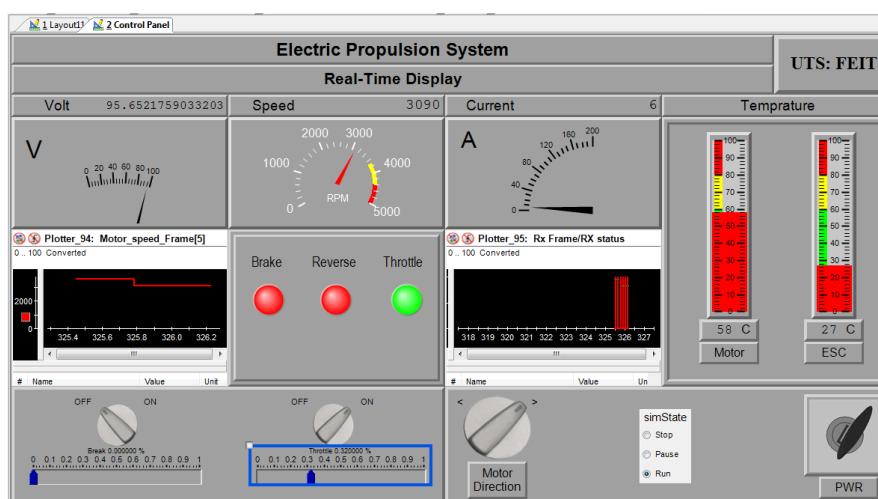


Figure 5: EPS Control Panel

The model was developed and programmed into the MicroAutoBox II boot. It is automatically converted to code, using the automatic code generation function of the real-time interface. The real-time simulation is running in dSPACE ControlDesk. This software allows logical configuration of simulation runs. Figure 5

shows the cockpit layout of the real-time simulation. The layout is used for setting up relevant parameters during experimentation. The MicroAutoBox II controller receives commands from ControlDesk through a host interface cable. The commands control the parameters including Throttle, Brake, Reverse motor direction and KHB power switch. These commands were interpreted by the controller logic and applied to the KHB motor driver (responsible for managing the speed and position and working as data acquisition through CAN bus). The ControlDesk dashboard was configured to allow control of power, throttle, brake, and direction. Indicators were configured to display controller and motor temperatures, motor speed, direction, motor current, voltage, CAN-Bus activity, power status, and a speed histogram.

4 Mass constraints

The development of efficient and compact HEV powertrains for low-cost constraints requires consideration of numerous, often competing factors. One such factor is vehicle mass, which is constrained by three competing parameters. Namely, these are the total stored energy in the vehicle, against the impact on vehicle emissions, against the purchase and ongoing operational costs. The motor chosen for this study has a mass of 16 kg. Estimation of the mass of other componentry was conducted to estimate the weight penalty as compared to an otherwise identical ICE-only vehicle. The battery was estimated to be 40 kg, power electronics and controller 10 kg, wiring harness including high-power cabling of 10 kg, and housings, powertrain components, and bracketry of 20 kg. Therefore, the nominal mass of the EPS is 96 kg. The mass of components that could be downsized or eliminated included the starter motor and ring gear (2.5 kg), 12 V battery (5 kg). This calculation leads to a net weight penalty of approximately 88.5 kg, or approximately 108% of the ICE-only vehicle weight. This figure was deemed to be an acceptable outcome.

5 Validation

5.1 Data Acquisition Methodology

A Data Acquisition Interface (DAI) module, integrated into the MicroAutoBox II was used for data collecting and recording. The DAI was programmed from within ControlDesk. Torque was measured using the SPARC dynamometer controller, and efficiency computation completed within MATLAB. The DAI module was programmed to measure and record the necessary parameters (current, speed and temperature) of the motor while it was running on the dynamometer. The complete experimental procedure required several iterations. To create the efficiency map, the motor was set to a fixed no-load speed (voltage) starting from the maximum speed down to 1000 rpm in steps of 500 rpm. At each speed interval, the load torque was increased from zero in steps of 0.5 Nm and maintained for 10 seconds. The maximum developed motor torque was determined when the brake torque applied by the dynamometer resulted in a non-stable operating point (that is, the motor speed could not be stabilized constant). At this point, brake torque was released, and the next no-load speed was set. The sampling frequency used for the preliminary data acquisition was 0.5 Hz. Once the whole load range of the motor was measured, the parameters were analysed and validated in Matlab.

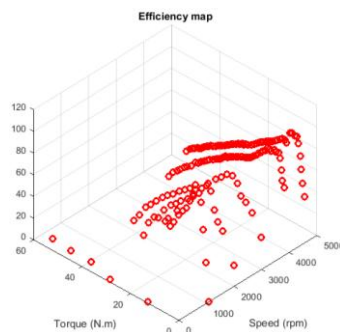


Figure 6: Efficiency map of the electric propulsion system.

At low rpm and high torque, the system approached the control limit of the dynamometer and results were not necessarily accurate [20]. To complete testing as comprehensively as possible, when the control limit was reached, the dynamometer was controlled for a speed of zero, which is not practically possible using

the equipment available, and results in a system speed of around 15 rpm. This speed allows us to approximate speed/torque characteristics of the motor at close to zero rpm. However, this test could not be sustained for long periods due to the possibility of mechanical failure of the motor. The current supplied to the motor did not exceed 105 A in these results, despite the motor being rated to 180 A peak/125 A continuous. This was because of the elevated case temperatures evident, which indicated that mechanical failure was likely at higher loads. Because of the air-cooled design of the motor, this was a significant limitation.

Figure 6 shows the three-dimensional efficiency map for the motor. The low-efficiency regions are a low-speed, high load conditions. The average efficiency is about 85% for the system, which includes power loss in the motor, controller, and mechanical losses. The manufacturer-rated power of the motor could not be reached during testing. Specifically, this was 12 kW continuous and 30 kW peak. However, the rated peak efficiency of 92% was demonstrated, and a peak efficiency of 95.4% was observed during testing. Rated peak torque of 90 N.m (stall) could not be observed, due to limitations of the apparatus. A maximum torque of 52.5 N.m was measured at 50 rpm. It is doubtful that the rated peak torque can be practically achieved due to mechanical limitations in the construction of the motor.

The test facilities at UTS that were used in this study are shown in Figure 7. They consist of an electric propulsion system, and a Horiba Schenck WT190 water-cooled eddy-current dynamometer. The motor is connected with dyno through a custom-machined companion flange and shaft adapter, as well as a GWB473-series Cardan shaft. An ABB DCS550 DC drive provides the DC power. The supply is capable of supplying up to 157.5 kW at 450 V DC. For testing constant-duty power levels, it was set to 96 V and up to 120 A. The test was controlled through the Horiba Schenck SPARC controller and the dashboard in ControlDesk.

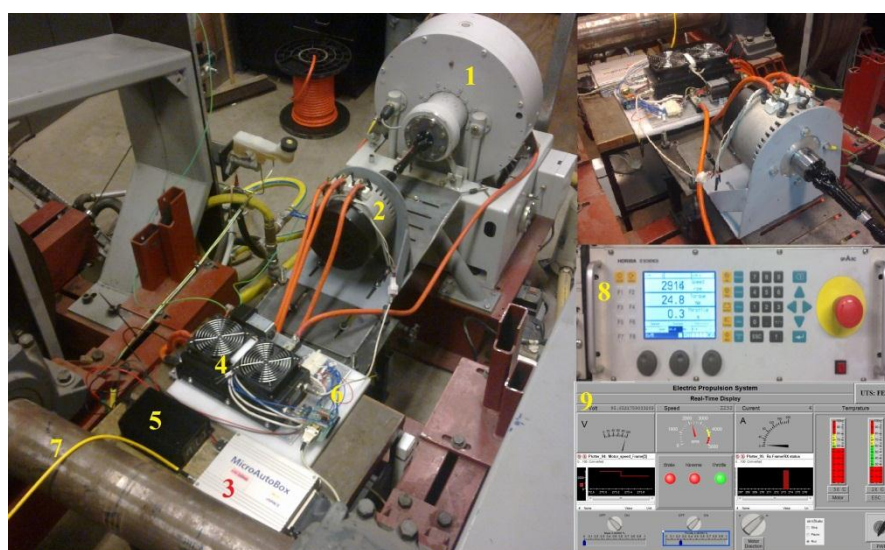


Figure 7: EPS test facility at UTS.

1-Dynamometer WT190. 2- Mars 0913 PMSM/BLDC. 3-MicroAutoBoxII. 4-KHB1260124. 5-Step-down 96 V/13.5 V. 6-Relays Board. 7-PC host interface. 8- SPARC control (Dyno stand controller). 9-Control Desk.

5.2 Testing results

The experimental validation procedure consisted of various steady state and transient tests ranging from maximum torque runs to the continuous power of the motor. Table 2 shows the results obtained for some of the tested parameters.

Our results show that maximum power of 9.8 kW was obtained in the region of 2600-3000 rpm. Figure 8 shows the maximum torque and power curve of the motor. Motor efficiency was calculated numerically as the output mechanical power of the motor divided by the AC power supplied to the motor by the controller. AC power was determined by multiplying the measured DC power supplied to the inverter by a fixed efficiency value of 98% [21].

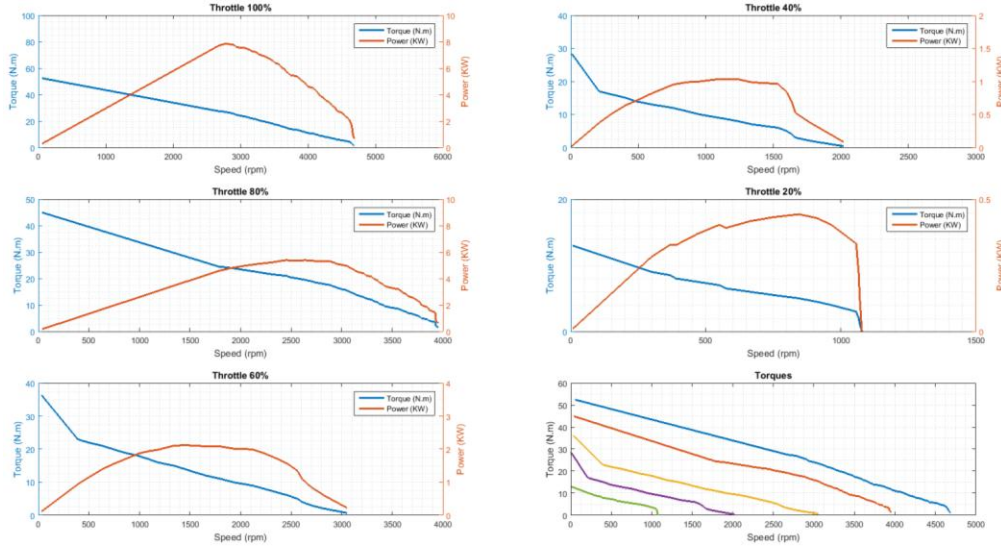


Figure 8: Torque and Power vs. Speed of the motor at different throttles.

5.3 Efficiency analysis

The mechanical power is the product of torque and speed of the motor Equation (6) was used to calculate the efficiency of electric motors directly (IEEE 112-B, CSA-390).

$$Motor\ Eff = \frac{Output\ mechanical\ power}{AC\ Input\ electrical\ power} \times 100\% \quad (6)$$

The average efficiency is 82%. Although our testing could not validate manufacturer claims, it shows that this motor can nevertheless meet our design target. The losses were not calculated individually, but can be classified as electrical losses, magnetic losses (core loss, iron power and copper loss), mechanical losses, and stray load losses, , previously investigated in [22], [23].

Table 2: EPS Validation Results

Peak Power	9.8 kW
Peak Torque	54 Nm
Continuous Power	8 kW @ 2800 rpm
Continuous Torque	28 Nm @ 2800 rpm
Continuous Power (2 minutes)	4 kW @ 4000 rpm
Continuous Torque (2 minutes)	10 Nm @ 4000 rpm
Peak Efficiency	95.4%

6 Motor-in-the-Loop

Hardware-in-the-loop (HIL) simulation is a standard step in a rapid control prototyping [24]. The system allows for the integration of the PM motor (the “hardware”) in a comprehensive virtual system. The facility comprises a real PM motor coupled to the accurate real-time driver, and virtual vehicle model simulated through the dynamometer. It is the basis for a broad range of HIL-testing functions. The simulation must capture the bi-directional interactions between its actual and virtual components in order to test a real system in simulation. Figure 9 summarizes the structure of a motor in the loop simulator. The setup uses a control unit and real-time tools (dSPACE) to ensure real-time simulation. Furthermore, the setup uses a fixed step-size integration routine within the Matlab Real-Time Workshop, to ensure that its virtual simulator is constantly in synch with real-time. In particular, the setup enables the rapid prototyping of different vehicle driveline options without installing actual componentry in the vehicle. It allows driveline model to command motor speed and measure torque through the dynamometer [25].

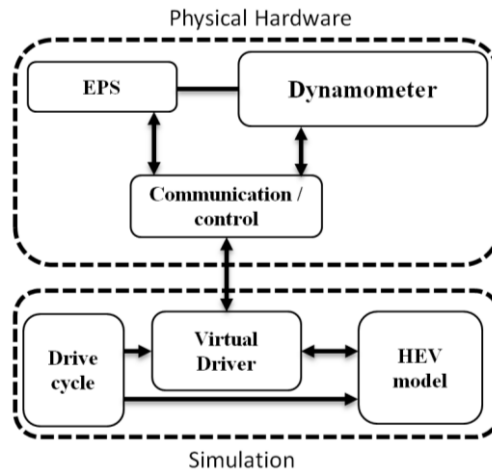


Figure 9: Motor in loop setup

In the case of our mild HEV hardware-in-loop setup, it is fully integrated, emulating the desired vehicle, drivetrain, and driver concurrently in real time [26]. The motor command comes from the power management module (Kelly controller) rather than directly from the virtual driver that is handled by MicroAutoBox II. To illustrate the use of the above setup for HIL system simulation, consider a drive cycle at the beginning of which the motor is idling, and the velocity is zero. As the target velocity starts to increase, the virtual driver within simulation recognizes the difference in demanded and actual motor velocities and increases the speed position appropriately. This speed position signal is passed to MicroAutoBox II and is processed into a signal that is sent to the motor through the Electronic Speed Control interface. The motor response to this signal by producing torque measured by the dynamometer. This torque value is then used as input to the simulation module capable of calculating the impact of the supplied torque on motor velocity. The updated motor velocity is subsequently translated to motor speed. The updated vehicle velocity is also provided to the driver, which again compares this value to the driving schedule and determines the speed position for the following step. During the experiment, the simulation runs in parallel with the hardware and communicates with MicroAutoBox II at a frequency of 1 MHz.

7 Conclusion

An experimental validation of the rated characteristics of a PMSM electric machine was conducted. The experimental validation used HIL techniques implemented on a dSpace MicroAutoBox II supervisory controller, which controlled a motor controller and, in turn, the PM motor. The HIL system was designed and implemented in the MATLAB/Simulink environment and transferred directly into dSpace ControlDesk. The rated torque and power characteristics could not be achieved in the current testing, although it was found that the motor could still achieve design parameters set for use in a Mild Hybrid Electric Vehicle. The motor exceeded the manufacturer-rated peak efficiency of 92%, achieving a peak efficiency of 95.4%.

The HIL technique with Motor-in-the-loop allows the same control setup to be used after validation for control of the motor when it is deployed in the prototype vehicle. Developing an HIL control system at this stage dramatically reduces the prototyping cycle time as no further design work is required for building a control environment within the prototype vehicle.

Acknowledgments

First, we would like to express our sincere gratitude to our supervisor, Prof. Nong Zhang. We also wish to express our thanks to the UTS – Green Energy Vehicle Innovations (GEVI) team, for their assistance throughout the completion of this paper.

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Authors



M. Awadallah received BSc Eng. degree in communications and electronics engineering from Modern Academy for engineering, Cairo, Egypt in 2006 and the Diploma in Embedded Systems from Information Technology Institute (ITI), Cairo, Egypt, in 2007. He is currently pursuing the PhD degree at University of Technology Sydney (UTS), Sydney, Australia. His research interests include has been involved in research in areas of hybrid and control of automotive systems.



Peter Tawadros received the B.E. degree in mechanical engineering from the University of Sydney, Australia, in 2007. He is currently a Manager, Mechanical Laboratories, School of Elec, Mech and Mechatronic Systems, UTS, and a PhD candidate at the same school. His research interests efficiency gains from the implementation of regenerative braking in hybrid electric vehicles (HEVs) as well as human-hybrid vehicles



Dr. Paul Walker is a Chancellors Postdoctoral Research Fellow at UTS, focusing research on innovative drivetrain and powertrain technologies. His current research includes dynamics and control of vehicle powertrains and development of novel hybrid and electric vehicle powertrain architectures, including design, integration and transient dynamic analysis.



Prof. Nong Zhang received the B.E. degree from the Northeastern University, Shenyang, China, in 1982, the M.E. degree from Shanghai Jiao Tong University, Shanghai, China, in 1984, and the Ph.D. degree from the University of Tokyo, Tokyo, Japan, in 1989. He has been with several prestigious universities in China, Japan, the United States, and Australia, respectively. In 1995, he joined the UTS, NSW, Australia, where he has been a Professor of mechanical engineering with the School of Electrical, Mechanical and Mechatronic Systems since 2009.