THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

Evaluation of a Mild-Hybrid Electric Combat Vehicle with Energy Management

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Abstract

The desire to reduce fuel consumption and gas emissions, along with increasing demands on electrical energy is driving the evolution of vehicle power system architectures well beyond the conventional single alternator and battery. Amongst the different power system architectures available, are mild-hybrid electric architectures. Such architectures may offer flexibility in balancing the trade-offs associated with minimising fuel consumption, and greater capacity to meet electric energy demands. They allow for a wide range of energy management strategies to be investigated. Such strategies are able to accommodate for the need to reduce fuel consumption, undesirable gas emissions, and the need to meet the increased dependence on electrical energy. The strategies can be implemented by vehicle power management systems running energy management algorithms. Such systems are becoming more common in commercial vehicles, however, they are not commonly found in current military vehicles. This thesis focusses on evaluating the impacts caused to vehicle acceleration, fuel consumption, the time to fully charge/discharge the vehicle battery pack, and the electrical conversion efficiency, when introducing energy management strategies into a baseline mild-hybrid electric combat vehicle under different military stationary and moving scenarios. The scenarios were selected because current vehicle manufacturers and academia have primarily focussed on investigating energy management strategies in urban environments. In comparison, a study involving military scenarios allows a new application domain to be investigated. The thesis describes the mild-hybrid electric combat vehicle baseline, and presents the results of comparing the baseline against one that has been extended to include additional energy management strategies under different military scenarios.

Statement of Declaration

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship

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Date: 18/10/2017

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List of Publications

[1] **M. Salazar**, and N. Ertugrul, “Potential Enhancements to Military Vehicle Power Management Systems”, *Australasian Universities Power Engineering Conference, AUPEC13*, Nov. 2013, Tasmania.

Acronyms

DAQ	Data Acquisition Unit
ICE	Internal Combustion Engine
ISG	Integrated Starter Generator
RPM	Revolutions per minute
VEPMS	Vehicle Electrical Power Management System

Chapter 1: Introduction

1.1 Background

It is estimated that there are over one billion internal combustion engine vehicles currently in operation around the world [1], with a forecasted 3% compound growth rate each year [1]. Such vehicles consume fuel based from oil, and it is estimated that 48 million barrels of oil per day are consumed globally [2]. When this fuel is combusted an estimated 10 billion tonnes of carbon dioxide emissions are emitted per year [2]. Reducing fuel consumption is desirable for fuel cost savings, delays in reaching peak oil, and reductions of undesirable carbon dioxide emissions [3]. The challenge to reduce fuel consumption and carbon emissions has motivated countries to set vehicle fuel consumption and carbon dioxide emission targets for vehicle manufacturers to meet by 2020 and beyond [4][5][6]. Consequently, this trend is shaping the evolution of vehicle power systems.

Another trend influencing the evolution of vehicle power systems is the increasing integration of new electronic technology into modern vehicles, causing an increasing demand for electrical energy [7]. Modern vehicles are being equipped with a variety of electronic devices and a large amount of their mechanical functionality has been replaced with electro-mechanical systems [8]. Part of this growth is the need and desire for enhanced functionality, improved precision, autonomy and control [8][9].

In response to the observed trends regarding the increase in vehicle fuel and electrical energy consumption, alternative vehicle power system architectures are evolving beyond conventional ones that included a single alternator and battery [7][8][9]. Alternatives include architectures based on 42V DC power systems [7][8], those with multiple voltage levels [10], dual alternators and batteries [11], or those which make use of multiple power sources and loads [11]. In addition there are more electric vehicle architectures including series, parallel and mixed micro, mild, or full hybrid electric vehicles, plug-in hybrid electric vehicles, fuel cell vehicles, and battery electric vehicles [12].

Amongst the different power system architectures available, the hybrid electric vehicle architecture is one that offers good flexibility in balancing the trade-offs associated with minimising fuel consumption, limitations of battery capacity for propulsion, and greater capacity to meet electric energy demands. Furthermore they do not require the electrical grid for charging batteries in comparison to electric vehicles and plug-in hybrid electric vehicles.

Furthermore, hybrid electric vehicles allow for a wide range of energy management strategies to be investigated [14]. They are able to support energy management strategies such as: motor assist, stop/start, and regenerative braking [14]. Additional strategies include load shedding, load starting and shutdown sequencing, monitoring safe operating bounds, optimal selection of power sources, minimising electrical usage, and energy storage charge/discharge control [15]. Such strategies are able to accommodate for the need to reduce fuel consumption, undesirable gas emissions, and the need to meet the increased dependence on electrical energy. The strategies can be implemented by vehicle power management systems running energy management algorithms [13]. Such systems are becoming more common in the commercial sector through vehicle manufacturers [13], however, they are not commonly found in current military vehicles [16].

This thesis focuses on investigating energy management strategies applied to a hybrid electric architecture, using a case study. The case study involves investigating a military vehicle that includes a mild-parallel-hybrid power system. This case study has been selected because current vehicle manufacturers and academia have primarily focussed on investigating hybrid electric vehicle power management strategies in urban environments [16]. In comparison, a case study involving a military off-road environment allows a new application domain to be investigated [16].

The thesis describes the case study, and presents the results of comparing a baseline architecture against one that has been extended to include additional energy management strategies. The case study provides further insights into assessing the benefits of implementing energy management strategies to mission endurance. Furthermore, the results also contribute towards the development of energy management algorithms.

1.2 Thesis Overview

Chapter 1 gives an introduction into the area of vehicle power system architectures with energy management, and introduces the study for the thesis.

Chapter 2 describes the operating environment considered for the thesis study

Chapter 3 discusses a mild hybrid electrical combat vehicle model to evaluate energy management strategies.

Chapter 4 discusses a vehicle power management system model required to implement energy management algorithms in a mild hybrid electric combat vehicle.

Chapter 5 discusses the experimental environment used to evaluate vehicle power management system architectures with energy management.

Chapter 6 discusses the results of evaluating a baseline combat vehicle extended with additional energy management strategies.

Chapter 7 presents the conclusions reached from the study and offers recommendations for future work in the research field.

Chapter 2: The Operating Environment

2.1 Background

The research study investigates the impacts of energy management strategies to vehicle acceleration, electrical conversion efficiency, fuel consumption, and battery charging/discharging times, in a mild hybrid electric combat vehicle under different military operating scenarios and constraints.

In military scenarios a combat vehicle interacts and responds to changes in its environment based on the mission tasks, the weather, the terrain characteristics, the commander's intent and driver behavior, and the threats encountered in the battle space [17].

A generic military vehicle operation scenario involves the following sequence of events [18]:

- Mission objectives are received by the vehicle fleet commander,
- The commander decides how the mission will be completed by identifying the mission tasks required,
- The commander decides what vehicles, equipment, personnel and resources are needed to complete the mission tasks and delegate's them to sub-ordinates,

- The commander’s sub-ordinates operate the vehicle to execute the assigned mission tasks and they adapt accordingly to event ‘e’ occurring in the battle space which requires task ‘t’ to be completed using equipment ‘i’ for time duration ‘d’.

In order to abstract the amount of variations encountered in the above scenario the following profiles are defined for all military vehicle operation scenarios:

- Speed and Acceleration Profiles
- Terrain Incline Profiles
- Electrical Loading Profiles

Defining only these profiles accommodates modelling the variations that may arise from executing the mission with respect to variations in the terrain, and driver behaviour in accelerating and decelerating the vehicle, and the variations in the way electrical loads are used in response to events in the environment and the battle space. A sub-set of profiles are selected from all possible variations that could occur in the generic scenario described above. The profile selections are based on arbitrarily selected vehicle mobility constraints and military performance requirements and specifications. These profiles including weather and environmental conditions are given in the following sections.

2.2 Weather and Environmental Conditions

The operating environment is assumed constant. The relevant parameters used are given in Table 1:

Table 1 Environmental constants

Vehicle Head Wind	0.1 m/s
Vehicle Coefficient of Drag	0.55 Ns^2/m^2
Density of air	1.2kg/m^3
Acceleration due to gravity	9.81 m/s^2

2.3 Speed and Acceleration Profiles

The range of vehicle speeds and accelerations chose for scenario generation are constrained to vehicle performance and specifications and are given in Table 2:

Table 2 Speed and acceleration profiles

Speeds (km/hr)	0, 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 65, 70, 80, 100, 110, 120
Accelerations (m/s^2)	0.8547, 0.9547, 1.0547, 1.1547, 1.2547, 1.3547

2.4 Terrain Incline Profiles

A combat vehicle is required to operate over both urban and cross country roads. Cross country roads may encounter fording conditions, and gradients. Rough courses may extend from 6 to 7 km per day. They also need to traverse through several types of obstacles such as vegetation features, sand banks, fording through puddles or creeks. Such terrain complexities can be modelled by varying the coefficient of friction. Terra-mechanic behaviours involving wheel and terrain interactions can also affect the coefficient of friction. However, for the purpose of this study the terrain is assumed to be a smooth surface to produce no slippage with a constant friction of coefficient. The terrain is characterised by a gradient/incline and a coefficient of friction.

Table 3 Terrain profiles

Incline (degrees)	-30, -26, -21, -15, -12, -10, -5, -2, 0, 2, 5, 10, 12, 15, 21, 26, 30
Coefficient of Friction	0.0136

2.5 Electrical Load Profiles

The electrical current levels have been determined based on experimental measurements. A representative military vehicle was used to measure the current consumed by combat vehicle loads. The measurements were obtained by using a data acquisition unit with voltage and current transducers measuring the voltage and current of the vehicle battery’s terminals.

Different power levels for each of the electrical loads are also considered and classified as low, medium or high. The loads are grouped depending on their application during defined events. The load groupings are shown in Table 4.

Table 4 Electrical load categories

Defined Event (including load intensity scale)	**Load group description applicable to the defined event**
Rain (low or high)	These are electrical loads that may be turned on during raining conditions.
Cold (low or high)	These are electrical loads that may be turned on during cold weather conditions.
Hot (low or high)	These are electrical loads that may be turned on during hot weather conditions.
Light mission loads (low, medium, high)	These are electrical loads that may be turned on when a mission requires a passive stance such as surveillance, or reconnaissance
Heavy mission loads (low, medium, high)	These are electrical loads that may be turned on when a mission requires an aggressive stance such as close mounted combat, or electronic warfare.
Moving current offset	This is the estimated average current level that applies when the vehicle is in motion
Stationary current offset	This is the measured average current level that applies when the vehicle is stationary and not being operated

To select a set of discrete electrical loading conditions in the simulation, a random on/off profile is created for each of the loads in a particular group. Then the total current for each group is calculated. Selected load group combinations are chosen at random and then added to produce the total current loading condition.

The selected load group combinations to choose from are shown in Table 5:

Table 5 Load Group Combination Cases

Case Number	Loading Conditions
1.	hot
2.	cold
3.	rain
4.	cold + rain
5.	hot + rain
6.	night
7.	night + cold
8.	night + hot
9.	cold + rain + night
10.	hot + rain + night
11.	night + cold + missionLightLow
12.	night + cold + missionLightMedium
13.	night + hot + missionLightLow
14.	night + hot + missionLightMedium
15.	cold + rain + night + missionLightLow
16.	cold + rain + night + missionLightMedium
17.	hot + rain + night + missionLightLow
18.	hot + rain + night + missionLightMedium
19.	cold + rain + night + missionHeavyLow
20.	hot + rain + night + missionHeavyMedium
21.	cold + rain + night + missionHeavyMedium
22.	hot + rain + night + missionHeavyHigh

The random electrical load selection process is repeated for an arbitrary large number of times, currently it is 10,000 times. This simulates different current consumption scenarios that could be encountered depending on environmental, missions and battle space condition variations.

An offset is then applied to each power level for moving or stationary scenarios. The statistical results of the simulation are shown in Figure 1 and Figure 2.

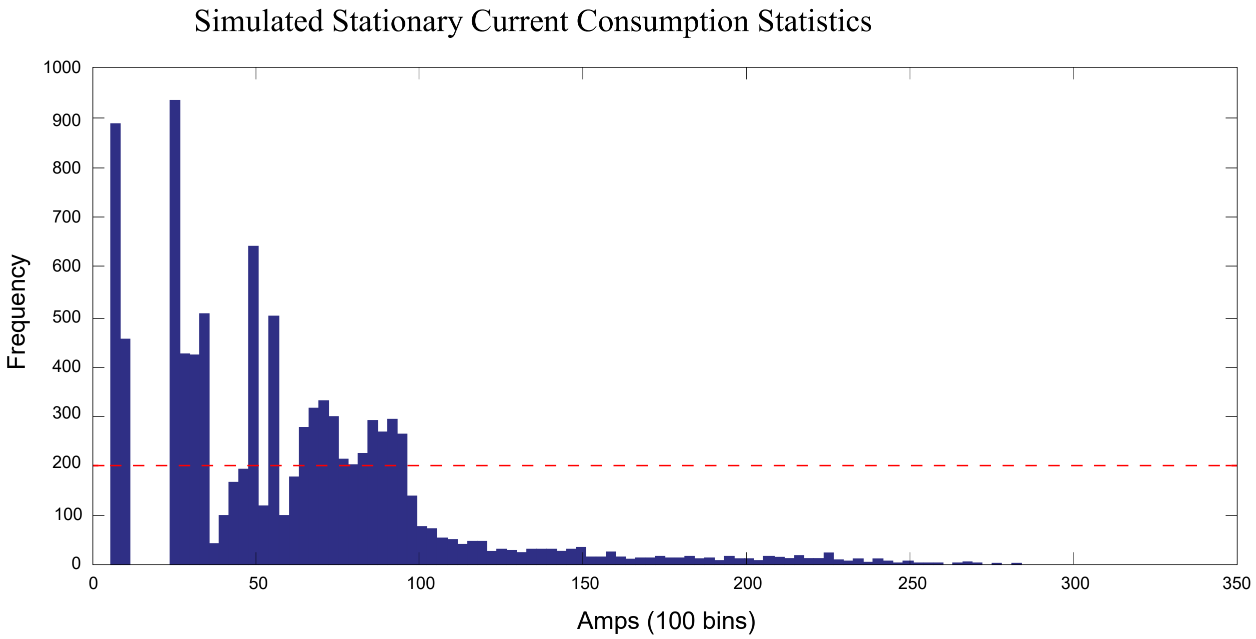


Figure 1 Statistics of current consumptions for stationary scenarios

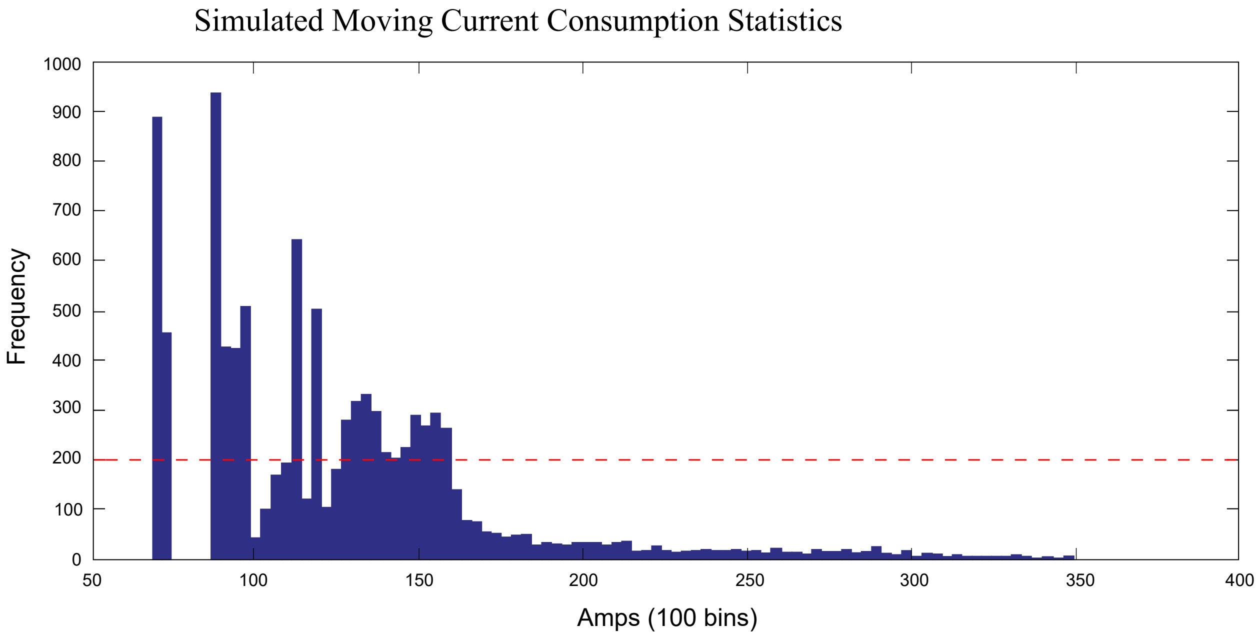


Figure 2 Statistics of current consumption in moving scenarios

A histogram with a bin size of 100 is included in Figure 1. The histogram shows the distribution of current consumption levels across the 10,000 random scenarios. The histogram approximates the statistical distribution across the random scenarios, and serves as a means to select suitable electrical loading levels. Similarly, Figure 2 is also a histogram, the main variation between Figure 1 and Figure 2 is the addition of a constant current load associated with the vehicle engine being turned on.

Based on Figure 1 and Figure 2, it can be seen that some current consumption levels occur more frequently than others. For the purpose of this study only the centre values of the bins with a frequency of 200 times or more (i.e. those above the red dash line shown in the figures) are selected as the current consumption levels for scenario generation, and are given in Table 6:

Table 6 Current consumption load levels used in the simulation study

Current Levels of Stationary Cases (A):	3.51, 5.09, 6.67, 8.25, 11.4, 14.6, 17.7, 19.3, 20.9, 24.1, 27.2, 28.8, 30.4, 33.5, 36.7, 39.9, 41.4, 43, 44.6, 46.2, 90.5, 92, 93.6, 95.2, 96.8
Current Levels of Moving Cases (A):	3.51, 11.4, 24.1, 36.7, 46.2, 67.3, 70.5, 75.2, 78.4, 83.1, 86.3, 92.6, 95.8, 101, 104, 107, 115, 124, 135, 156, 159

Chapter 3: Mild Hybrid Electric Combat Vehicle Model

3.1 Background

This chapter discusses a model for a mild hybrid electric combat vehicle. The model is used to investigate the impact of implementing energy management strategies on vehicle acceleration, electrical conversion efficiency, fuel consumption and charging/discharging times, under different military scenarios. The model includes the following eight main components:

- Diesel Internal Combustion Engine
- Auto Transmission and Drive Train (6 speed)
- Integrated Starter Generator (ISG)
- Converters (Bi-directional inverter and bi-directional DC/DC converter)
- Battery packs (two connected in parallel, each consists of 2x12 Volts 65Ah Lithium Ion Batteries connected in series)
- Diesel Fuel Cell
- Vehicle Power Management System

The vehicle being modelled is an aspirational vehicle that intends to extend the functionality of an existing prototype being proposed for use within the Australian Army. Therefore, the modification proposed in the model includes allowing the vehicle power management system to support control and optimisation algorithms that implement energy management strategies including start/stop, electric motor assist, including hybrid and pure electric drive, regenerative braking, and electrical load shedding. Note that such strategies are already implemented in commercial hybrid electric vehicles, and they are becoming more common in the commercial sector. Given that the defence sector is influenced and becoming more reliant on vehicle developments in the commercial sector, hybrid electric vehicles may become contenders in future Australian military vehicle acquisition projects [16][19][20]. Such vehicles also have several benefits relevant to military scenarios in regards to lowering fuel consumption, improving torque and acceleration, accommodating increased electrical load capacity, fast battery charging, silent mobility and extending silent watch operations [19][20].

The main focus of the thesis study is on the energy management strategies and not on detailed vehicle models. For this reason the sub-components of the vehicle are modelled to a level of fidelity as determined by quasi-static steady state look up tables. This is a common method used amongst the literature for the study of energy management strategies for hybrid electric vehicles [14]. Therefore, the vehicle being modelled includes sub-components currently available in the market. A top view of the vehicle is shown in Figure 3.

3.2 Mild-Hybrid Electric Combat Vehicle Model

The model is a hypothetical vehicle and most of its sub-components with the exception of the clutch, vehicle power management system, batteries and fuel cell are based on components found in a prototype combat vehicle being considered for use within the Australian Army. The vehicle power train topology modeled is represented in Figure 3. The vehicle power management system is not shown in Figure 3 and will be discussed later in Chapter 4.

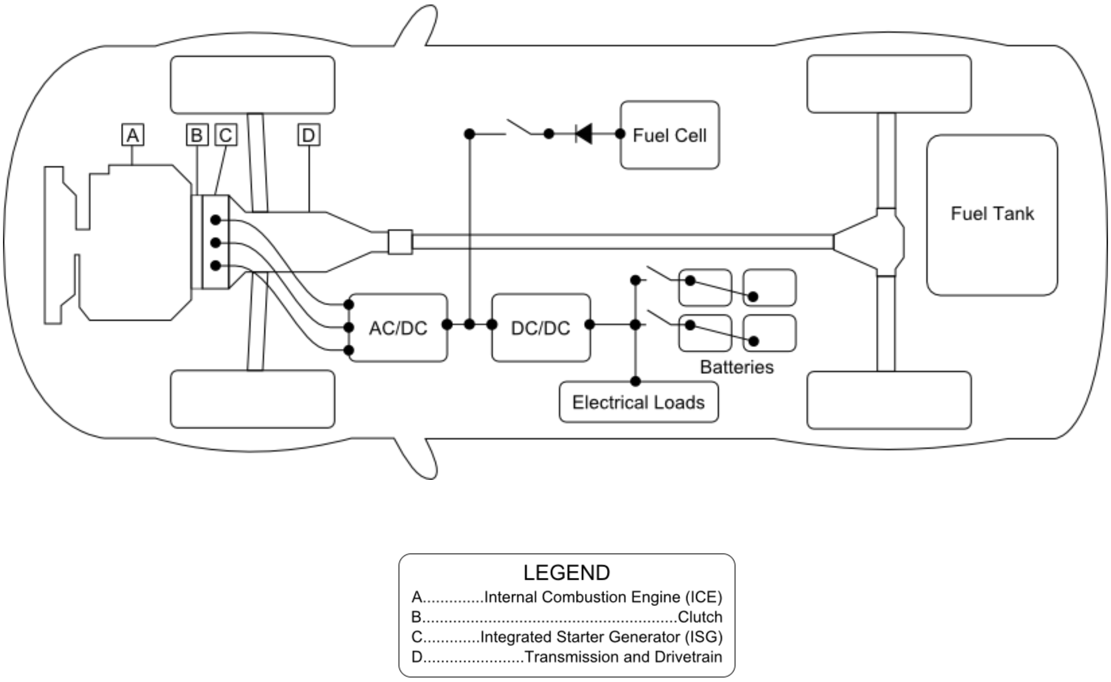


Figure 3 Mild-hybrid electric combat vehicle power system architecture

As it is well known, a vehicle includes thermal, mechanical, hydraulic, pneumatic, electrical and electronic components. It is a multi-domain dynamic system which operates under certain environmental conditions and operational scenarios [17]. Ideally the model of a vehicle should accurately predict both the transients and steady state conditions of the vehicle dynamics. In addition, the model should also capture aging, degradation effects and the ability to inject faults. However, to reduce mathematical complexity and computational power, the models are of low to medium fidelity. In this study, the vehicle is modeled as a moving mass, with a constant aerodynamic drag coefficient, and friction coefficient between the wheel and terrain. The elevation of the terrain is considered and the vehicle dynamics is modelled considering only the longitudinal forces due to propulsion, vehicle mass with equivalent rotational inertia, friction, gravity, and wind and air resistance.

3.2.1 Wheels and Vehicle Chassis

The wheel characteristics can have a considerable impact to fuel consumption which can be attributed to the following effects [22]:

- wheel vibration
- wheel deformation
- wheel to ground surface effects due to terra-mechanic effects
- wheel turning

- slippage
- tyre pressure variations
- spinning air drag
- braking dynamics

However, to simplify the experiment and keep the experiment controlled, and focused on only energy management strategies, the wheel parameters are restricted to the wheel radius and rotational inertia and these are assumed constant.

The wheel radius is obtained from manufacturer's data [23]. Inertia effects due to wheel rotation are included in a rotational inertia mass factor applied to the weight of the vehicle. The vehicle wheels are assumed to travel straight in leveled terrain with only vehicle pitch considered.

The following vehicle parameters are used in the model which is based on common parameters of a representative prototype combat vehicle.

Table 7 Vehicle wheel and chassis parameters

Vehicle Parameter	**Values**
Vehicle Mass	10500 kg
Rotational Inertial Bulk Mass Factor	1.06
Vehicle Width	2.4 m
Vehicle Height	2.269 m
Wheel Diameter	1145.2 mm

3.2.2 Internal Combustion Engine (ICE)

The diesel ICE has been selected because this is a common power source for 4WD off-road vehicles, prime mover trucks, and military vehicles [24]. The engine modeled is a 3.2 liter six cylinder turbo charged diesel engine. The model is based on manufacturer data specifications regarding the mechanical power, torque and fuel consumption with respect to the output engine speed [24]. The characteristics shown in Figure 4 are used to model the diesel engine.

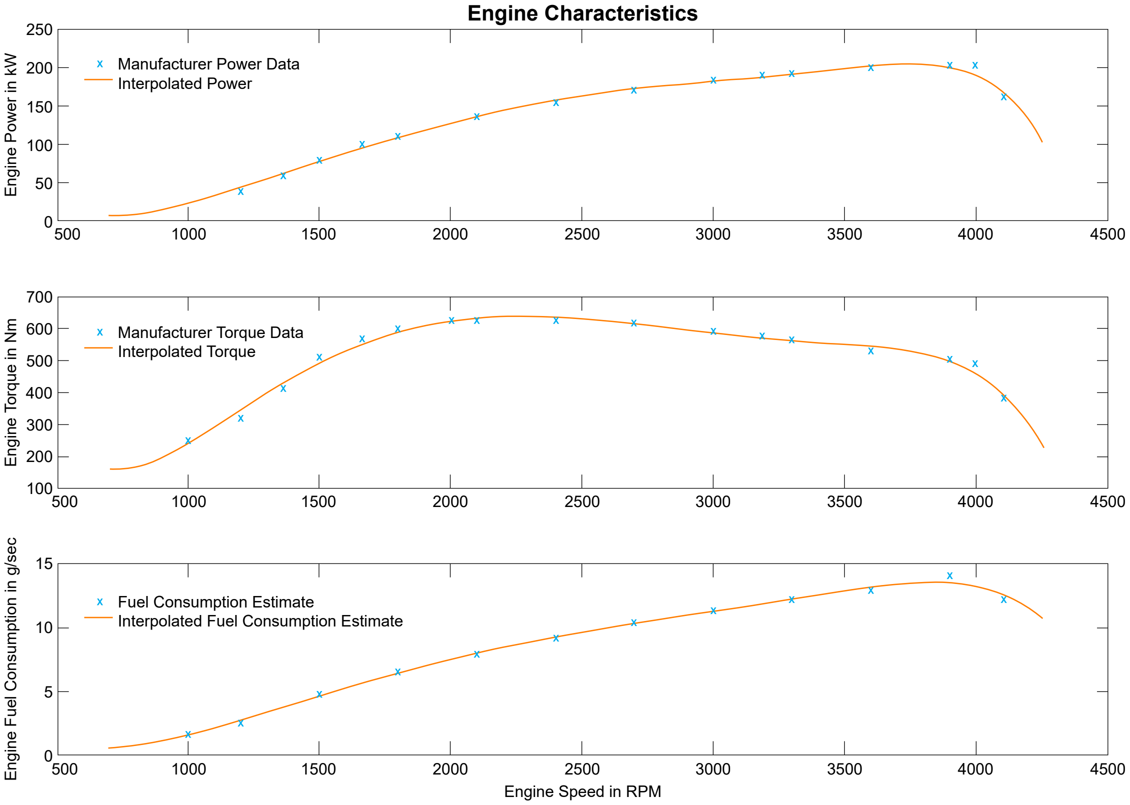


Figure 4 Internal combustion engine characteristics used in the model

Figure 4 displays three charts. Reading from top to bottom, the charts represent values for the engine power, torque, and the fuel consumption that result when the engine is rotating at different speeds. The data points for the power and torque charts are extracted from manufacturer data, these data points are seen as blue crosses. New points are then interpolated based on the manufacturer's data points and form the orange curve. The data points for the fuel consumption chart are estimated from manufacturer data, these points are seen as blue crosses, and these are interpolated to produce the cubic spline curve, shown in orange, which is fitted through the interpolated points for each chart. The range of the interpolated points is chosen to align to the speed range of the ISG. The range alignment allows using the interpolated points as a quasi-static look up table in order to find the overall power and torque contribution resulting from different rotational speeds of the ICE and ISG.

3.2.3 Clutch Model

The clutch shown in Figure 3 is modeled as an ideal clutch, hence there is no system lag, vibration, or slippage and assumes 100% mechanical transfer efficiency.

3.2.4 Integrated Starter Generator (ISG)

An ISG is an electrical machine that is able to function as a generator to produce electricity and also as a motor. The ISG is integrated between the engine and the automatic transmission as shown in Figure 3.

An ISG may produce in excess of 50kW which is sufficient for the projected future electric energy demands of military vehicle functions, which in addition to automotive electrical loads may include combat mission loads such as high speed turrets, radar and laser sensors, and support for export power by providing mobile power for tactical electric grids, and as a re-charging station for soldier mobile devices [19][20]. The ISG offers additional benefits to support energy management strategies including stop/start, electric motor assist, and regenerative braking [16][20].

In addition, an ISG offers improved energy storage charging through regenerative braking, and may provide faster battery charging, and electric propulsion which is beneficial to reduce sound levels in a military environment and reduce fuel consumption [17][19].

The ISG model used in this study is based on manufacturer data specifications (see Figure 5) regarding the mechanical power, torque and DC electrical power generated with respect to rotational speed [25]. These characteristics are used to estimate generation and motoring efficiencies in the model.

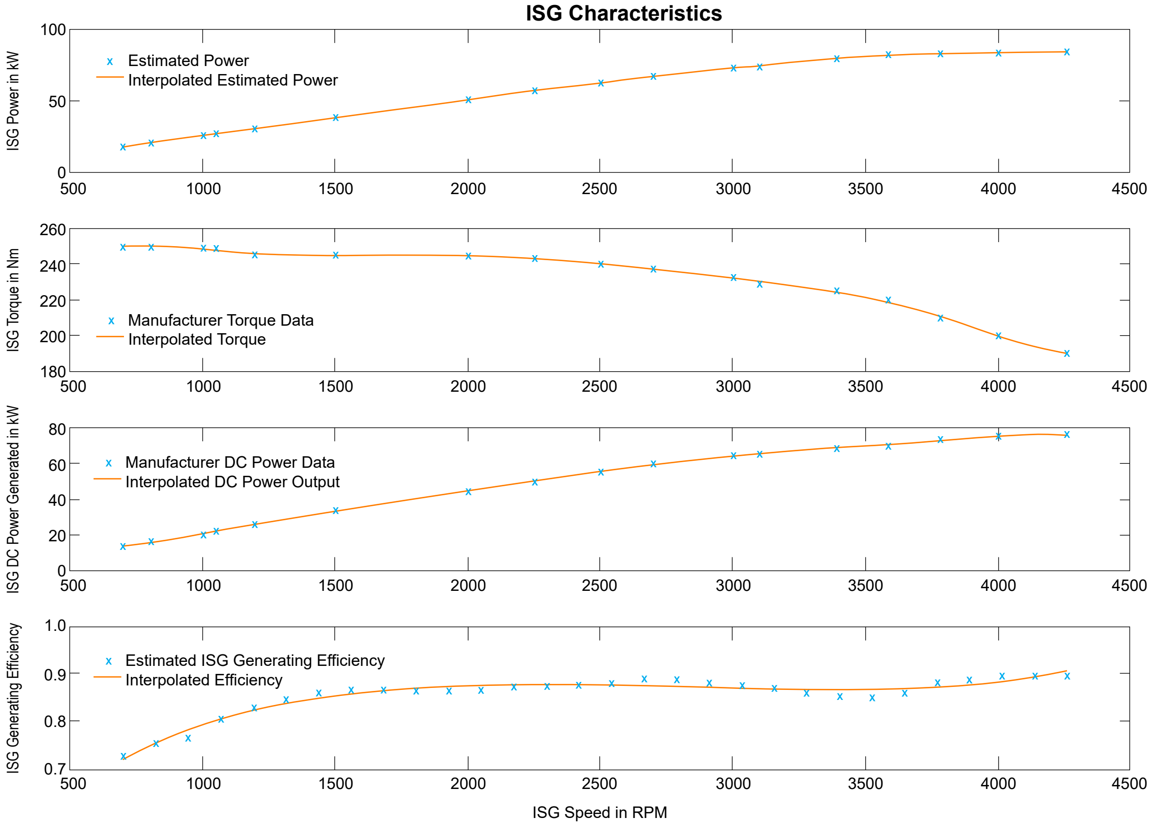


Figure 5 Integrated Starter Generator model curves

Figure 5 displays four charts. From top to bottom, the first chart is the ISG motoring power generated across different rotational speeds. The blue crosses are estimates of the motoring power based on manufacturer data. A cubic spline curve, shown in orange, is fitted through these points. The second chart is the ISG motoring torque generated across different rotational speeds. The blue crosses are data points extracted from manufacturer data, and fitted with a cubic spline curve shown in orange. The third chart is the DC power generated by the ISG across different rotational speeds, similarly to the second chart the blue points are data points extracted from manufacturer data and fitted with a cubic spline curve shown in orange. The fourth chart is an estimation of the efficiency of the ISG in converting mechanical to electrical power. The estimates are calculated based on manufacturer data and are shown as blue crosses, and have been fitted with a cubic spline shown in orange. It should be noted that the starting characteristics are not included in the model. However, since the starting power can be significant in vehicles, the starting power required was determined experimentally using a handheld Yokogawa data acquisition unit with voltage and current transducers attached to the battery terminals of a vehicle representative to the one being modelled. The chart below displays the measured starting electrical power calculated based on voltage and current sensor readings.

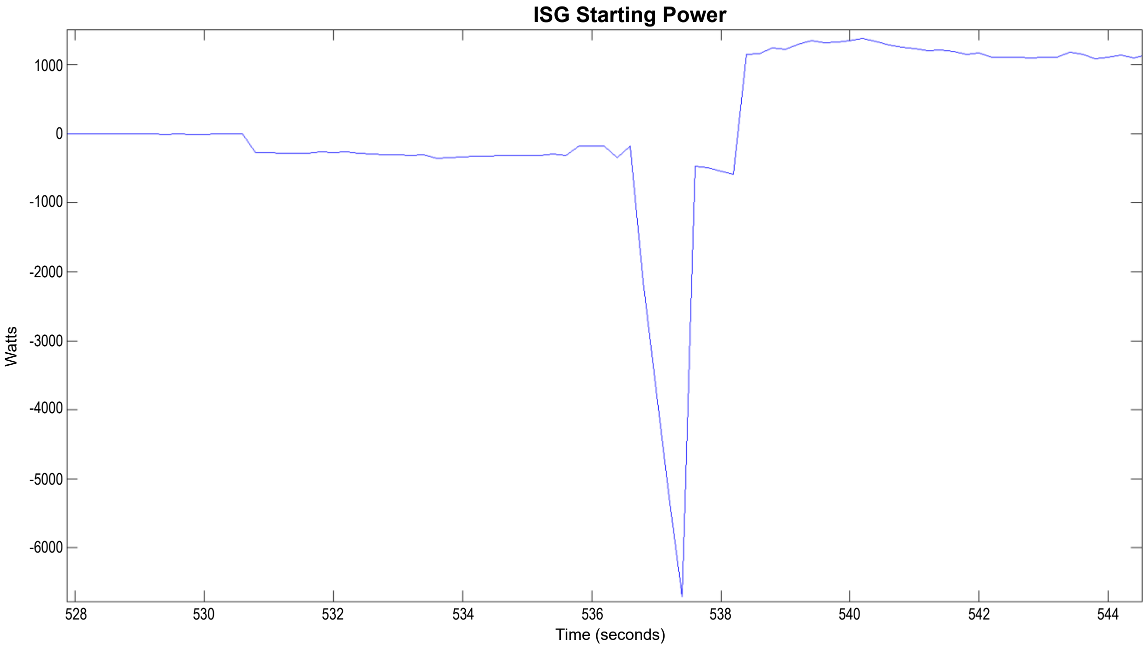


Figure 6 Starting electrical load consumption

3.2.5 Fuel Cell

The diesel fuel cell is selected to provide charging during silent watch and extend silent watch endurance. The fuel cell is modeled based on the following characteristic curves obtained from the literature [26]. A fuel cell can extend silent watch operations, and allow charging the batteries whilst the vehicle is off, after usage.

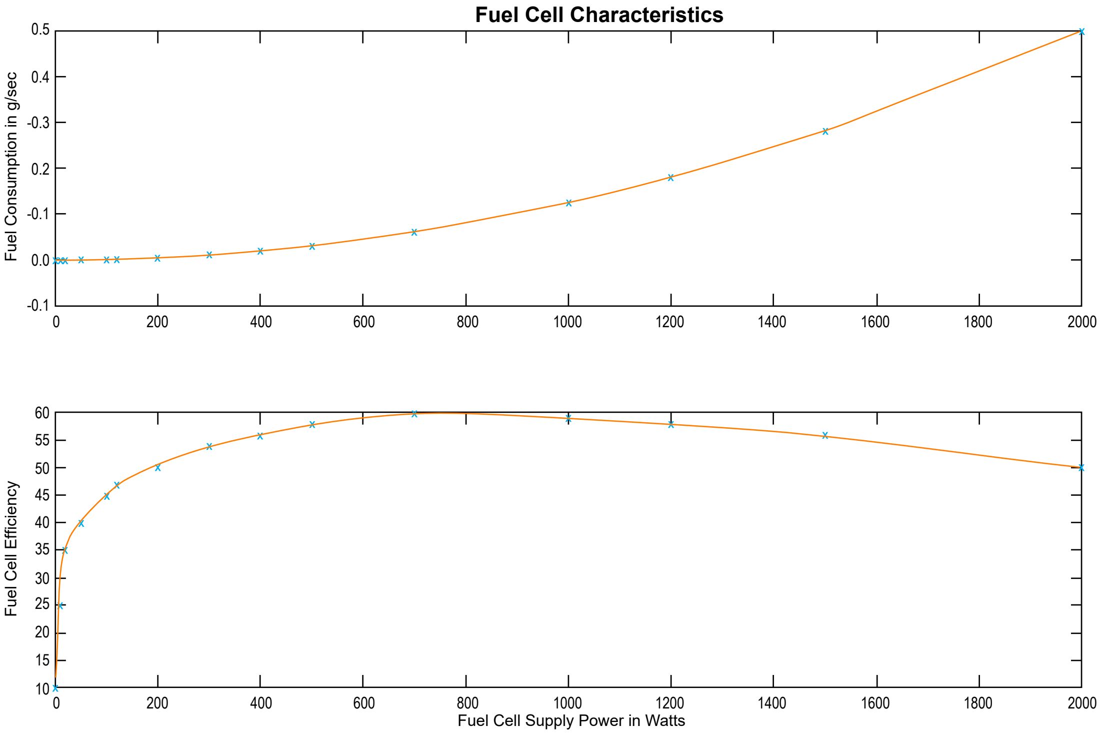


Figure 7 Fuel cell model curves

Figure 7 shows two charts. The first chart shows the fuel consumption of the fuel cell across different electrical loads. The blue crosses are data points extracted from a representative fuel cell referred to in the literature [26]. The points have been fitted with a cubic spline curve shown in orange. The second chart shows the fuel to electrical power conversion efficiency across different electrical loads. Similarly to the first chart the blue crosses are extracted from the literature [26], and fitted with a cubic spline curve shown in orange.

3.2.6 Transmission and Drive-train

The transmission and drive-train includes a 6-speed automatic transmission, transfer case, cross drive and final drive differential. The transmission and drive-train is modeled as an ideal gearing system with no slippage, vibration effects and with 100% mechanical power transfer efficiency. The following specifications are based on manufacturer gear ratios for each of the components included in the transmission and drive-train.

Table 8 Transmission Model Parameters

Gears	**Gearing Ratios [27]**
1st	4.17
2nd	2.34
3rd	1.52
4th	1.14
5th	0.87
6th	0.69
Transfer Case High Range	1.075
Transfer Case Low Range	1.916
Cross Drive	1.083
Final Drive Differential	2.105
Total Transmission Power Efficiency	100%

The model takes into account rotational inertia through a bulk mass factor applied to the vehicle mass.

3.2.7 Converters

The bi-directional inverter allows for the ISG to be used as a generator and a motor. It also provides the ability to supply export power when required. The export power scenario however will not be explored in this study. Most electrical loads in military vehicles require a DC power source. Hence, the inverter provides the AC to DC conversion needed to power the vehicle’s DC electrical loads. The bi-directional inverter and DC/DC converter offer opportunities for electrical motoring, motor assist, stop/start, regenerative braking, improved battery charging and improved DC bus voltage regulation.

3.2.7.1 Bi-directional AC/DC Converter

The AC/DC converter is modelled as a power conversion process. The efficiency of the AC/DC converter is bulked together with the ISG efficiency and it is referred to in Figure 5. It is common for electrical efficiencies to be very close in value for both generation and motoring, as such; the efficiency from Figure 5 is assumed to be the same for both generation and motoring.

3.2.7.2 Bi-directional DC/DC Converter

The DC/DC converter is modelled as a power conversion processe with their respective conversion efficiencies shown in Table 9. The efficiencies correspond to different current flows during generation and motoring.

Table 9 DC/DC Average Converter Efficiencies

Motoring	83.82%
Generation	91.22%

3.2.8 Battery Model

In the battery model a 12 Volt 65Ah (C/20) Lithium Ion battery [31] is used, which was equipped with a Yokogawa data acquisition unit (DAQ) [32] with current and voltage transducers connected to its terminals. The DAQ measured the voltage and current readings as the battery was discharged at different rates using an Elektro-Automatik programmable load [30]. The time to discharge the battery was also measured. The battery was charged using a dedicated battery charger after each discharge. These measurements were used to derive a model for the vehicle’s battery pack.

The modelled battery pack consists of two battery packs in parallel. Each pack has two 12 Volt 65Ah (C/20) Lithium Ion batteries in series. The model relates voltage as a function of discharge/charge current and time to discharge/charge. The charge model assumes the charging time is the same as the discharge time for a particular discharge rate. A flat battery is defined when the battery reaches 20.1 Volts, and to be fully battery when it reaches 24 Volts.

Discharge Characteristics

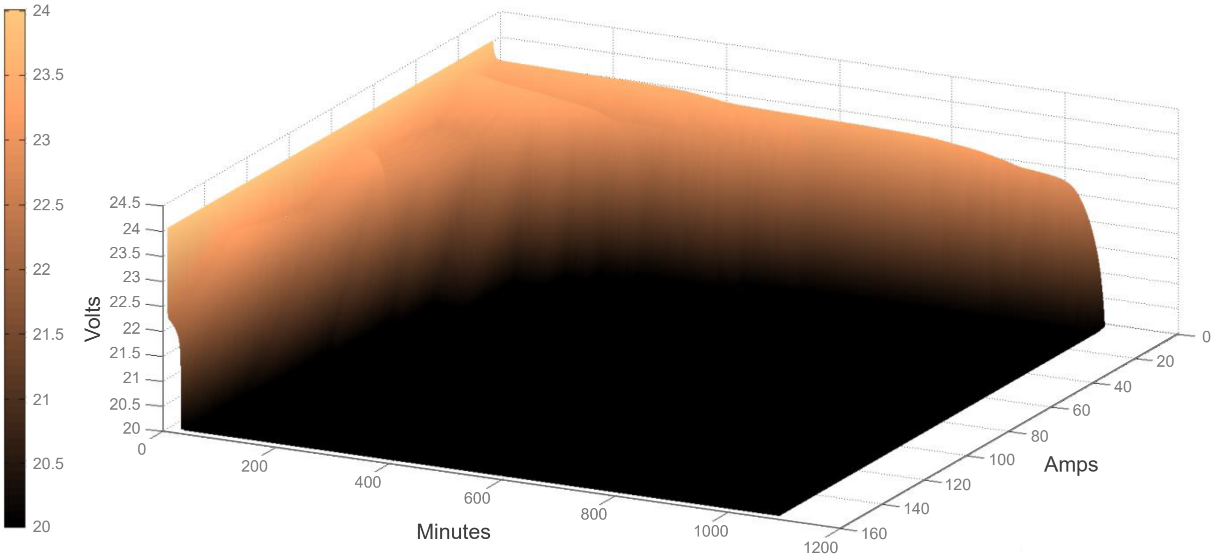


Figure 8 Battery pack discharge model

Figure 8 shows an interpolated 3D surface which approximates the battery pack's voltage as a function of discharge time and discharge current. The colour represents the voltage level of the battery back at a particular time for a particular current load. The brightest orange colour represents the maximum voltage of the battery, and the darkest colour represents the voltage of a flat battery pack i.e. 20.1 Volts. The 3D surface is used to estimate the discharge time taken for the battery pack to drop from being fully charged to flat, across different loading conditions when the engine is off. The estimate is done by interpolating the 3D surface to find the discharge time corresponding to a particular discharge current when the battery has dropped voltage from 24 Volts to 20.1 Volts.

Charging Characteristics

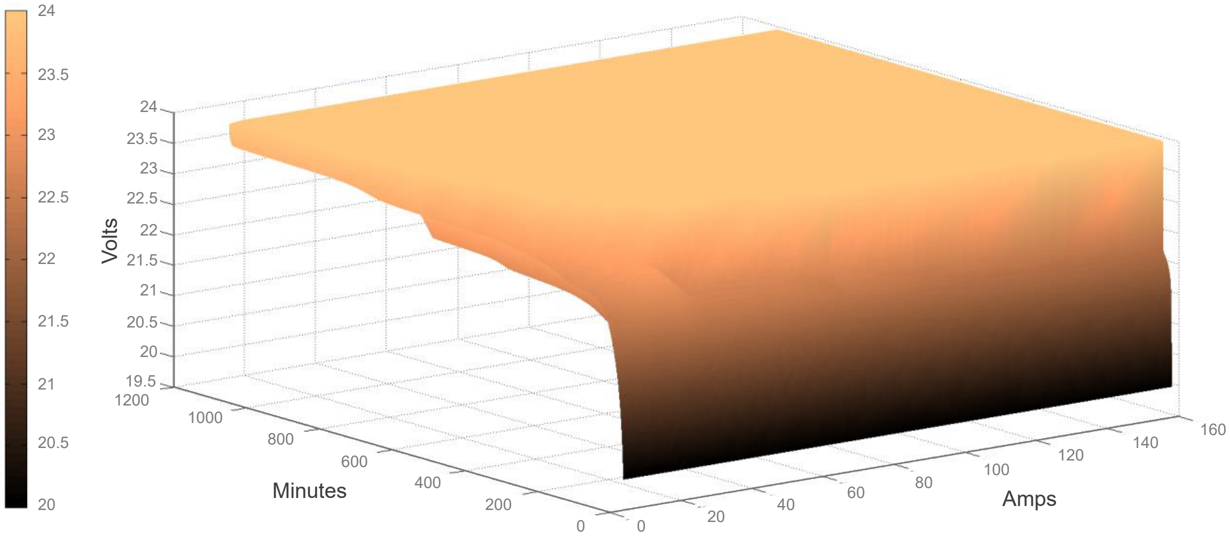


Figure 9 Battery pack charge model

Figure 9 is similar to Figure 8; however, it shows an interpolated 3D surface which approximates the voltage as a function of charging current and charging time. The 3D surface is used to estimate the charge time taken for the battery pack to reach a fully charged state from being fully flat, whilst the engine is off, and the fuel cell is providing 2kW of constant charging power, and experiencing different vehicle current loading conditions. The charge time is estimated by interpolating the 3D surface to find the charge time corresponding to a particular charge current when the battery has increased voltage from 20.1 Volts to 24 Volts.

Chapter 4: Power Management System Model of the Vehicle

4.1 Background

The vehicle described in Chapter 3 can be used to implement energy management strategies as observed in commercial mild hybrid electric vehicles. Due to the mobile nature of the system, the energy management strategies of such vehicles primarily aim to lower fuel consumption [33]. Other aims may include lowering carbon and toxic gas emissions, increasing provisions for electrical energy and torque assist. These aims are also useful for military vehicles [19][20].

An important aim for military applications is also to improve mission endurance. Mission endurance can be attributed to energy management strategies that achieve a good trade-off between depleting the energy capacity of fuel based power sources and electrical energy based power sources. The remaining capacity of such power sources gives an indication of mission endurance. There are other aspects that affect mission endurance such as the amount of time spent troubleshooting, repairing or maintaining the vehicle and its sub-systems, or the amount of time required to re-fuel a vehicle, and replace or re-charge vehicle batteries. Other benefits of introducing energy management strategies in military applications is extending silent watch mission and improving stealth by using silent mobility [20].

The energy management strategies in such vehicles are commonly implemented by a vehicle power management system running energy management algorithms, aimed at managing two main modes of operation: charge depletion and charge sustaining mode [34].

During charge depletion mode the following energy management strategies are applicable: load shedding, power source selection, stop/start, and motor assist with limited electric motoring [34]. In addition, during charge sustaining mode the following three energy management strategies are applicable: power source selection, load shedding and regenerative braking. This study primarily investigates the impact of these energy management strategies to vehicle acceleration, electrical conversion efficiency, fuel consumption and charging/discharging times, under different military scenarios. Each of these energy management strategies are discussed below.

4.2 Energy Management Strategies

4.2.1 Power Source Selection

The electrical load demand in military vehicles is increasing due to additional mission electrical loads being introduced such as radios, networking, situational awareness, satellite communication devices, radar sensors, and jammers, and also modern vehicle systems such as electromechanical components [20]. Note that, this increase in electrical energy demand results in the need to introduce additional power sources into military vehicles [11].

A military vehicle may include auxiliary power units, to power electrical loads especially during engine off conditions referred to as silent watch [33]. Power source selection involves taking advantage of the different characteristics of multiple power sources to meet the vehicle power demands [37]. It is done by making decisions of which power sources to turn on and off, setting their power level and power level durations [11]. The study includes selecting the power level between the Internal Combustion Engine (ICE) and the ISG to meet propulsion power demands. It also includes selecting the power level between the ICE, ISG, and fuel cell during stationary idling conditions when charging the battery, and selecting between power levels between fuel cell and battery to meet electrical load demands when the vehicle is stationary during silent watch operations.

4.2.2 Load Shedding

Modern vehicle electrical loads include additional power states to the standard on and off states [15]. Electrical loads may also include stand-by or idle modes which are low power consumption states when the load detects or requires minimal inactivity [15]. There is also different power levels associated with usage activity and are sometimes classified as low, medium or high [15][35].

Load shedding involves making decisions of which electrical loads to turn on and off and when to transition between power level states (e.g. standby, inactive, low, medium, high power, on, or off), and for how long to remain in those states [36]. Another aspect included in a load shedding strategy is based on graceful turn on/off transition sequences, to minimise impacts of power spikes due to variations in currents of different types of loads during start up and shutdown, and to protect computer and information systems from data corruptions during start and shutdown [33]. For the purpose of this study it is assumed that mission and vehicle loads include such functionality. The main aims of this strategy are to reduce electrical energy consumption. Note that, to model load shedding in the power management case in this study a random current level reduction factor is applied to the electrical load profiles of the scenario.

4.2.3 Stop/Start

Stop/start involves turning off the ICE during stand still durations, instead of idling the vehicle [35]. The ISG then starts the ICE once the driver decides to continue moving. The result of this strategy is also to reduce fuel consumption.

4.2.4 Electric Motor Assist

Electric motor assist involves operating the ISG as a motor to assist the ICE to contribute towards the total torque demands of the vehicle [35][14]. Turning the ICE off for a limited amount of time to allow the ISG to provide all the torque demands of the vehicle allows for short range silent mobility and lowering fuel consumption [20]. The range for electric motoring is highly dependent on the battery capacity. This study investigates the relationship between electric motoring requirements and battery sizing. It is expected that due to the current limitations in size and weight of battery technologies that electric motoring is not yet feasible to provide all the propulsion demands, as such electric motoring is limited in its application to military conditions.

4.2.5 Regenerative Braking

As it is known, regenerative braking involves absorbing the rotational kinetic energy transferred from the rotating vehicle wheels to the ISG. As stated in [14][35], this can occur when the ICE is turned off, and the vehicle slows down or as it descends sharing the braking load with the wheel brakes. The rotational kinetic energy transferred to the ISG is then converted to electrical energy for the purposes of charging the vehicle battery or powering vehicle electrical loads. Note that, to implement this strategy the vehicle is required to determine when to turn off the ICE and clutch, set the power electronic converters to battery charge mode and set the duration and power level to charge the battery. In addition, to prevent all the rotational kinetic energy converting to useless heat at the wheel brakes, it is also important to control the amount of wheel braking compared to the braking effect of regenerative braking. In conclusion, regenerative braking considerably contributes to charging the vehicle batteries without consuming fuel.

4.3 Vehicle Power Management Systems

The implementation of the energy management strategies described above requires a vehicle power management system running energy management algorithms that make use of information from sensors to control the required power sources and loads to execute the strategies [33][37].

The hardware components of a vehicle power management system are shown in Figure 10, which is also considered in this study.

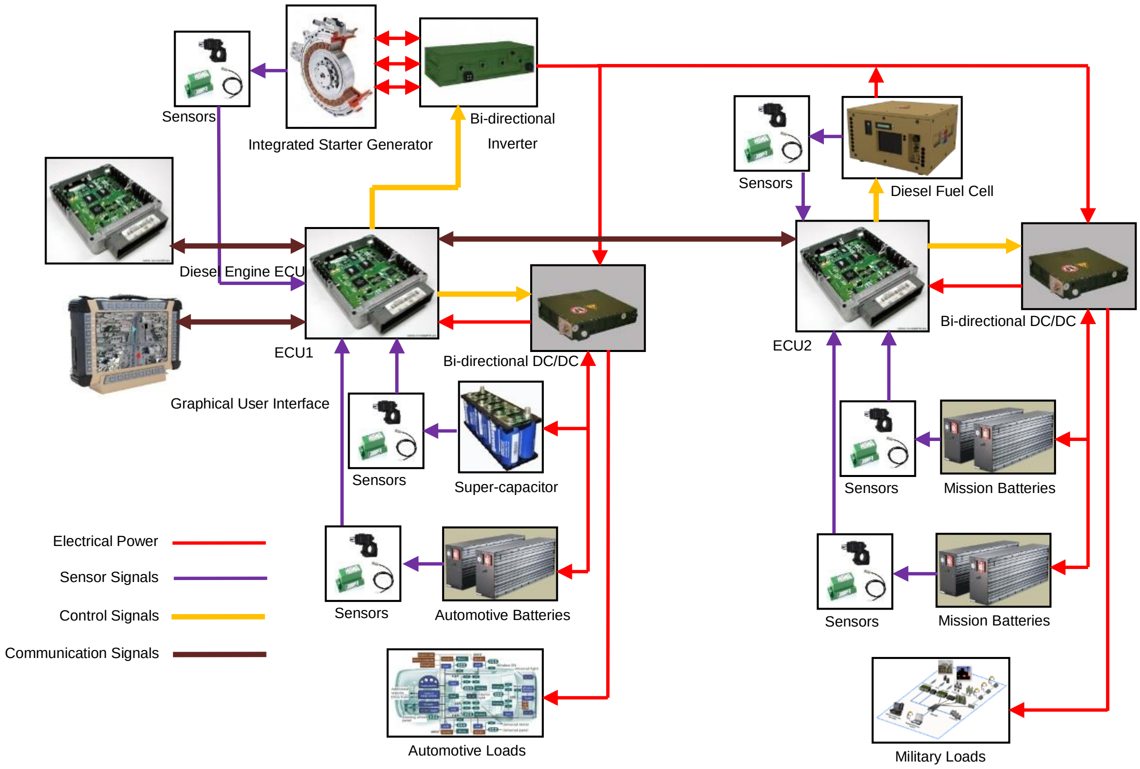


Figure 10 Vehicle Power Management System Example

The vehicle power management system shown in Figure 10 includes the following five major components:

- Sensors
- Actuators
- Electronic Control Units (ECU)
- Power Converters
- Control and Optimisation Algorithms
    - Power Flow State Machine
    - Cost Function(s)
    - Energy management algorithms

ECU 1 and ECU 2 shown in Figure 10 are networked to communicate with each other. ECU 1 is also networked with the vehicle's engine ECU to monitor the engine and send control demands to turn the engine on or off. Furthermore ECU 1 is networked to a graphical user interface that displays state information to a user regarding the vehicle's power system and for accepting user commands. ECU 1 processes sensor information from the ISG in order to control the ISG bi-directional inverter, and processes sensor information from the super capacitor and automotive batteries to provide control to the bi-directional DC/DC converter used to regulate the power to automotive electrical loads. ECU 2 processes sensor information from the diesel fuel cell, for monitoring and controlling the fuel cell. Furthermore, ECU 2 processes sensor information from the mission batteries to control a secondary bi-directional DC/DC converter used for regulating power to electrical loads for military missions.

ECU 1 hosts the control and optimisation algorithms, which include a vehicle power system state machine, energy management algorithms and parameters entered from the user related to the optimisation cost functions.

In addition to the above example, a conceptual diagram showing the vehicle power management system integrated into the power system architecture specific to the study is given below in Figure 11.

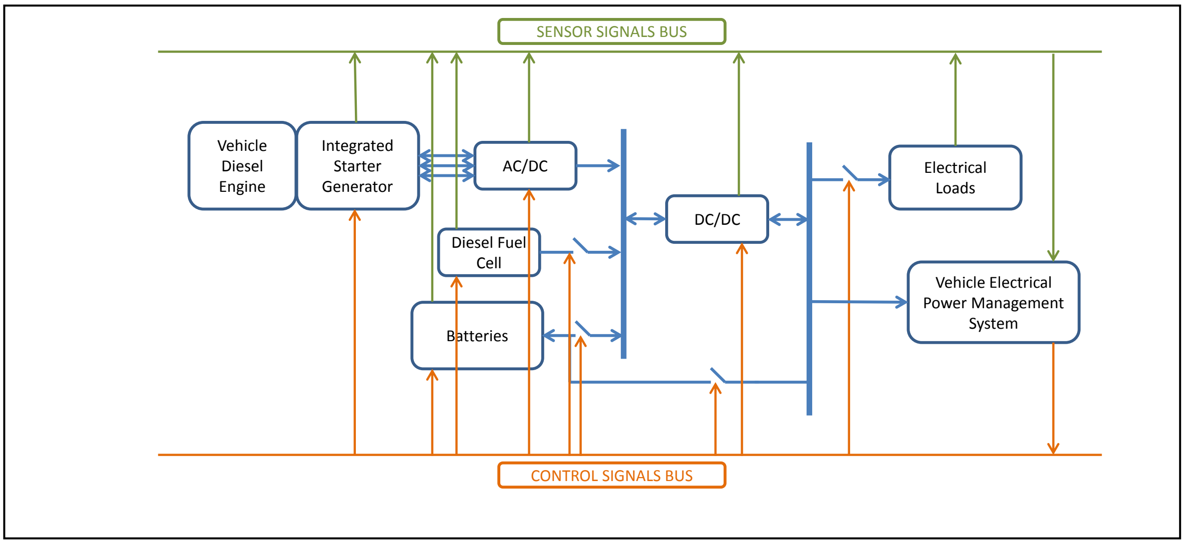


Figure 11 Mild-hybrid electric combat vehicle with Vehicle Electrical Power Management System

The conceptual diagram shows how the vehicle electrical power management system being modelled in the study integrates to the modelled vehicle power system components. The sensor signals from the ISG, batteries, diesel fuel cell, AC/DC and DC/DC converters, and electrical loads are collected from a sensor signals bus shown in orange, which are then processed to control these components through the control signals bus shown in green.

The functionalities that may be included in modern vehicle power management systems are discussed below. The functionalities are introduced with the aim of improving mobility by controlling the amount of mechanical and electrical torque supplied to the vehicle. Ensure an optimal fuel or electrical conversion efficiency, reduce electrical power consumption, or for fault prevention and protection.

4.3.1 Vehicle Power Management System Functionality

A power management system may include the following functionalities:

1. Monitoring of buses', power sources' and loads' voltage, current and temperature [37][21],
2. Seeking a desired or optimum system operating point corresponding to a system wide cost function [37][38],
3. Bus voltage regulation [21][39],
4. Load and power source turning on and off sequencing during start up and shut down [11][39][38],
5. Load shedding from a high power level to a low power level and to the off state [11][37][38],
6. Power source level control and combination scheduling and transitions [11][38],
7. Scheduling and decision making related to the use of start/stop, motor assist and regenerative braking strategies [37].
8. Electrical power management functionality (see Appendix B)

Note that, an important component of power management systems are energy management algorithms which should perform the processing of sensor information in real time in order to achieve suitable control signals that can ensure an optimal or suitable trade-off between reducing fuel consumption, electrical energy conversion efficiency, battery degradation, and improved mobility. Such energy management algorithms are discussed in the subsequent section.

4.3.2 Energy Management Algorithms

Energy management algorithms involve solving control problems at the sub-component and system level [37][21][38]. Optimal control is achieved by finding a solution to the problem described below [36][37].

Given an initial vehicle power system state x_0, the problem is to find a control law $\pi = \{u_0, u_1, \dots, u_{N-1}\}$ that minimises the cost function:

$$J_\pi(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k[x_k, u_k(x_k)]$$

Subject to the system equation constraint:

$$x_{k+1} = F_k(x_k, u_k), \qquad k = 0,1, \dots, N-1$$

$J_\pi(x_0)$ Represents the total cost across the drive cycle divided into $k = 0,1, \dots, N-1$ discrete intervals, and using the control law π

$g_N(x_N)$ Represents the final cost at the last interval N of the drive cycle

$g_k[x_k, u_k(x_k)]$ Represents the cost of applying the control rule $u_k(x_k)$ at state x_k

As an example, the vehicle power system state may include the vehicle speed, incline and electrical load demand. The control law may comprise the following parameters: battery charge duration and power level, battery discharge duration and power level, engine on and off signal, ISG on and off signal, transmission gear setting, fuel cell power level, and load shed factor. The control law should be applied at each interval of the drive cycle to minimise the cost function.

Specific to this study the following parameters have been selected to evaluate energy management algorithms and to assist in the formulation of a cost function for optimal control: acceleration, time to fully charge/discharge the battery, fuel consumption and electrical efficiency. Each of these parameters is then updated based on the following sensor inputs: vehicle speed, vehicle pitch, and electrical load current levels provided to the vehicle power management system model.

As stated above, solving the optimal control problem involves optimisation. Optimisation approaches can include methods to select solutions based on their cost function values. It also involves finding a means of generating solutions, and then a means to search through the solution space and select the best solution. The type of solution method depends on a number of factors [14][22][35][37]:

- System boundary conditions, constraints, and whether it is a discrete or continuous system
- System equation (including dynamics, controls, stochastic effects, noise, disturbances, etc.)

- Cost function definition
- Prior knowledge of the drive cycle
- Conditions for optimality

Different algorithms have been studied in the literature to assist in solving the optimal control problem. Some of these are optimal and others are near or sub-optimal, some examples are shown below, and a proposed classification is included.

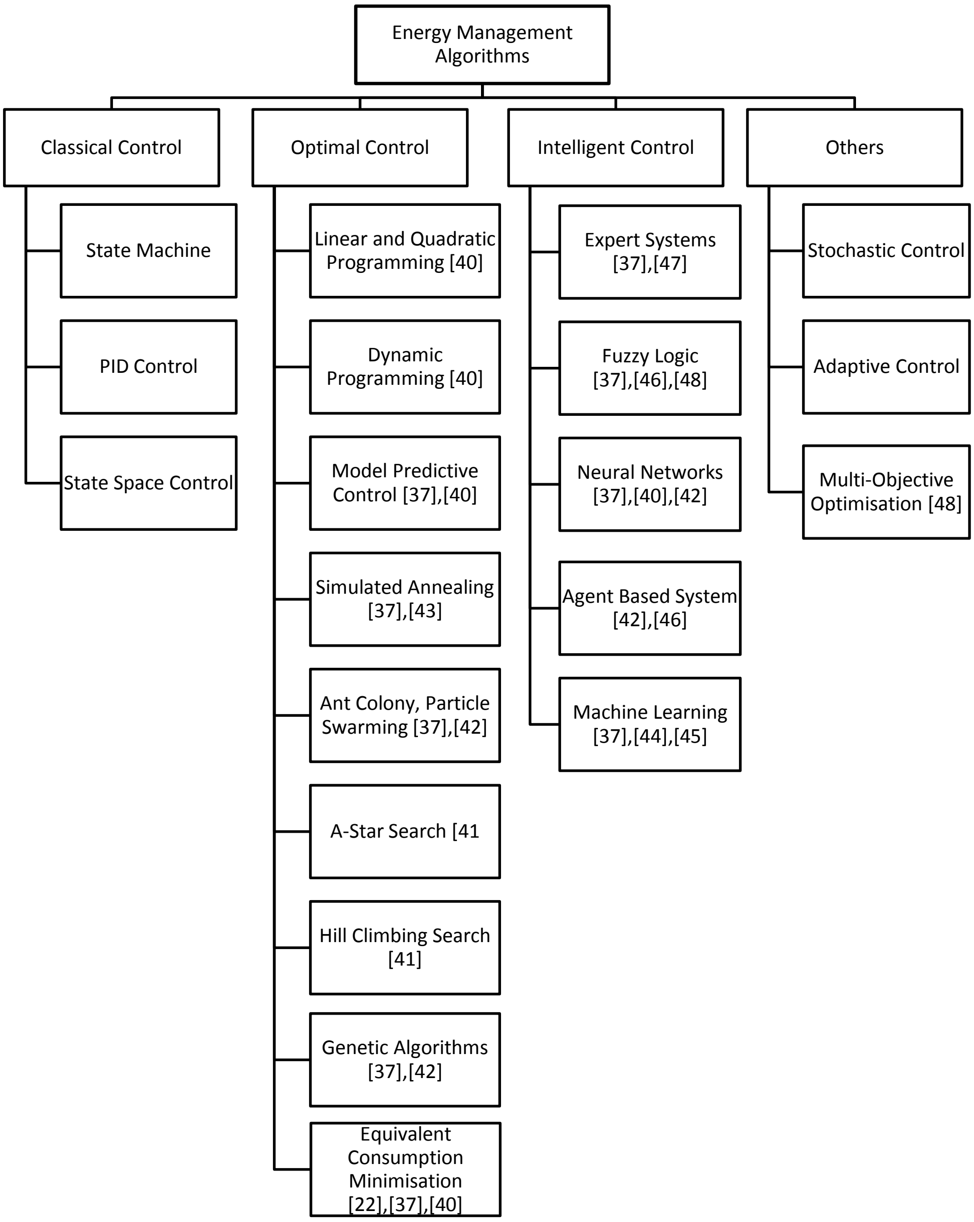


Figure 12 Examples of energy management algorithms and their proposed categories

The categories shown in Figure 12 are proposed, because there is currently no agreed categorisation to date in the field of energy management algorithms. There are a variety of algorithm attributes which can be used for categorisation such as: whether the algorithm aims for a global optima or near global optima, allows for local optima or near local optima, if it can adapt in real time or not, if it requires a priori off line information or not, if it is supervised or unsupervised, and if it is near real time, or implemented off-line before it is used on-line. The algorithm categories shown in Figure 12 are based on the type of algorithm. Classical control algorithms are known in the literature. Optimal control algorithms are based on attempting to search for near global or local optima based on an arbitrary cost function. Intelligent algorithms are based on the knowledge of experts, or learned knowledge, and are algorithms drawn from the fields of machine learning, and artificial intelligence, to assist in making intelligent control decisions. It should be noted that some algorithms drawn from the machine learning and artificial intelligence disciplines may or may not aim for optimality. The 'Others' category refers to algorithms which sit outside the Classical, Optimal or Intelligent Control categories.

Amongst the diversity of energy management algorithms are Dynamic Programming algorithms. Such algorithms are implemented off-line and have been referenced widely in the literature. They are often used as a benchmark for comparing on-line power management algorithms and to assist in the development of energy management algorithms. Model predictive control is an on-line version of dynamic programming. Algorithms that are based on Fuzzy Logic and Neural Networks are applicable to military scenarios because they can accommodate dealing with uncertainty, and a wide range of conditions, as encountered in military scenarios. Hence, some of these algorithms amongst others relevant to military conditions are briefly described below.

4.3.2.1 Dynamic Programming [37][22]

The idea behind dynamic programming is based on breaking down a large problem into sub-problems. If an optimal solution exists for the sub-problem then by finding the optimal solution for each sub-problem recursively you can find the optimal solution for the entire problem.

4.3.2.2 Model Predictive Control [35][22]

Model predictive control can be thought of as applying Dynamic Programming over a forecasted state space. The forecasted state space relies on a model of the system to be controlled and extrapolates future states over a selected time horizon.

4.3.2.3 Fuzzy Logic Control [35][42]

This method abstracts inter-relationship between sensor inputs and control outputs into a set of control laws expressed as IF (test conditions) - THEN (control actions) statements. The test conditions may include logic operators similar to AND, OR, or NOT by defining membership functions that clusters a range of sensor or control values to be a member of a defined set. The defined set may correspond to linguist terms such as HIGH, MEDIUM or LOW. This method allows for expert knowledge to be converted into control laws. The membership functions and control laws may also be discovered through simulation runs or learned.

4.3.2.4 Neural Networks [35]

Neural networks allow for estimating the relationships between a set of sensor inputs and control outputs through supervised or un-supervised learning. A network of specified functions is developed between the inputs and outputs of the power management system. The combination between the inputs and outputs of each of the network functions produces an estimate of the relationship between expected sensor inputs and desired control outputs. This technique may also be used to estimate component behaviour based on their operating conditions.

4.3.2.5 Genetic Algorithms [37][42]

Genetic algorithms can be used as an optimisation method to search for a desired solution. The principles of this method are inspired by the process of evolution through natural selection. The problem is abstracted to mimic the evolution process. Solutions are represented as a binary string of 1 and 0s which can be thought of as the genetic code of species. Species are able to combine their genetic code through reproduction, and their genetic code can also mutate. The replications and mutations that produce species that survive according to a selected fitness criterion are promoted to continue reproducing; those that do not survive are discarded. The end result of this process is species that meet the selected fitness criterion. The genetic code for the specie may be a combination of energy management strategy control laws and operating scenarios, and the fitness criteria a cost function that can include acceleration, fuel consumption, battery cycling or power conversion efficiency.

4.3.2.6 Multi-Objective Optimisation [53]

Multi-objective optimisation seeks to find a solution that is the best trade-off between interdependent or conflicting objectives. It depends on finding the Pareto front through a search. The Pareto front is a condition where if any parameter is modified beyond that specific condition, it will cause a detrimental impact on any of the defined objectives. This method could determine the best trade-off between fuel consumption and battery cycling, or other inter-dependent objectives.

4.3.3 Energy Management Algorithm for the Mild-Hybrid Electric Combat Vehicle

The control aspects of the energy management problem for the Mild-Hybrid Electric Combat Vehicle shown in Figure 3 can be captured using a power flow state machine that can represent the transitions between power flow modes during vehicle operations. The power flow modes are highlighted in Figure 13 and Figure 14. There are two main power flows of concern which are charge depleting and charge sustaining power flows.

Charge depleting power flows are present when the vehicle’s battery pack is being discharged. They occur during the following modes of operation: Parked (refer to Figure 13(a)), Starting/Cranking (refer to Figure 13(b)), Motor Assist (refer to Figure 13(c)), and Electric Drive (refer to Figure 13(d)). It should be noted that power flow losses are not shown in these figures.

Figure 13(a) displays the electrical power flow during Parked Mode. During this mode the power flows from the battery to the electrical loads are represented with a red arrow. The power flow during Parked Mode forms part of the baseline which does not include additional power management functionality. The amount of power transferred depends on the battery discharge efficiency, the electrical loads in use, and the level of load shedding that each electrical load is able to provide. It should be noted that load shedding is an extension of the baseline and is part of the case which includes energy management functionality.

Figure 13(b) displays the power flows when the vehicle battery pack is discharged to crank the engine and power electrical loads. During Starting/Cranking Mode electrical power is transferred from the batteries to the electrical loads, and through the AC/DC and DC/DC converters to the ISG, this power flow is shown by the red arrows. The ISG then converts the electrical power into mechanical power to start the engine; this power flow is shown as an arrow transitioning from red which represents electrical power to light purple representing mechanical power. The power flow during Starting/Cranking Mode forms part of the baseline. Using load shedding during this mode forms an extension of the baseline in terms of energy management.

Figure 13(c) shows the power flow when the vehicle battery pack is discharged during Motor Assist mode. During Motor Assist mode electrical power is transferred from the battery pack to the electrical loads and through the bi-directional converters to the ISG, as shown by the red arrows. The ISG then converts the electrical power into mechanical power, and assists the ICE in providing additional mechanical power to the wheels, as shown in the light purple arrows. Motor Assist mode is an additional power flow as part of extending the baseline with energy management.

Figure 13(d) shows the power flow when the vehicle battery pack is discharged during Electric Drive Mode. In Electric Drive Mode electrical power is transferred from the battery pack to the electrical loads and through the bi-directional converters to the ISG, as shown by the red arrows. The ISG then converts the electrical power into mechanical power, in order to drive the wheels as shown in the light purple arrows. Electric Drive Mode is an additional power flow as part of extending the baseline with energy management.

Charge sustaining power flows are present when the vehicle's battery pack is being charged. They occur during the following modes of operation: Generating (refer to Figure 14(a)), Idle Charging with Fuel Cell Assist (refer to Figure 14(b)), Fuel Cell Charging (refer to Figure 14(c)), and Regenerative Braking (refer to Figure 14(d)). It should be noted that power flow losses are not shown in these figures.

Figure 14(a) shows the power flow when the vehicle battery pack is charged during Generating Mode. In Generating Mode mechanical power is transferred from the ICE to the wheels and the ISG, as shown by the light purple arrows. The ISG then converts the mechanical power into electrical power which flows through the bi-directional converts to the electrical loads and the battery pack, as shown in the light blue arrows. Generating Mode forms part of the baseline. Using load shedding during this mode forms an extension of the baseline in terms of energy management.

Figure 14(b) shows the power flow when the vehicle battery pack is charged during Idle Charging with Fuel Cell Assist Mode. In Idle Charging with Fuel Cell Assist Mode mechanical power is transferred from the ICE to the ISG, as shown by the light purple arrows. The ISG then converts this mechanical power into electrical power which flows through the bi-directional converts to the electrical loads and the battery pack, as shown in the light blue arrows. In addition to the electrical power generated by the ICE, electrical power generated from the fuel cell flows through the bi-directional DC/DC converter to the electrical loads and the battery pack. Idle Charging with Fuel Cell Assist Mode is an additional power flow as part of extending the baseline with energy management.

Figure 14(c) shows the power flow when the vehicle battery pack is charged during Fuel Cell Charging Mode. In Fuel Cell Charging Mode electrical power generated from the fuel cell flows through the bi-directional DC/DC converter to the electrical loads and the battery pack. Fuel Cell Charging Mode forms part of the baseline. Using load shedding during this mode forms an extension of the baseline in terms of energy management.

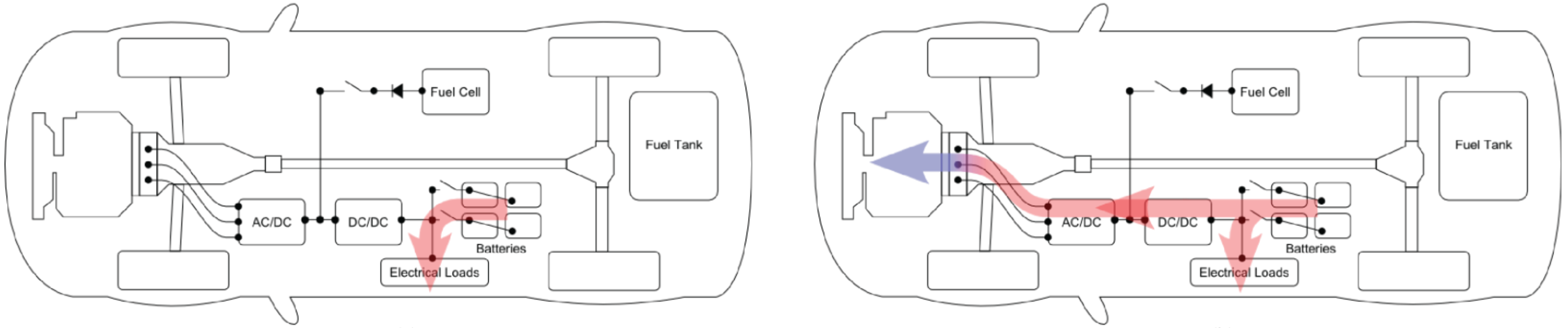
Figure 14(d) shows the power flow when the vehicle battery pack is charged during Regenerative Braking Mode. In Regenerative Braking Mode the ICE is turned off, and mechanical power is transferred from the rotating wheels to the ISG, as shown by the light purple arrows. The ISG then converts the mechanical power into electrical power which flows through the bi-directional converts to the electrical loads and the battery pack, as shown in the light blue arrows. Regenerative Braking Mode is an additional power flow as part of extending the baseline with energy management.

Power Flow Modes

Charge Depleting Power Flows

Parked Mode (part of baseline)

Starting/Cranking Mode (part of baseline)

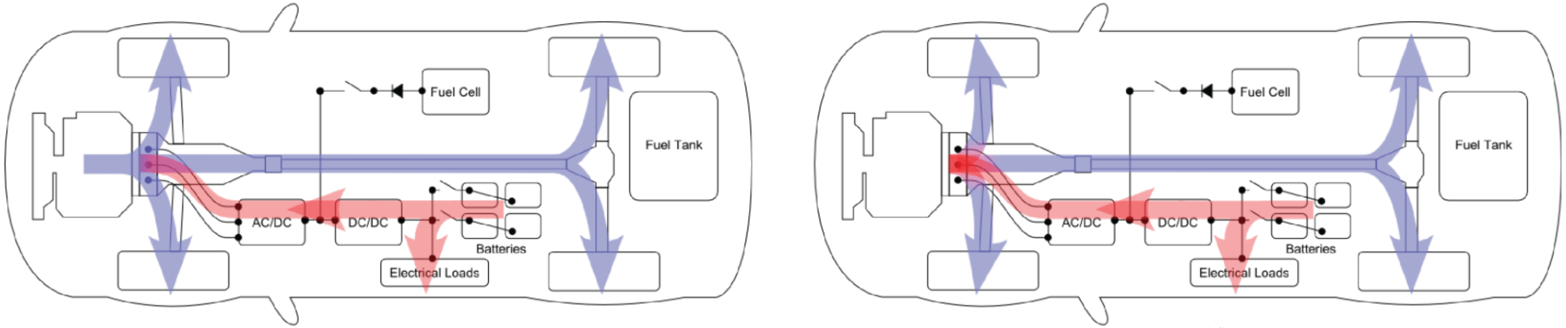


(a)

(b)

Motor Assist (modification to baseline)

Electric Drive (modification to baseline)



(c)

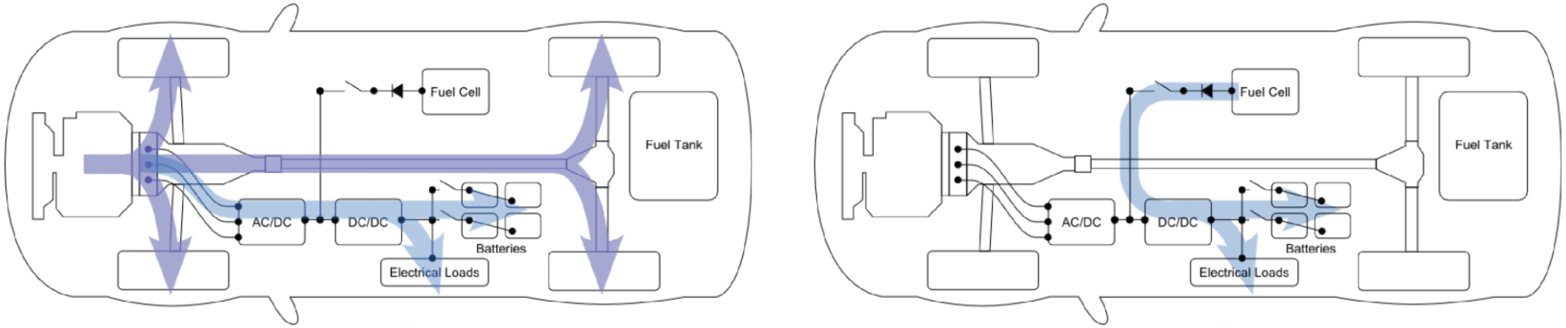
(d)

Figure 13 Charge Depleting Power Flows

Charge Sustaining Power Flows

Generating (part of baseline)

Fuel Cell Charging (part of baseline)

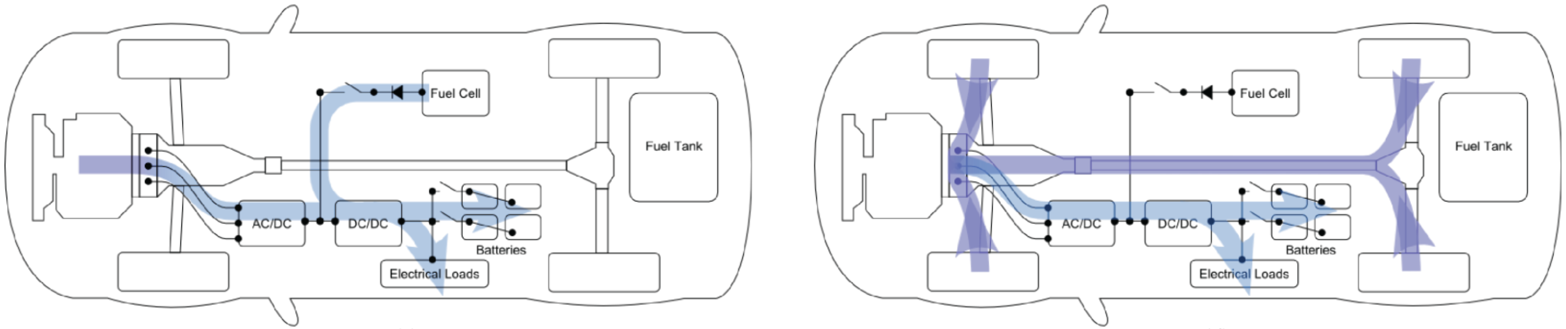


(a)

(b)

Idle Charging with Fuel Cell Assist (modification to baseline)

Regenerative Braking (modification to baseline)



(c)

(d)

Figure 14 Charge Sustaining Power Flows

4.3.3.1 State Transition Control Rules

Charge Depletion Modes

When the vehicle is in motion, accelerating or decelerating, and the battery SOC is greater than a set threshold, then the power management system can select between the following power flow modes: Electric Drive shown in Figure 13(d), or Motor Assist shown in Figure 13(c).

The control law for Electric Drive Mode is based on setting the discharge power and duration, engine and clutch off, and the gear setting. The control law is similar during Motor Assist Mode except that the engine and clutch are set on. The best cost function output between Electric Drive and Motor Assist mode determines which of the two energy management strategies are chosen.

When the vehicle is stationary, and the battery current loading is less than or equal to the parasitic current load, the gearing is set to parked, and the battery SOC is greater than a set threshold, then the vehicle transitions to Parked Mode in Figure 13(a). The control law for Parked Mode is based on the total amount of load shedding implemented by each electrical load. This control sets the battery discharge power level and discharge duration.

When the vehicle is firstly stationary, then accelerating, the battery current loading is greater than or equal to the starting current load and the battery SOC is greater than or equal to a set threshold, then the vehicle transitions to the Starting Mode shown in Figure 13(b).

Charge Sustaining Modes

When the vehicle is in motion, accelerating or decelerating, and the battery SOC is less than or equal to a set threshold, then the power management system can select between the following power flow modes: Generating Mode shown in Figure 14(a), or Regenerative Braking mode shown in Figure 14(d). The control law during Generating Mode is given by the charge power level and duration, engine and clutch on signal, and setting the gears. The control law for Regenerative Braking is also based on charge power level and duration and setting the gear, however, the engine and clutch is off. The best cost function output between generating and regenerative braking determines which energy management strategy is chosen.

When the vehicle is stationary, the battery current loading is greater than the parasitic current load and SOC is less than or equal to a set threshold, then the power management system can select between the following power flow modes: Fuel Cell Charging or Idle Charging with Fuel Cell Assist as shown in Figure 14(c) and Figure 14(b) respectively. The control law for Fuel Cell Charging is based on turning the fuel cell on and setting its power level, as well as having both the engine and clutch off. The control settings for Charging with Fuel Cell Assist is based on setting the gear to neutral, the engine and clutch are on and the fuel cell is on and set to a given power level. The best cost function output between Fuel Cell Charging and Charging with Fuel Cell Assist determines which of the two energy management strategies are chosen.

Chapter 5: Experimental Environment

5.1 Background

The aim of this thesis is to evaluate the impacts caused to acceleration, fuel consumption, time to fully charge/discharge, and the electrical conversion efficiency, when introducing energy management strategies into a baseline combat vehicle under different military operating scenarios.

The baseline vehicle topology shown in Figure 3 is a representative combat vehicle prototype with limited energy management functionality. It uses an integrated starter generator only for cranking the engine and generating electricity during idle and moving conditions, and it can only charge the battery during engine off conditions using the fuel cell. Furthermore the electrical loads in this baseline do not support loads being placed in idle low power consumption states (i.e. load shedding).

Table 10 shows the differences between the baseline vehicle and the vehicle with extended energy management strategies.

Table 10 Baseline energy management extension comparison

Vehicle Characteristic	**Baseline**	**Baseline with extended energy management**
Motor assist	No	Yes
Stop/Start	No	Yes
Fuel Cell Power Level Control	No	Yes
Regenerative Braking	No	Yes
Electric Motoring	No	Yes
Electrical Generation	Yes	Yes
Electric Start	Yes	Yes
Speed Profile	Same	Same
Terrain Incline Profile	Same	Same
Electrical Current Level Profile	Same	Same with a random current reduction factor applied to the profile (to simulate load shedding)

5.2 Evaluation Methods

A method to evaluate and compare the baseline against the case with energy management is to undertake an assessment regarding the costs and benefits of modifying the baseline. In general the costs may be concerning finances, scope complexity and schedule constraints, and the benefits may be associated with improved operational performance. Therefore, each of the benefits and costs need to be weighed against each other to see if the benefits associated with the modifications far outweigh the costs. The expected costs of modifying the baseline are financial and include the labour costs associated with design and implementation of the modifications. Hence, the expected benefits of the modification are related to improved fuel consumption, mobility, energy efficiency, and stealth. Note that, the expected benefits may also have secondary benefits such as financial savings due to less fuel consumption, extending mission endurance as a result of reducing fuel and battery cycling. They could also include improvements in stealth, and a reduction of carbon emissions as a result of lowering fuel consumption.

Furthermore, there may be other costs and benefits that need to be identified and quantified in order to perform a complete and detailed cost and benefits analysis. However, in order to simplify the complexities of exhaustively assessing every different type of direct or indirect known or undiscovered cost and benefit, a set of parameters that are important to vehicle operations are identified for comparison. The parameters include vehicle acceleration, fuel consumption, time to fully charge/discharge the battery, and electrical energy efficiency. Assessing the acceleration has been selected because it is an indication of improvements in mobility. The time to charge/discharge, fuel consumption and electrical efficiency each have a direct and indirect impact to mission endurance.

The next section discusses different options available through the literature to evaluate the costs and benefits of vehicle power system architectures with energy management, and discusses the method of choice selected and developed specific to this study.

5.3 Experimental Environments

During the experiments, the study components that require careful control are: the operational environment, vehicle operator behaviour, the characteristics of both the baseline vehicle and its sub components, and those of the modified baseline.

Ideally, the vehicle including energy management should be built and tested operating under different battle space conditions in a controlled manner. The same tests should then be repeated using the vehicle baseline for an accurate comparison. However, this is difficult to achieve given time and financial constraints. In addition, it is difficult to eliminate all the variations that may occur between tests with respect to the operational environment, operator behaviour, and vehicle system behaviour. As such an experimental environment that can timely facilitate conducting a large number of experimental runs, and that can introduce a high level of control over possible test regimes and variations is ideal. Such experimental environments are lab based and include modelling and simulation software, or representative hardware [37]. Examples of concept diagrams for such environments are described in the sub-sections below.

5.3.1 Human in the loop with hardware and software in the loop

The concept example for a human in the loop with hardware and software in the loop algorithm test bed as shown in Figure 15 comprises the following components:

- A simulation environment or virtual battle space which comprises of:
    - A Mission Scenario Generator that includes models of the environment, models of the battle space entities and their behaviours, and the mission tasks to execute by the vehicle operator,

  - A Vehicle Power System Model which includes software models for a vehicle engine, an integrated starter generator, and a diesel fuel cell, representative of those in Figure 11,
- Vehicle Power System Component Hardware representative of that in Figure 11, including the bi-directional AC/DC converter, bi-directional DC/DC converter, semi-conductor switches, lithium ion battery pack, and a programmable load to emulate vehicle electrical loads,
- An Experimental Data Logger, which processes virtual battle space data, and sensor and diagnostic data from the hardware components to generate the results of the experimental runs, which include the control performance of the energy management algorithm,
- The Item Under Test consists of the energy management algorithm that processes the dynamic state of the vehicle power system in order to control it.

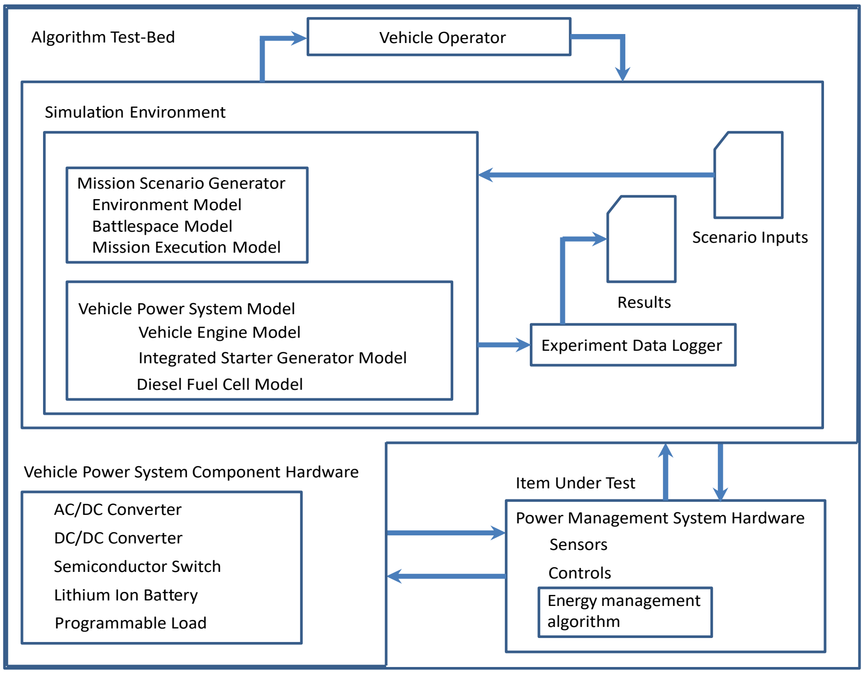


Figure 15 Human in the loop with hardware and software in the loop test environment

The operation of the test bed in Figure 15 is as followed: in order to initiate test bed experiments a scenario inputs file is created. The file includes values for parameters associated with the mission scenario of interest. The parameters include environmental conditions experienced in the virtual battle space, such as ambient temperature, pressure, terrain conditions, and wind speed. The file also includes values for initial locations of battlespace entities such as enemies, buildings, friendly forces, and civilians, along with parameters about their properties and behaviours. The file includes mission parameters which represent the tasks that the driver needs to perform as he/she drives through the virtual battle space. Furthermore, the scenario input file includes the parameter details for the vehicle power system, along with configuration settings for the vehicle power system hardware. In addition, the file holds parameters for sensor data monitoring and control, and settings for the experiment data logger used to generate experiment results.

Once the scenario inputs file is loaded into the test-bed, the experiment to compare the baseline with and without extended energy management can begin. The vehicle operator drives through the virtual battle space as seen through screen monitors. The operator drives by interacting with common vehicle controls such as a steering wheel, gears, accelerator and brake pedals, along with dashboard controls for operating vehicle and mission equipment to simulate the use of electrical loads. As the vehicle navigates through the virtual terrain, the operator’s power and torque demands are estimated by the energy management algorithm. The algorithm then produces control signals to the vehicle power system model and hardware components to select from the charge depletion or charge sustaining modes discussed in Section 4.3.3 and their durations. Furthermore the algorithm selects the amount of load shedding.

5.3.2 Hardware and software in the loop

The test environment in Figure 16 shows software models of the operational environment, vehicle operators and vehicle systems. Similarly to the test-bed described previously, it includes hardware of representative vehicle components. The software models interact with the hardware components, to stimulate the item under test. The components and operation of the conceptual hardware and software in the loop algorithm test bed as shown in Figure 16 are the same as described previously in Section 5.1. The only difference between the two test beds is that the vehicle operator is modelled in software.

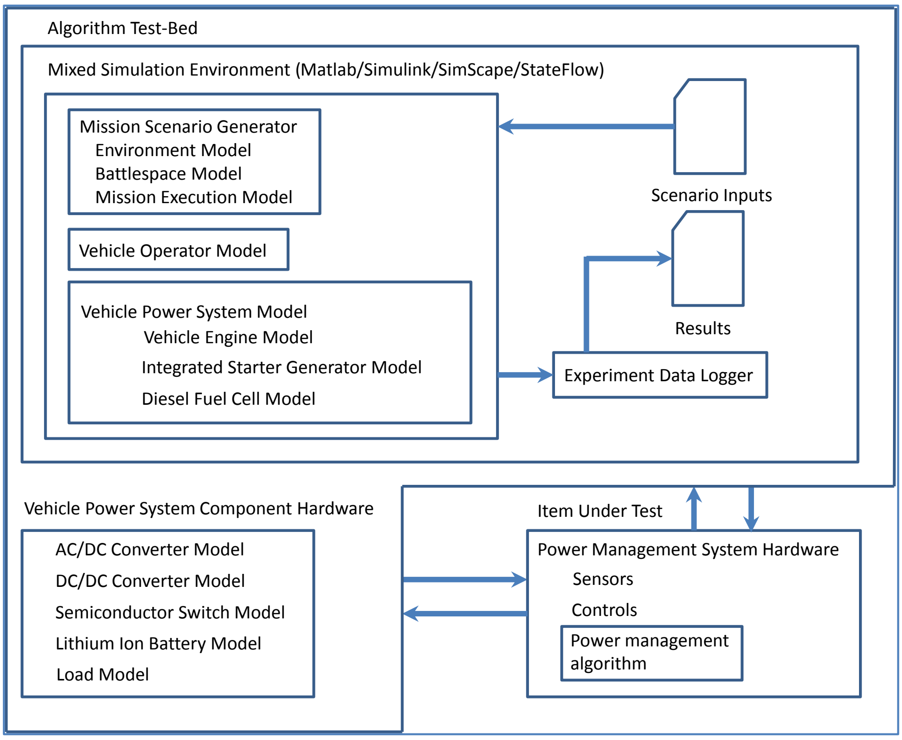


Figure 16 Hardware and software in the loop testing environment

5.3.3 Software in the loop

The components and operation of the conceptual hardware and software in the loop algorithm test bed as shown in Figure 17 are the same as described previously in Section 5.1. The only difference between the two test beds is that both the vehicle operator and the vehicle power system are modelled in software. Furthermore, the item under test is the energy management algorithm and it is hosted within the same simulation environment and not in hardware.

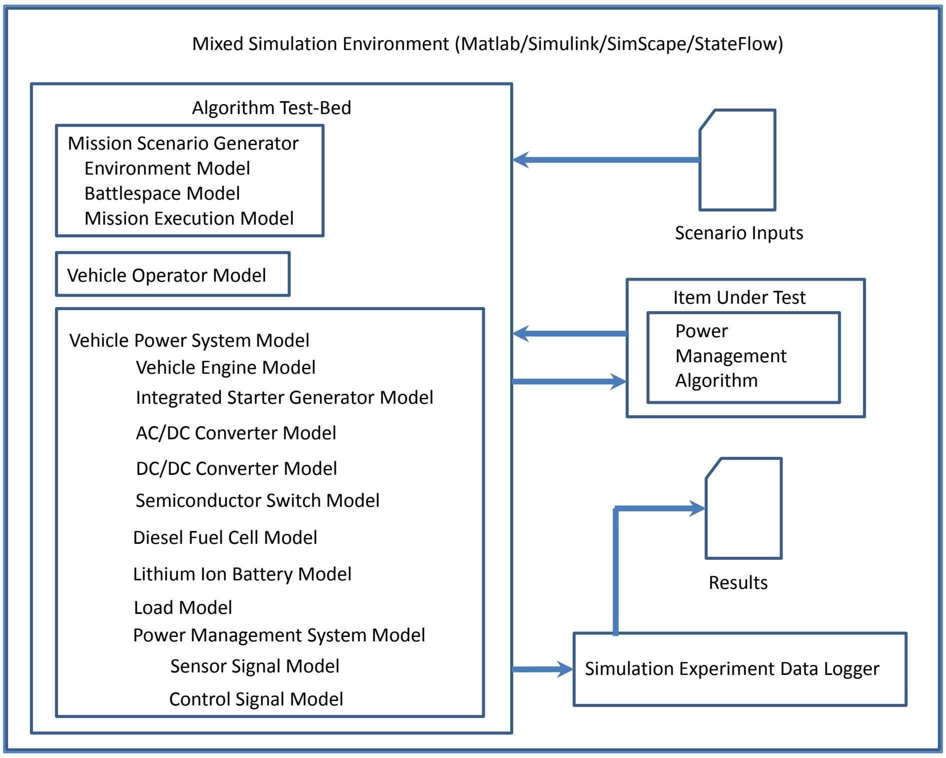


Figure 17 Software in the loop testing environment

In order to accommodate for financial and time constraints the software in the loop experimental environment is selected, developed, and implemented using Matlab. The Matlab environment is flexible to be used for specific customisations and for future development. The software environment includes the following components and models previously explained in Chapters 2 and 3, i.e. the operating environment and the combat vehicle platform:

Operating Environment

- Speed and Acceleration Profiles represented as an vector of likely discrete speeds and accelerations that the vehicle may experience
- Terrain Incline Profiles represented as a vector of possible discrete angles of the terrain
- Electrical Loading Profiles represented as a vector of likely discrete current loads that the vehicle power system may encounter in the battle space

Combat Vehicle Platform

- Diesel Internal Combustion Engine represented as a look-up table
- 6 Speed Auto Transmission and Drive Train represented as gear ratios
- Integrated Starter Generator (ISG) represented as a look-up table
- Converters (Bi-directional inverter and DC/DC converters) represented as efficiencies
- 2x24 Lithium Ion Batteries connected in parallel represented as a 3D look up table
- Diesel Fuel Cell represented as a look-up table

Each component above is a Matlab script included in Appendix A, and they are used for each power flow state across different operating conditions. Simulation results across different scenarios of interest are gathered and presented in the following chapter as 2D image maps for visual comparison.

Chapter 6: Results and Discussion

6.1 Background

The following section presents the results generated by using the implemented experimental environment discussed in Section 5.3.3, in order to evaluate the baseline's vehicle acceleration, fuel consumption, the time taken to fully charge/discharge the vehicle battery, and the electrical conversion efficiency against including additional energy management strategies as referred to in Table 10, across stationary and moving scenarios.

The evaluation parameters were chosen as they are of relevance in the military domain. For example, an improvement in take-off acceleration means an advantage when dashing from harm, and manoeuvring in high tempo war situations. An improvement in charge/discharge time gives an indication of mission endurance during silent watch (i.e. the engine is off and the vehicle is stationary). An improvement to fuel consumption is related to a reduction in logistic burden and the harm vulnerabilities associated with refuelling in the battle space, as well as reducing fuel costs. Reducing fuel consumption through electric drive allows improvements in stealth through noise reduction, reduction in IR emissions, and smoke emissions. An improvement in electrical conversion efficiency can be related to improvements in fuel consumption.

6.2 Charge depletion mode

Note that, as mentioned in Section 4.3.3 there are two main modes to consider in the simulation study, charge depletion and charge sustainment mode.

During charge depletion mode the relevant power flows for stationary scenarios are shown in Figure 13(a), and Figure 13(b). The power flow referred to in Figure 13(a) was selected for evaluation. Figure 18 below gives the simulation results of the discharge time taken to deplete each battery pack from 24V down to 20.1V, for different electrical load scenarios encountered during the chosen stationary scenario.

Figure 18 allows for a visual comparison against the baseline with respect to the amount of time in minutes that it takes to fully discharge the vehicle battery pack during silent watch (i.e. the engine is off and the vehicle is stationary), across multiple electrical power demands (vertical axis), and across different load shedding factors (horizontal axis). The colour represents the discharge time in minutes corresponding to a particular electrical load with a given load shed factor. The dark blue values in the colour scale represent the fastest discharging time, and the dark red values represent the longest time to discharge.

Note that, the grey values are conditions that exceed the battery model range. The baseline is highlighted and labelled in light blue and occurs when there is no load shedding, i.e. the load shedding factor is one.

As can be seen from the figure, including a load shedding factor extends the discharge time in comparison to the baseline without load shedding. As an approximation it can be seen that for electrical power loadings below 300W the endurance time may be extended between 20 minutes to more than 1 hour for a load shedding factor difference greater than 0.02%.

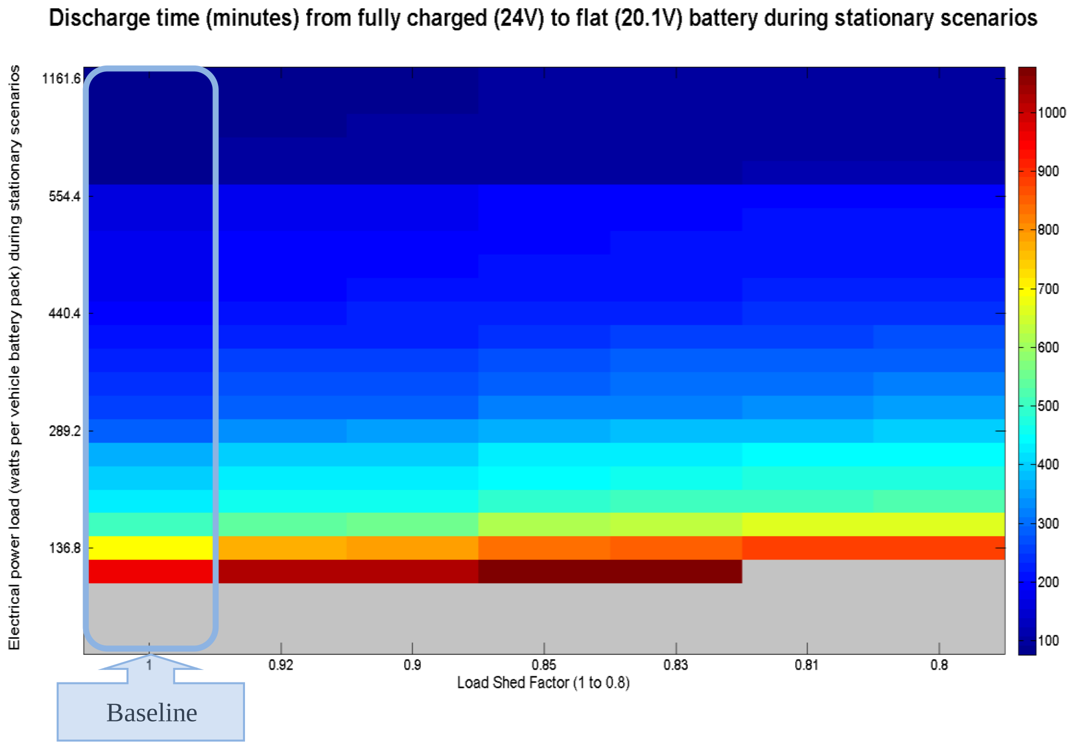


Figure 18 Full discharge times during parked mode

6.3 Charge sustainment mode

During charge sustainment mode, the relevant power flows for stationary scenarios are shown in Figure 14(b), and Figure 14(c). The power flow referred to in Figure 14(b) was selected for comparisons. Figure 19 gives the charging time taken to for the modelled fuel cell using 2kW to charge each battery pack from 20.1V up to 24V, for different electrical load scenarios encountered during the selected stationary scenario. The figure allows for a visual comparison against the baseline with respect to the amount of time in minutes that it takes to fully charge the vehicle battery pack during silent watch, across multiple electrical power demands (vertical axis), and across different load shedding factors (horizontal axis). The colour represents the charge time in minutes corresponding to a particular electrical load with a given load shed factor. The dark blue values in the colour scale represent the fastest charge time, and the dark red values represent the longest time to charge. Grey values are conditions that exceed the battery model range. The baseline is highlighted and labelled in light blue and occurs when there is no load shedding, i.e. the load shedding factor is one.

As can be seen from Figure 19 including a load shedding factor reduces the charging time in comparison to the baseline without load shedding.

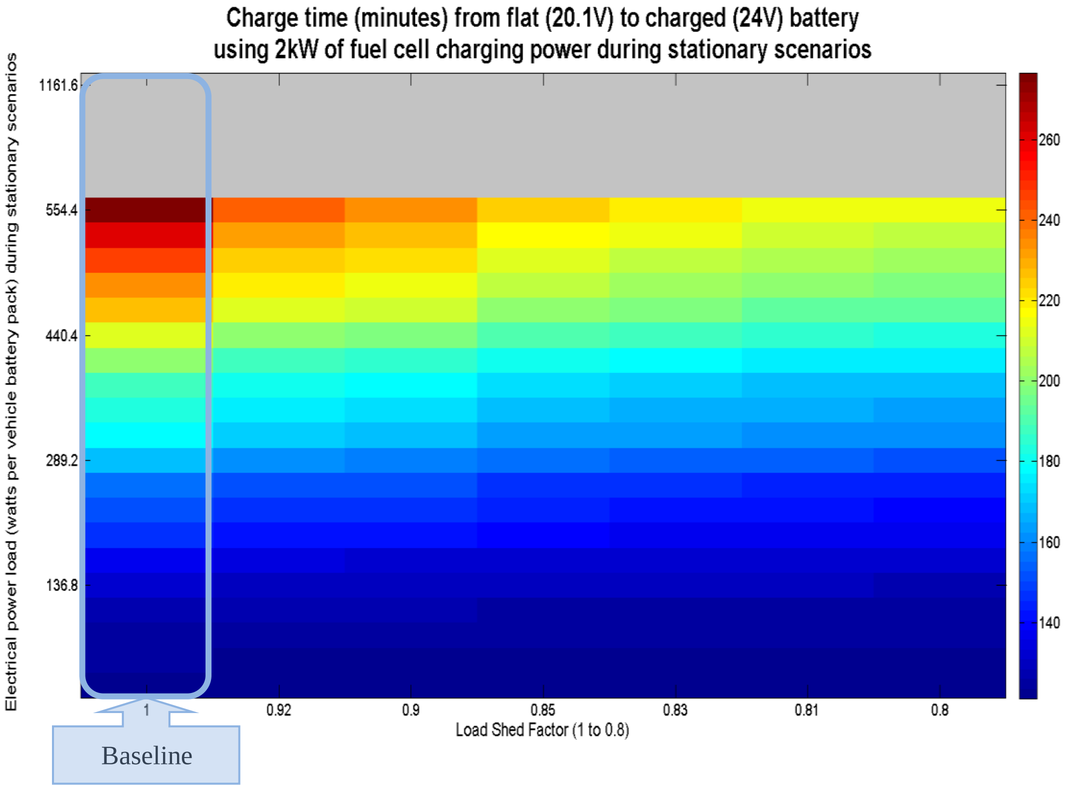


Figure 19 Charging times using 2kW of fuel cell power during stationary conditions

6.4 Moving Scenarios

As mentioned previously there are two main modes to consider, charge depletion and charge sustainment mode. During charge depletion mode the relevant power flows for moving scenarios are referred to in Figure 13(c) corresponding to hybrid electric mode, and in Figure 13(d) corresponding to electric mode. During charge sustainment mode the relevant power flows for moving scenarios are shown in Figure 14(a) which corresponds to electric generation mode, and shown in Figure 14(d) for regenerative braking mode.

The results of comparing vehicle acceleration, ISG efficiency, and ICE fuel consumption against the baseline for each of these modes are discussed below. The results are obtained by running the simulation script for moving scenarios given in Appendix A.

Similarly to the results for stationary scenarios, the results in this section are also presented as images, the horizontal and vertical axis represent the contributions of the ISG and ICE respectively. The torque produced is based on the RPM setting of the ISG and ICE. The total torque produced then results in the vehicle accelerating. The value for the vehicle acceleration is represented as a color for each ISG and ICE torque contributions. Similarly, the fuel consumption and the ISG electrical efficiency is also represented in color, based on the particular RPM setting of the ICE or ISG.

After analysing the results for different terrain inclines, and gear combinations, it was found that due to the constraints in the parameters of the vehicle model, the vehicle is restricted to accelerate from rest for terrain inclines of less than 12 degrees when using the highest gearing in hybrid electric mode. It was also noted that there was a large region of electrical and mechanical torque combinations that produced drive shaft speeds which exceeded the ISG and ICE speed range of 4260 RPM. A scenario which included values for fuel consumption and ISG efficiency that corresponded to driveshaft speed less than or equal to 4260 RPM, was the scenario of the vehicle accelerating from rest using the lowest gear ratio. The ICE fuel consumption is shown in Figure 21 and the ISG efficiency is shown Figure 22 for the scenario.

6.4.1 Acceleration from rest over a flat terrain using the lowest gear ratio

The results shown in Figure 20 below display the values for the acceleration produced by torque combinations with the lowest gearing applied across generation mode (i.e. the baseline) with the ISG off and the ICE on, electric mode which is when the ICE is switched off and the ISG on, regenerative braking when both ICE and ISG are off, and hybrid electric mode when both ICE and ISG are on. A region of interest is in the range between 1682.1 and 2909.7 RPM for ICE torque contributions and between 700 and 3523.4 RPM for ISG torque contributions. Note that, within this range the vehicle is able to accelerate considerably more than the baseline.

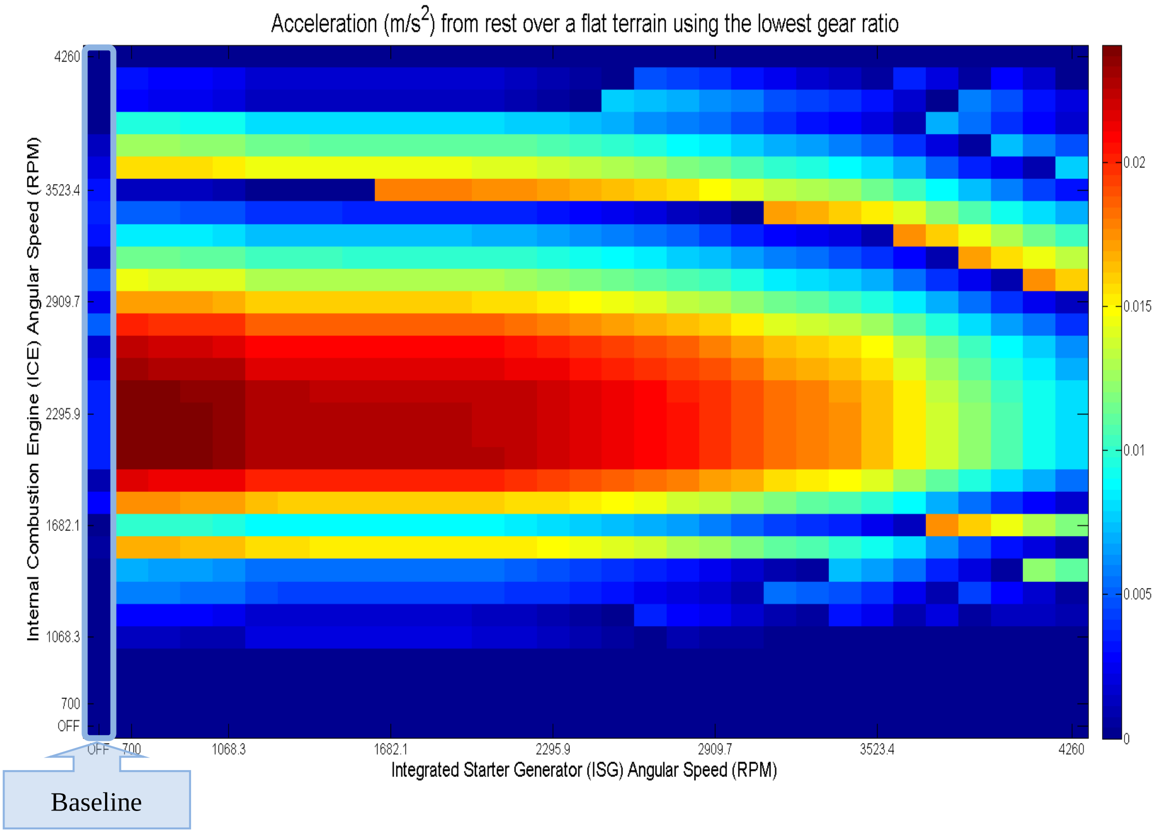


Figure 20 Acceleration over a flat terrain using the lowest gear ratio

Figure 20 allows for a visual comparison against the baseline with respect to the take-off acceleration, using the lowest gear ratio over a flat terrain, across different ICE and ISG torque combinations. The colour represents the take-off acceleration that results from the torques produced when operating them at different ICE (vertical axis) and ISG (horizontal) rotational speeds. The dark blue values in the colour scale represent the lowest accelerations, and the dark red values represent the highest accelerations. The baseline is highlighted and labelled in light blue and occurs when the ISG is off (i.e. used as a generator).

6.4.2 Fuel Consumption over a flat terrain using the lowest gear ratio

Figure 21 shows the fuel consumption across different torque contributions of the ICE and the ISG. The fuel consumption is based on the resulting driveshaft speed after the torque is applied by the ISG and/or ICE. The fuel consumption is calculated assuming that the ICE is used entirely to maintain the resulting driveshaft speed after the vehicle accelerates due to the applied torque.

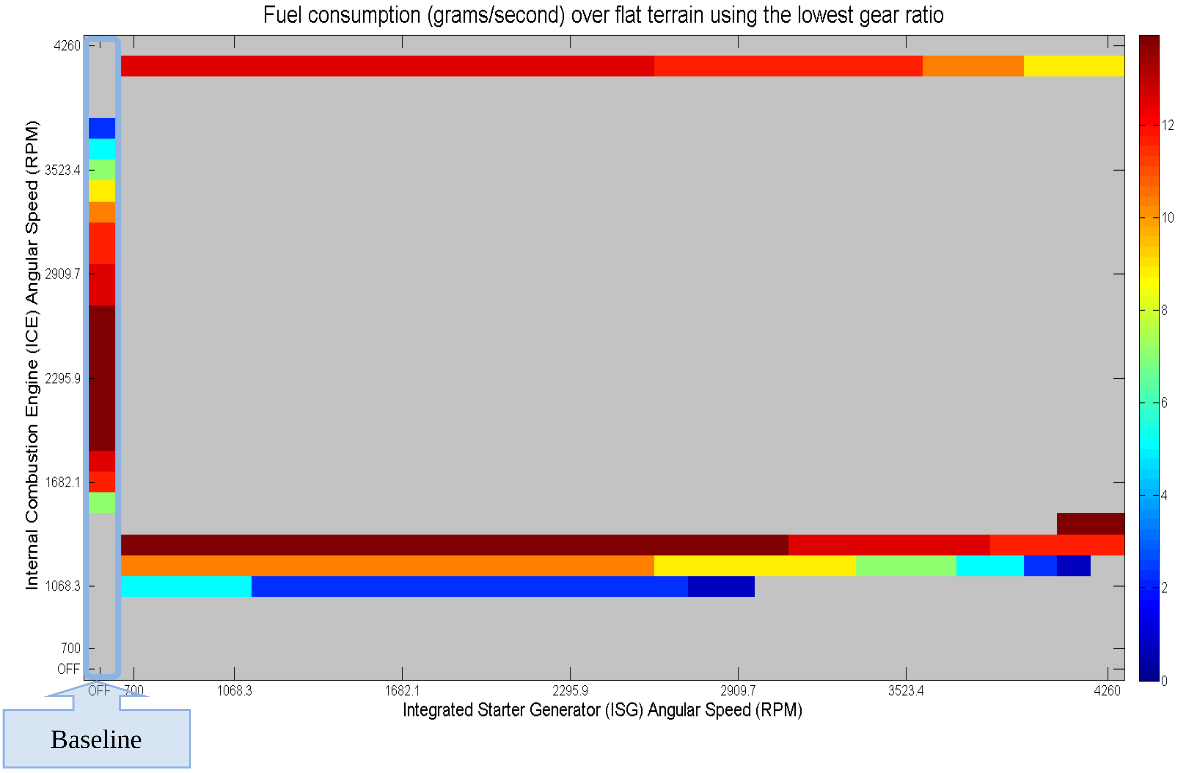


Figure 21 Fuel consumption over a flat terrain using the lowest gear ratio

The figure allows for a visual comparison against the baseline with respect to the fuel consumption, using the lowest gear ratio over flat terrain, across different ICE and ISG torque combinations. The colour represents the fuel consumption that results from the torques produced when operating them at different ICE (vertical axis) and ISG (horizontal) rotational speeds. The dark blue values in the colour scale represent the lowest fuel consumption, and the dark red values represent the highest fuel consumption. The baseline is highlighted and labelled in light blue and occurs when the ISG is off.

Note that the grey region in Figure 21 is a region outside the range of the ISG and ICE models i.e. regions were the drive shaft angular speed is greater than 4260 RPM.

6.4.3 ISG Efficiency over a flat terrain using the lowest gear ratio

Figure 22 shows the electrical conversion efficiency of the ISG across different torque contributions made by the ICE and the ISG. The efficiency is based on the resulting driveshaft speed after the torque is applied by the ISG and/or the ICE. In this test the efficiency is calculated assuming that the ISG is used entirely to maintain the resulting driveshaft speed after the vehicle accelerates due to the applied torque.

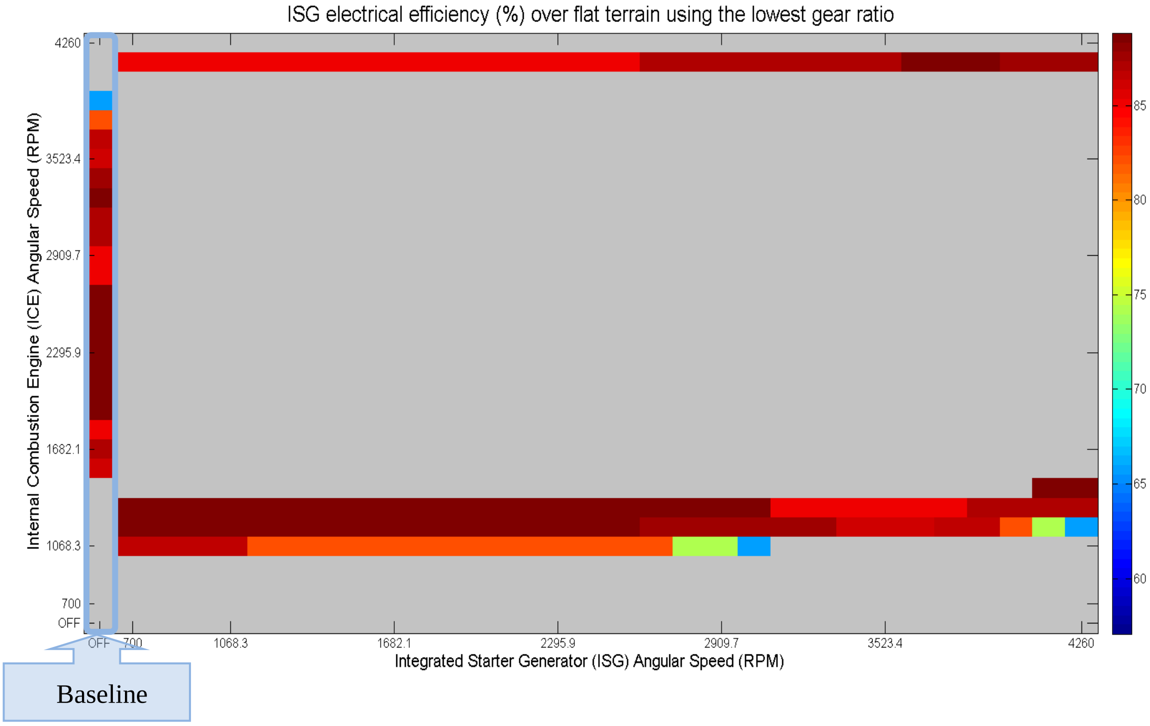


Figure 22 ISG Efficiency over a flat terrain using the lowest gear ratio

The figure allows for a visual comparison against the baseline with respect to the ISG efficiency in converting mechanical to electrical power and vice versa (assuming same conversion efficiency when generating and motoring), using the lowest gear ratio over flat terrain, across different ICE and ISG torque combinations. The colour represents the ISG generating or motoring efficiency that results from the torques produced when operating them at different ICE (vertical axis) and ISG (horizontal) rotational speeds. The dark blue values in the colour scale represent the lowest efficiency, and the dark red values represent the highest efficiency. The baseline is highlighted and labelled in light blue and occurs when the ISG is off.

Note that the grey region in Figure 22 is also a region outside the range of the ISG and ICE model.

6.4.4 Acceleration from rest over a flat terrain using the highest gear ratio

Figure 23 displays the values for accelerations produced by torque combinations with the highest gearing applied across generation mode (i.e. the baseline) with the ISG off and the ICE on, electric mode which is when the ICE is switched off and the ISG on, regenerative braking when both ICE and ISG are off, and hybrid electric mode when both ISG and ICE are on. Note that hybrid electric mode produces the highest accelerations compared to the baseline.

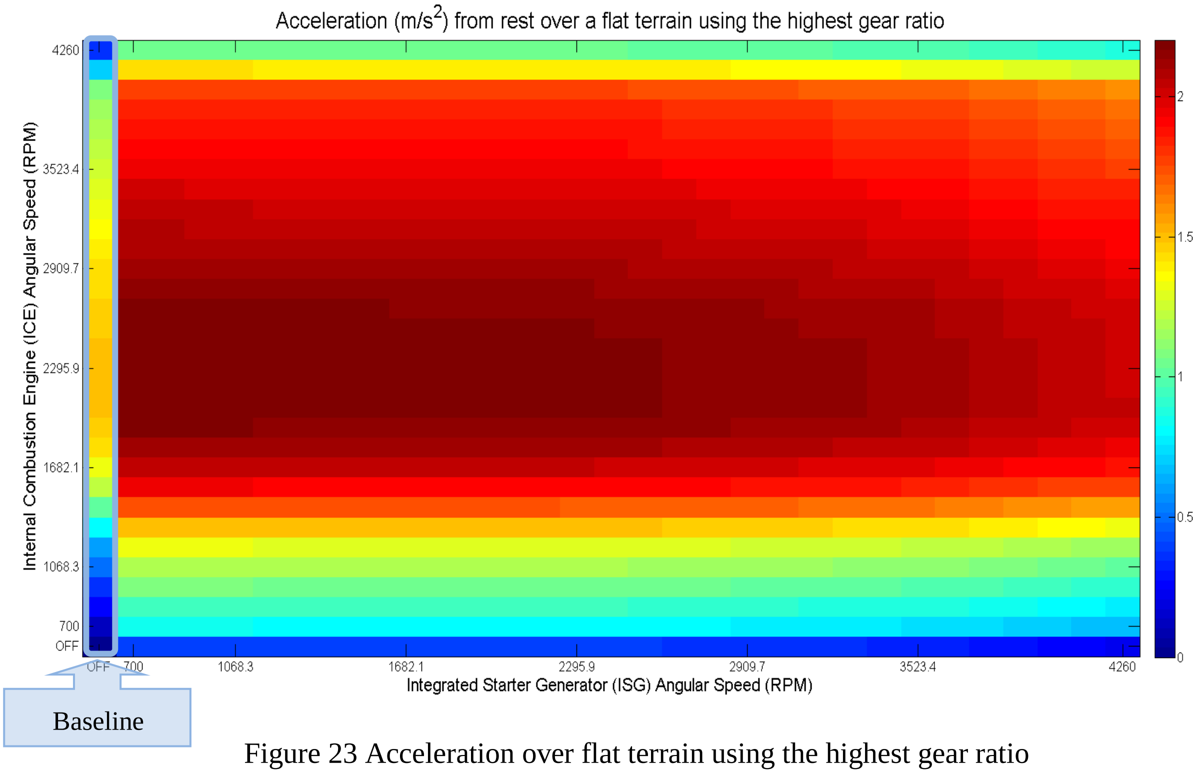


Figure 23 Acceleration over flat terrain using the highest gear ratio

The figure allows for a visual comparison against the baseline with respect to the take-off acceleration, using the highest gear ratio over flat terrain, across different ICE and ISG torque combinations. The colour represents the take-off acceleration that results from the torques produced when operating them at different ICE (vertical axis) and ISG (horizontal) rotational speeds. The dark blue values in the colour scale represent the lowest accelerations, and the dark red values represent the highest accelerations. The baseline is highlighted and labelled in light blue and occurs when the ISG is off.

6.4.5 Acceleration from rest over a 12 degree terrain using the highest gear ratio

Figure 24 shows the values for accelerations produced by torque combinations with the highest gearing applied over a terrain incline of 12 degrees across generation mode (i.e. the baseline) with the ISG off and the ICE on, electric mode which is when the ICE is switched off and the ISG on, regenerative braking when both ICE and ISG are off, and hybrid electric mode when both ISG and ICE are on. It can be seen that the vehicle is able to accelerate only in hybrid electric mode.

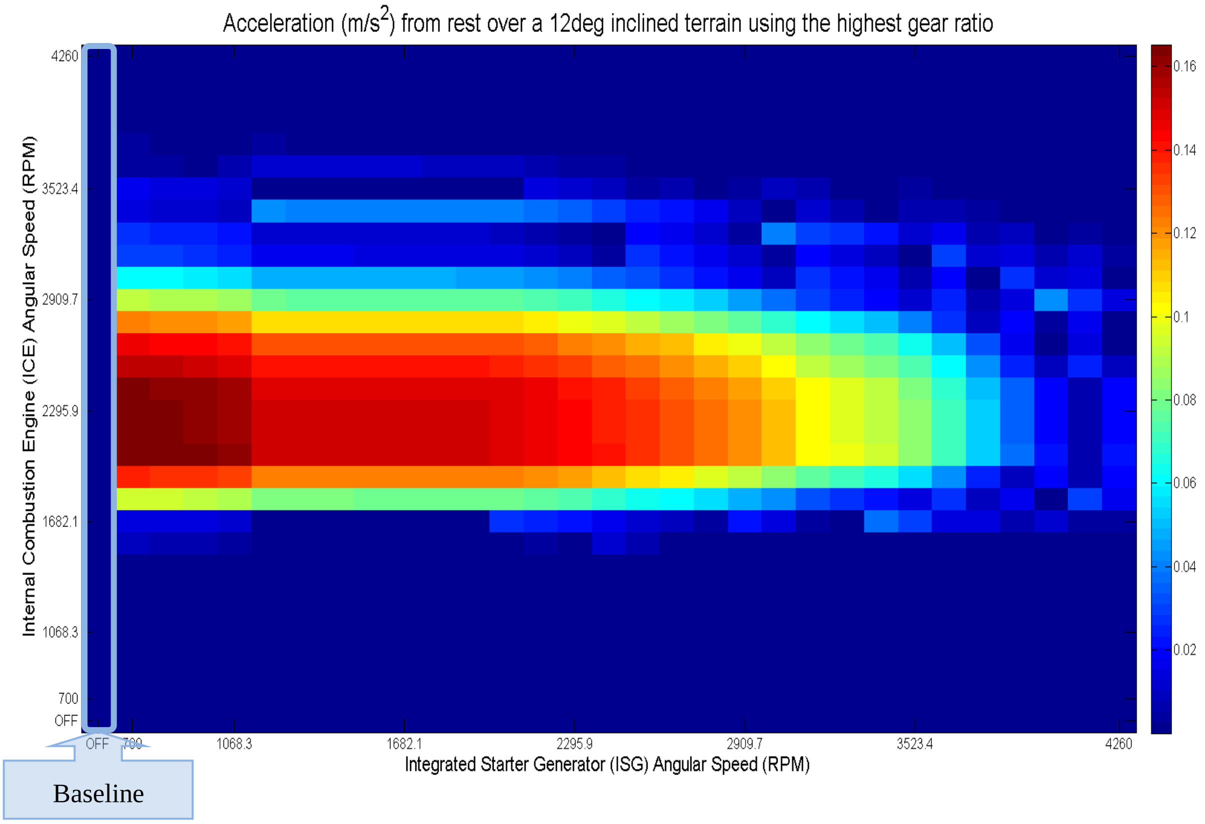


Figure 24 Acceleration over a 12 degree terrain using the highest gear ratio

The figure allows for a visual comparison against the baseline with respect to the take-off acceleration, using the highest gear ratio over a 12 degree inclined terrain, across different ICE and ISG torque combinations. The colour represents the take-off acceleration that results from the torques produced when operating them at different ICE (vertical axis) and ISG (horizontal) rotational speeds. The dark blue values in the colour scale represent the lowest accelerations, and the dark red values represent the highest accelerations. The baseline is highlighted and labelled in light blue and occurs when the ISG is off.

6.5 Summary of the simulation results

Moving and stationary scenarios have been explored across charge sustainment and charge depletion modes, showing the comparisons of extending the baseline to include additional energy management strategies. The results show that load shedding can slow the discharge time of batteries and reduce charging time. A change of 0.02 percent in the load shed factor may equate to making the battery pack discharge 30 minutes to 1 hour longer than the baseline or take 30 minutes to an hour less in order to charge the battery pack.

During moving scenarios including hybrid electric mode means higher take off accelerations compared to the baseline. Furthermore the vehicle is not able to accelerate from rest over a 12 degree terrain incline unless it is in hybrid electric mode. In comparing the fuel consumption and ISG electrical efficiency it is important to note that an optimal tradeoff between these quantities and vehicle acceleration is required. The ISG produces high torques at lower RPM than the ICE, however high ISG conversion efficiency is produced at higher RPM. The ICE reaches a maximum torque at around 2296 RPM however at this RPM fuel consumption is midway its maximum of approximately 15 grams/second. This warrants investigating in detail the mutual coupling of the ISG and ICE such that an optimal tradeoff between acceleration, fuel consumption and electrical conversion efficiency is reached.

The comparison method needs to be conscious of model limits and bounds. Most of the torque combinations resulted in driveshaft speeds which exceeded the ISG and ICE range of 4260 RPM. Only a limited region of ISG and ICE speeds (as shown in Figure 21 and Figure 22) fell within the ISG and ICE speed limits. Furthermore, the battery model was limited to charging and discharging currents of 152 Amps. The comparisons for moving scenarios assumed that there is sufficient battery power to drive the ISG, however upon closer observation the baseline battery pack is restricted in providing sufficient power to allow the ISG to operate across its entire RPM speed range. The baseline battery pack requires sizing modifications to accommodate for the ISG operating in electric and hybrid electric mode.

Chapter 7: Conclusions and Future Works

Vehicle power system architectures are evolving beyond conventional ones that include a single alternator and battery. The main drivers for this evolution are based on the desire to reduce fuel consumption and gas emissions along with the increase demand for on board electrical energy. Amongst the different power system architectures available, the hybrid electric vehicle architecture is one that offers flexibility in balancing the trade-offs associated with minimising fuel consumption, and greater capacity to meet electric energy demands. Hybrid electric vehicles allow for a wide range of energy management strategies to be investigated. Such strategies are able to accommodate for the need to reduce fuel consumption, undesirable gas emissions, and the need to meet the increased dependence on electrical energy. The strategies can be implemented by vehicle power management systems running energy management algorithms. Such systems are becoming more common in the commercial sector, however, they are not commonly found in current military vehicles.

This thesis has focussed on investigating energy management strategies applied to a hybrid electric architecture through a case study. The case study involved investigating a military vehicle that included a mild-parallel-hybrid power system. This case study has been selected because current vehicle manufacturers and academia have primarily focussed on investigating hybrid electric vehicle power management strategies in urban environments.

In comparison, a case study involving a military off-road environment allows a new application domain to be investigated. This thesis described the case study, and presented the results of comparing a baseline architecture against one that has been extended to include additional energy management strategies under different military operating scenarios. The comparison was performed through simulations using a software environment. The results of the comparison showed that hybrid electric drive produced higher take off accelerations compared to the baseline, and that a 12 degree incline can be traversed only through hybrid electric mode. The results also highlighted the tradeoffs between higher accelerations, fuel consumption, and electrical conversion efficiency.

The method for comparing against the baseline was restricted in terms of the models and component sizing. In future it would be advantageous to compare different vehicle power system architectures with energy management topologies and include the flexibility to also modify model parameters and sizing, in order to meet a set of performance requirements under a wider range of scenarios. Furthermore a wide range of energy management algorithms could be evaluated. This task would contribute to further synthesize the area of research into a system wide holistic approach that includes optimizing the vehicle power system architecture and its energy management algorithms in order to meet performance tradeoffs and specifications.

Appendix A: Matlab Scripts

The modelling and simulation components of the simulation environment include the following Matlab scripts and .mat files

1. Operating Environment
2. Combat Vehicle Platform
3. Simulation scripts for the stationary scenarios
4. Simulation script for the moving scenarios

Operating Environment (loadScenarios.m)

The file includes constants and data sets to capture selected scenarios that may be encountered by the vehicle based on the specifications referenced in Chapter 2. It includes information on the range of vehicle speeds, terrain inclines, vehicle forces, and the electrical loads that may be encountered in a scenario.

Combat Vehicle Platform (mhevModel.m)

The file includes the constants and constant data sets required to model the behaviour of the mild-hybrid electric combat vehicle. It includes data sets for the following sub-components: Vehicle and wheel dimensions, Engine, Integrated Starter Generator, Inverter, Transmission, DC/DC converter, Battery, Fuel Cell, and Electrical Loads. The model is not based on mathematical functions; it is a collection of empirical data sets and constants based on manufacturers and literature information.

Simulation script for the stationary scenarios

```
% State space for parking discharge mode
% Engine off

clear all;
mhevModel; %Load the vehicle model
loadScenarios; %Load scenarios

%Run the simulation
PbDinternal=zeros(length(Pls),length(loadShedFactor));
tbD=zeros(length(Pls),length(loadShedFactor));
Vf=10.1; %Voltage when the battery is fully discharged
Vdc=24; %The assumption is made that the DC bus voltage is maintained constant
tic;
for i=1:length(Pls)
    for ii=1:length(loadShedFactor)
        PbDinternal(i,ii)=Pls(i)*loadShedFactor(ii)/effBat;
        IbD=0.5*PbDinternal(i,ii)/Vdc;
        tbD(i,ii)=griddata(idm,vdm,tdm,IbD,Vf,'linear');
    end
end
toc;
```

```
% State space for fuel cell and idle speed charge mode
% Engine off

clear all;
mhevModel; %Load the vehicle model
loadScenarios; %Load scenarios

%ISG Power
Widle=1200; %RPM
Pdcidle=interp1(Wr,PdcR,Widle); %Watts
PidleOnOff=[0 Pdcidle]; %Include when there is no idle charge assist

% Generate cost maps for Idle Fuel Cell Charge Mode
Pbch=zeros(length(PidleOnOff),length(Pls),length(loadShedFactor),length(Pfc));
PbCinternal=zeros(length(PidleOnOff),length(Pls),length(loadShedFactor),length(Pfc));
costFuelFc=zeros(length(PidleOnOff),length(Pls),length(loadShedFactor),length(Pfc));
costEffFc=zeros(length(PidleOnOff),length(Pls),length(loadShedFactor),length(Pfc));
tbC=zeros(length(PidleOnOff),length(Pls),length(loadShedFactor),length(Pfc));
Vf=23.9;
VdcIdle=28; %The assumption is made that the DC bus voltage is mantained constant
Vdc=24;

% Run simulations
costIsgEff=[0 isgEffCost(Wr,effISGGen,Widle)];
costFuelIce=[0 iceFuelCost(Wr,FeR,Widle)];
tic;
for k=1:length(PidleOnOff)
    for i=1:length(Pls)
        for ii=1:length(loadShedFactor)
            for j=1:length(Pfc)
                Pbch(k,i,ii,j)=effDCDCDown*Pfc(j)+PidleOnOff(k)-Pls(i)*loadShedFactor(ii);
                PbCinternal(k,i,ii,j)=effBat*Pbch(k,i,ii,j);
                costFuelFc(k,i,ii,j)=fcFuelCost(Pfc,FuelComFc,Pfc(j));
                costEffFc(k,i,ii,j)=fcEffCost(Pfc,effFc,Pfc(j));
                if k==2
                    IbC=0.5*PbCinternal(k,i,ii,j)/VdcIdle; %Idle charging and fuel cell
                else
                    IbC=0.5*PbCinternal(k,i,ii,j)/Vdc; %No idle charging, fuel cell only
                end
                tbC(k,i,ii,j)=griddata(idm,vdmc,tdm,IbC,Vf,'linear');
            end
        end
    end
end
toc;
```

Simulation script for the moving scenario

```
      clear all;
      mhevModel;
      loadScenarios;

      syms Fdr ms vws Rds Rrs Rgs ps Cds Ads rws gs Crs beta v(t) a(t) d(t) Tes Tms xdrs Ugs Nfs
Ngs Nhls gearRatio vinit;
      assume(ms>0); %vehicle mass with inertia factor in kg
      assume(ps==1.2); %air density at standard conditions
      assume(vws>0); %wind speed in m/s
      assume(Ads>0); %vehicle drag cross section area m2
      assume(Cds>0); %vehicle drag coefficient
      assume(gs==9.81); %gravity in m/s2
      assume(Crs>0); %coefficient of rolling resistance
      assume(Fdr>=0);
      assume(Tes>=0);
      assume(vinit>=0);

      Tdr=Tes+Tms;
      gearRatio=Nhls*Ngs*Nfs*Ugs*xdrs;
      Fdr=gearRatio*Tdr/rws; %Hybrid mode
      Rds=(Ads*Cds*ps)/2;
      Rgs=gs*ms*sin(beta);
      Rrs=Crs*gs*ms*cos(beta);

      Dv=diff(v);
      v(t)=dsolve(Fdr==(ms*Dv+Rds*((v-vws)^2)+Rgs+Rrs), v(0)==vinit);
      v(t)=simplify(v(t));
      pretty(v(t))

      %acceleration
      a(t)=diff(v(t),t);
      a(t)=simplify(a(t));
      pretty(a(t))

      %distance
      d(t)=int(v(t),t);
      d(t)=simplify(d(t));
      pretty(d(t))

      %Scenario comparisons

      %Simulation Constants
      %Environment
      vws=vw; %m/s head wind speed
      ps=p; %kg/m3 ambient air density
      gs=g; %m/s2 acceleration due to gravity

      %Vehicle
      ms=m; %kg vehicle mass
      rws=rw; %Wheel radius in metres
      Ads=Ad; %m2 vehicle drag surface area estimate
      Cds=Cd; %Drag coefficient
      Crs=Cr; %0.0155; %Coefficient of rolling friction
      xdrs=xdr; %Cross drive
      Ugs=Ug; %Total transmission power efficiency
      Nfs=Nf; %Final gear ratio ie differential (back and rear)

      %NOTE: The braking forces are ignored for the comparison

      cont=[0 1:length(Wr)]; %Control settings for angular speed setting of the ICE and ISG

      %Acceleration at final speed less than steady state speed
      accelMax=zeros(length(cont),length(cont));

      dbstop if error;
```

```
      tic;
      vi=1;
      for vi=1:length(veh_speed)
          for incli=1:length(incl)
              for hli=1:length(ghl)
                  for geari=1:length(r_gear)
                      for ei=1:length(cont)
                          for mi=1:length(cont)
                              %CHARGE SUSTAINING MODES
                              %When  ei>1  and  mi=1  then  this  is  Generating  Mode  (Baseline)
(We=Wr(ei),Tm=0)
                              if ei>1 && mi==1
                                  Tes=interp1(Wr,TeR,Wr(cont(ei)));
                                  Tms=cont(mi);
                              end
                              %When ei=1 and mi=1 then this is Regenerative Mode (Te=0,Tm=0)
                              if ei==1 && mi==1
                                  Tes=cont(ei);
                                  Tms=cont(mi);
                              end
                              %CHARGE DEPLETION MODES
                              %When ei>1 and mi>1 then this is Hybrid Mode (We=Wr(ei),Wm=Wr(mi))
                              if ei>1 && mi>1
                                  Tes=interp1(Wr,TeR,Wr(cont(ei)));
                                  Tms=interp1(Wr,TmR,Wr(cont(mi)));
                              end
                              %When ei=1 and mi>1 then this is Electric Mode (Te=0,Wm(mi)=Wr)
                              if ei==1 && mi>1
                                  Tes=cont(ei);
                                  Tms=interp1(Wr,TmR,Wr(cont(mi)));
                              end

                              %Set variable parameters
                              vinit=veh_speed(vi); %m/s
                              beta=incl(incli);
                              Ngs=r_gear(geari); %Gears
                              Nhls=ghl(hli);

                              t1=0.0001;
                              accel_start=eval(subs(a(t1)));
                              if accel_start<0
                                  accelMax(ei,mi)=0;
                              else
                                  tss=max(eval(solve(subs(a(t))==0.0001)));
                                  vss=eval(subs(v(tss)));
                                  speedSS=veh_speed(veh_speed<=vss);
                                  if isempty(speedSS)
                                      accelMax(ei,mi)=0;
                                  else
                                      %Find max and min acceleration between the valid speed
                                      %scenario range of speedSS
                                      tvmax=max(eval(solve(subs(v(t))==max(speedSS))));
                                      vmax=eval(subs(v(tvmax)));
                                      accelMax(ei,mi)=eval(subs(a(tvmax)));
                                  end
                              end
                          end
                      end
                  end
              end
          end
      end
      toc;
```

Appendix B: An Introduction to Electrical Power Management Systems for Military Land Vehicles by Manuel Salazar

A vehicle electrical power management system provides monitoring and control at both the sub-component and power system level to address the following power management functions: electrical fault prevention and protection, and reducing electrical power consumption and conversion losses. This report gives an introduction to vehicle electrical power management systems. It describes examples of military vehicle power management technologies currently available, followed by an insight into next generation electrical power management systems.

Note that, the demand for electrical power on board military vehicles is increasing. It is a result of more electric and electronic equipment being integrated into vehicles for upgrades or enhancements to automotive and mission systems. To accommodate for more electrical power demand, extra power sources are being incorporated into the vehicle. Having the vehicle power system include more electric and electronic equipment and more electrical power sources intensifies the challenges associated with the power management functions of electrical fault prevention and protection, and reducing electrical power consumption and conversion losses. A Vehicle Electrical Power Management System (VEPMS) aims to address the power management functions through monitoring and controlling the vehicle's electrical power system.

A VEPMS comprises a variety of components including sensors, actuators, power regulators, controllers and human machine interfaces working together to address the power management functions. Current options to address the power management function of electrical fault prevention and protection include but are not limited to using Health and Usage Monitoring System functionality to support Condition Based Maintenance, and using a Battery Management System to extend the life of the battery. The power management function of reducing power consumption and conversion losses can be addressed by controlling when electrical loads or power sources are activated, or when to place electrical loads in low power consumption states.

In looking beyond the current features and functions of a VEPMS, an evolutionary path for future VEPMSs could be their monitoring and control functionality becoming tightly integrated to power sources and loads. The power sources and loads could then be networked and more tightly integrated to the vehicle chassis, and include system-wide control optimisation, intelligent and autonomous behaviour.

B1. Introduction

Additional electrical and electronic equipment is being incorporated into military vehicles in order to enhance or upgrade automotive and mission systems. Incorporating additional electrical and electronic equipment results in an increase demand for electrical power. In order to accommodate for more electrical power, extra power sources are being incorporated into the vehicle, such as, additional or larger batteries and alternators, and Auxiliary Power Units. Other power sources, such as Lithium-ion batteries, Integrated Starter Generators, solar panels, and fuel cells are also possible options to address the increase power demands. Having the vehicle power system include more electric and electronic equipment and more electrical power sources intensifies the challenges associated with implementing the following power management functions: electrical fault prevention and protection, and reducing electrical power consumption and conversion losses. A Vehicle Electrical Power Management System (VEPMS) aims to address the power management functions through monitoring and controlling the vehicle's electrical power system. This report provides an introduction to VEPMSs, followed by a brief discussion of their possible evolutionary path.

B2. Vehicle Electrical Power Management Systems

A VEPMS monitors and controls the entire vehicle's electrical power system, including the generation, distribution, storage and consumption of electrical power. Monitoring and control is used to address the following power management functions: electrical fault prevention and protection, and reducing electrical power consumption and conversion losses. The implementation details of the power management functions vary depending on the amount, type and usage profile of the electrical loads, power sources, and energy storage devices included in the vehicle's electrical power system. Implementation variations and details are not discussed in depth within this report, the reader is referred to [1] and [2] for details regarding implementation variations based on different vehicle electrical power systems.

A VEPMS is not necessarily implemented as one complete system from a single manufacturer. It comprises a number of components working together to realise the power management functions [1-4], these components include:

- sensors used for monitoring temperature, voltage or current variations,
- electronic control units that run software to process sensor information and send control signals to actuators and power electronics,
- actuators that support reducing power consumption by switching loads on or off, provide temperature control for reducing power conversion losses and preventing overheating, and protect devices by isolating them from faults,
- power electronics to compensate against voltage and current variations, and
- human machine interfaces to interact with operators when faults occur, and provide sensor information that can assist operators to make decisions for fault prevention, and reducing power consumption and power conversion losses.

The following sections provide a brief description of options to address the power management functions of electrical fault prevention and protection and reducing electrical power and conversion losses, as applicable to military vehicles.

B2.1 Electrical Fault Prevention and Protection

A VEPMS can control the power sources and electrical loads in such a manner as to reduce component usage, hence reduce the likelihood of faults occurring [5]. It can monitor and protect equipment against power spikes and undesired transient conditions [6]. It can provide mechanisms to gracefully turn equipment on and off in order to prevent faults during engine start and shutdown [3]. Realising the implementation of these functions commonly requires voltage, current and temperature sensors connected to Electronic Control Units (ECUs). Voltage, current and temperature sensor readings are processed by the ECUs to estimate component usage, electrical transients or faults. The processed sensor signals are then converted into control signals that isolate or regulate the power sources or loads through power electronic switchgear. Converting sensor signals to control signals may be done through simple rule based algorithms, classical control, state space control or using computational intelligence techniques.

The timeliness to isolate power sources depends on the accuracy of the sensor information, and the processing speed of the ECUs converting sensor signals to control signals. Precision and timeliness to regulate power sources depends on the power capacity, power switching losses and switching rates of the power switches, and their response time to control commands.

A VEPMS can provide Health and Usage Monitoring System (HUMS) functionality by estimating the health and age of the vehicle power system components. HUMS functionality supports predicting when power system components should be replaced, hence reducing the likelihood of electrical faults [7-9]. It can also support Condition Based Maintenance (CBM) to maintain components only as required and not periodically [7]. Additionally, if a fault occurs, a VEPMS can provide troubleshooting and fault diagnostic support, which minimises troubleshooting downtime [3, 7].

Military vehicles depend on vehicle batteries for starting and during silent watch missions when the engine is off. A VEPMS can include a Vehicle Battery Management System (VBMS) to monitor and control the charge and discharge of batteries [10]. The controlling functionality provides battery cell balancing, voltage regulation, and battery protection [3, 10, 11], which reduce the likelihood of battery faults. The monitoring functionality can include State of Charge (SoC) and State of Health (SoH) estimations [12-14], and charge and discharge time estimations [7, 11]. The estimations support the provision of warnings to prevent excessive discharge, and notifications for battery replacements [7].

The functionality discussed above is realised by a combination of software and hardware devices. The hardware devices include sensors, electronic control units, and data acquisition units. Hardware devices used for the control aspects of battery management such as cell balancing, voltage regulation and battery protection include power electronic switch gear controlled by ECUs based on sensor information.

Sensor information is processed by ECUs to produce estimations of component and system health, usage, and age. The performance of the implemented functionality depends on the accuracy of the ECU sensors and the status, the accuracy of the health and usage estimation algorithms, the ECU computational constraints to run the algorithms, as well as the human machine interactions used to guide operators through component maintenance and troubleshooting.

B2.2 Reducing Electrical Power Consumption and Conversion Losses

Reducing power consumption is specifically important when loads are being powered solely from the vehicle's batteries, which is a common situation in military operations. Load shedding is a means to reduce power consumption. It involves turning off equipment that is not required to accomplish a task, or placing them in low power consumption modes [15]. To reduce power consumption the VEPMS can allow the operator to group electrical loads required for specific mission tasks, and then activate them only as required [15, 16].

In electrical power systems involving more than one power source (e.g. batteries, auxiliary power unit, and alternator), it is possible to reduce electrical power flow conversion losses by selecting the combination of power sources that can meet the electrical demands with least conversion losses [17].

Vehicle electrical power systems that make use of an internal combustion engine for electrical power generation are common in the military. Within such systems reducing electrical power consumption through load shedding has desirable secondary effects of lowering fuel consumption [18].

The functionality above is realised by a control system including sensors, ECUs and power electronic switch gear. Sensor information is processed by the ECUs and control signals are generated to control power electronic devices that can control when power sources and loads are switched on or off, or for power regulation. The performance of the control system greatly depends on the ECUs' control algorithms and the switching speed and power capacity of the power electronic switch gear used to perform load shedding and power source control.

B2.3 Military VEPMS Technology Examples

The following section briefly discusses three commercially available examples of VEPMS technologies applicable to military vehicles.

B2.3.1 Ultra Electronics PALS Battery Monitoring System

The Ultra Battery Monitoring System uses a standalone sensor placed at each battery terminal of a 2x12V battery pair to measure voltage, current and temperature. It then uses a proprietary algorithm to calculate, for each battery within the battery pair, the SoC, SoH and the time remaining until each battery discharges for the applied electrical load [19]. The system can also provide additional data such as:

- “Reserve State of Health”, which gives an indication of the ability to provide current for an extended period of time [20];
- “Cranking State of Health”, which gives an indication of the ability to source high levels of current for a short time [20]; and
- Data on the number of engine starts, peak starting current, time taken to start, minimum voltage, and current draw during vehicle off state (i.e. parasitic load consumption) [20].

Figure 1 shows images of the physical configuration of the unit, showing the terminal sensors attached to the batteries, wiring, data acquisition control unit, and user display.

Figure 1 PALS Battery monitoring system physical components [20, 21]

Overall, this system provides useful information to the operators, enabling them to better utilise battery power within the vehicle, and assist them to prevent flat battery faults. The functionality assists operators to reduce electrical energy consumption and for battery electrical fault prevention and protection.

B2.3.2 Ultra Electronics PALS VEPMS

The Ultra VEPMS includes a ruggedized computer referred to as the EA Processor, and a series of load power distribution units referred to as power nodes as shown in Figure 2.

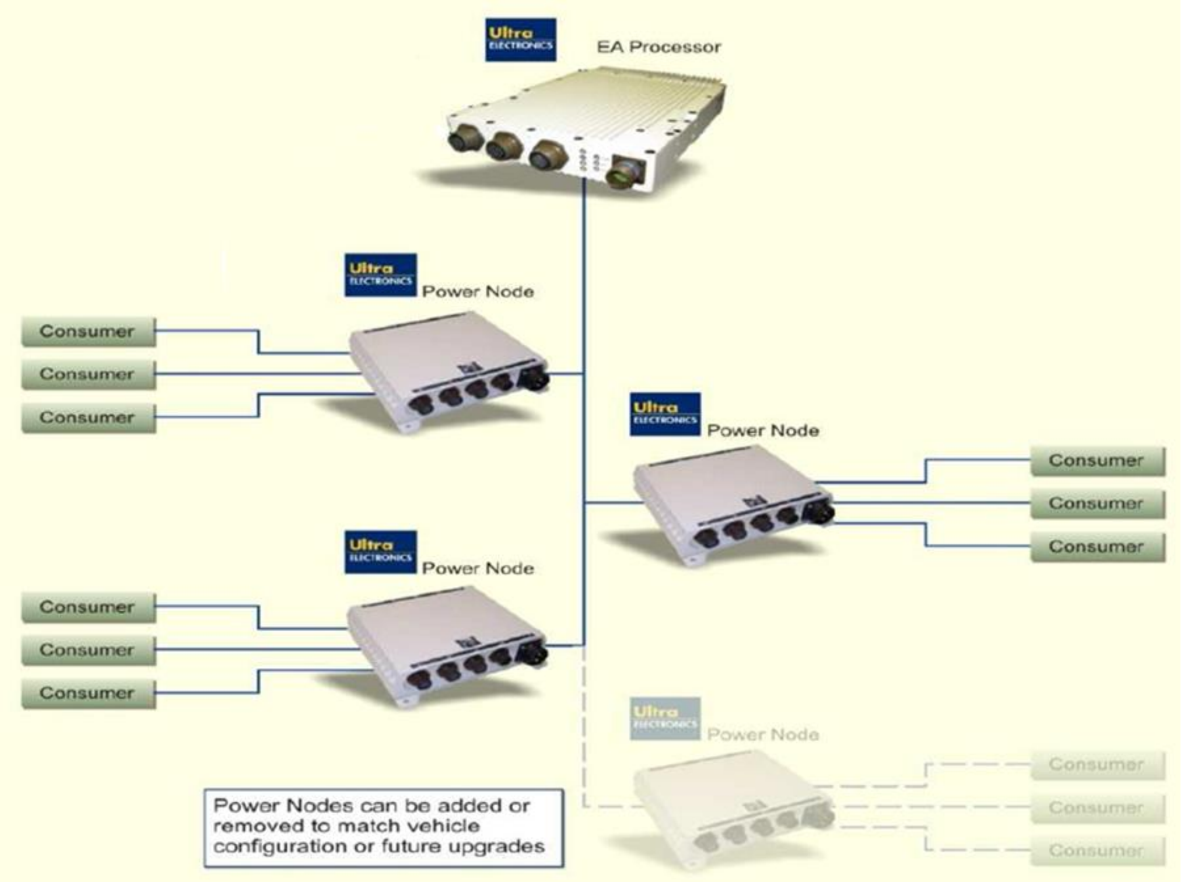


Figure 2 Ultra VEPMS ruggedized computer and power nodes [16]

Each power node can power up to eight electrical loads, and can disconnect individual electrical loads based on current trip levels if there is a fault. The disconnection current trip levels are programmable via the EA Processor proprietary power management software. Each current channel is measured and the information sent to the EA processor via CAN. The power nodes also use watchdog timers and Built-in-Test functionality to reset or test themselves and recover from malfunctions. Programmable current trips and the Built-in-Test functionality facilitates electrical fault prevention and protection.

The use of power nodes facilitates load shedding. Through the EA processor power management software, the user or a technician can configure which loads are turned on based on a certain mode of operation, such as silent watch. The user can then switch between modes and ensure only the necessary loads are on during the selected mode of operation. The ability to load shed contributes to reduce electrical energy consumption.

The Ultra VEPMS provides information on the current loads that are powered and their individual power usage, total power usage, battery state of charge and silent watch time remaining (when combined with an Ultra battery monitoring system as discussed above). The functionality assists operators to reduce electrical energy consumption and for battery electrical fault prevention and protection.

B2.3.3 Global ET VEPMS

Global ET has been developing a VEPMS [22] that includes a series of smart switches that can be controlled through software, to turn electrical loads off and on, and also provide pulse width modulation in order to provide power regulation. This allows for fault isolation, load shedding, and graceful start up and shutdown transitions. The VEPMS is being developed to be integrated into military vehicles [23].

B2.3.4 Summary of examples

The three examples associated with military VEPMS cover limited aspects of monitoring and controlling a vehicle electrical power system. Battery monitoring systems are most common, followed by load shedding systems as in Section 2.3.2, which require user interactions and pre-programming. The Global ET VEPMS is a more modular system that can apply to a wider range of devices in a vehicle power system, as it is a collection of networked programmable smart switches that can be integrated into the vehicle to provide isolation and power regulation for individual power sources and loads or a group of power sources and loads. The system also requires less human interaction.

Although most individual vehicle power sources and loads include their own internal power management systems, system wide power management is currently not common in the military and only exists based on specific requirements. In comparison to the military, system wide power management is more common in the commercial sector through the introduction of electric and hybrid electric vehicles. It is expected that advancements in electrical and hybrid electric vehicle technologies in the commercial world will gradually be introduced in the military domain. The section below discusses a possible evolutionary path beyond the current state of military VEPMS.

B3. Future of Electrical Power Management Systems

The military VEPMS technologies described above are of System Readiness Level (SRL) 7 to 9 and make use of sub-components that have Technology Readiness Level (TRL) 7 to 9 (see [24] for definitions of TRL and SRL). The following section of the report presents future technologies that are of lower TRL or SRL. These technologies range from being conceptual to those being investigated by research institutions and industry. The evolutionary path of a VEPMS is dependent on the development drivers and technology enablers occurring over time. Development drivers are current or future events that cause the need for technological development. Technology enablers are scientific or engineering breakthroughs that facilitate a technology to mature faster. This section provides a brief report on a possible evolutionary path a VEPMS is likely to follow based on observed development drivers and technology enablers that could bring the technology from TRL 1 to 4 to TRL 7 to 9.

B3.1 Development Drivers

The need to provide more on-board electrical energy, reduce fuel consumption and carbon emissions have resulted in increased development of alternative vehicle power systems. Some examples include: 42 Volt Power Systems [25], Multi Voltage Power Systems including DC and AC [4], Multiple Power Source and Loads [17], Parallel and Series Hybrid Electric [26], Fuel Cell or Battery Powered Electric Vehicles [27]. Consequently addressing this need influences the development for VEPMS.

Another driver for VEPMS development is the introduction of novel energy conversion technologies such as multi-fuel fuel cells, energy harvesting of kinetic, background EM or thermal energy.

There is also the concept of tightly integrating different types of power system technologies; for example: super capacitors with batteries [28], or flywheels and electrical generators. In order to save space and weight, research is being conducted to increase the level of integration of the vehicle power system with the vehicle chassis. For example, structural batteries are being investigated which attempt to make batteries become part of the vehicle body [29], and similar concepts are being investigated for power converters and their electronic controls [30].

Other drivers include the introduction of different types of electrical loads [27, 31], for example: electrical propulsion, directed energy weapons, electric armour, high power transmitters, jammers, pulsed lasers, and electronic warfare countermeasures. Additionally, there are potential additional electrical loads on the vehicle associated with individual soldiers, remote equipment and deployed stations.

The use of military autonomous vehicles is increasing. This is a driver to introduce autonomy and intelligent behaviours within vehicle power systems. More of such functionality is expected to be introduced into modern VEPMS.

Taking into account the observed trends in development drivers discussed above, it is anticipated that future VEPMSs are likely to incorporate a network of rugged and robust electrical power management devices. They are likely to be highly integrated to both the vehicle and their power system, and allow for system wide monitoring, control and optimisation of the vehicle's electrical power system. This network of power management devices is expected to have high levels of autonomy and intelligent behaviour. They will monitor and control multiple power sources and adapt to a wide range of conditions in electrical load usage, changes in the environment or changes in power system configurations, and power requirements. The next section lists the technology enablers that could facilitate and speed the process of developing such electrical power management systems from TRL/SRL 1 to 4 to TRL/SRL 7 to 9.

B3.2 Technology Enablers

A range of technology enablers that could accelerate the development and maturity of the future VEPMSs in Section 3.1 are advancements in the following:

1. Accurate design, optimisation and simulation tools, for faster solution exploration and to realise tight integration of the VEPMS into the vehicle and reduce space and weight footprint.
2. Material science, to reduce space and weight footprint of the VEPMS, and for improved electrical conversion properties

3. Manufacturing and integration engineering processes to reduce space and weight footprint of the VEPMS
4. Computer architectures, for accommodating increased power management algorithm computational requirements, and reduce space, weight and power footprint of the VEPMS.
5. Sensor, networking and information technologies to improve the accuracy, speed and robustness of shared vehicle network information,
6. Semi-conductor technologies for power electronics,
7. Power electronic topologies, to improve electrical conversions, and the space and weight footprint of the VEPMS
8. Mathematical models of current and novel electrical power systems, to be used in power management optimal control algorithms, and
9. Real-time power management strategies and algorithms for state estimation, optimal control, and autonomous behaviour.

B3.3 Possible Technology Evolution Path

Based on the development drivers and assuming the realisation of the technology enablers discussed above, a possible evolutionary path for the function and features of future VEPMSs discussed in Section 3.1 is as followed:

- Accurate monitoring, and control functionality will eventually extend to all power sources and loads in the vehicle's power system, initially they will only provide limited control at the power system level,
- Each power source and load will then evolve to include tightly integrated power management devices with networking capabilities to communicate with each other, which will facilitate increased levels of optimal control at the power system level, and increased levels of intelligent and autonomous behaviors,
- The next evolution path is having the above devices tightly integrated to the vehicle chassis which provide intelligent and autonomous system behavior.

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