POWER MANAGEMENT OF HYBRID MILITARY VEHICLES USING OPTIMAL CONTROL

by

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Abstract

With increasing costs for fuel there is a growing interest in improving fuel efficiency and performance of military vehicles by employing (1) hybrid drive train architecture; (2) reliable vehicle power system structure, and (3) effective power management strategies of multiple power sources (engine, battery and ultracapacitor) and vehicle electrical loads. However, current ruled-based power management strategies that focus primarily on traction fail to meet the rapidly increasing requirements of military vehicles, including: (1) better fuel economy; (2) the ability to support pulsed power weapon loads; (3) maintaining battery SOC for power offloading applications, and (4) the ability to perform load scheduling of vehicle non-traction electrical loads to save energy.

In this thesis, we propose an optimal control based algorithm in conjunction with a rule-based control strategy to optimally manage three power sources (engine, battery and pulsed power supply module) and an effective power management solution for vehicle non-traction electrical loads such that: (1) all traction, non-traction and pulsed power needs are met; (2) power drawn from the engine for specific mission is minimized; (3) a certain desired battery SOC is guaranteed for offloading power, and (4) the ability to perform load scheduling based on different mission requirements. The proposed approach is validated using simulation of a mission specific profile and is compared with two other popular control strategies. The improvements in power efficiency, desired SOC level and ability to perform optimal load scheduling are demonstrated.

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List of Abbreviations

E_c	Instantaneous energy stored in the ultracapacitor
E_{C-full}	Energy stored in the ultracapacitor at full charge
ETC	Electrothermal-chemical
g	Gravity
M	Vehicle mass weight
i_C	Current from the ideal ultracapacitor
i_L	Ultracapacitor output power
I_L	Battery charge or discharge current
LQR	Linear quadratic regulator
PPS	Pulsed power supply
P_{req_total}	Total power requirement
$P_{req\_traction}$	Power requirement of traction motors
$P_{req\_nontraction}$	Power requirement of non-traction electrical loads
$P_eng(k)$	Engine output power
$P_{bat}(k)$	Power of the battery
$P_{tPPS}(k)$	Power of the traction PPS module
$P_{wPPS}(k)$	Power of the weapon PPS module
Q	Battery capacity
R_{ch}	Battery cell chemical resistance
R_{ohm}	Battery cell ohm resistance
SOC	State of charge
SOC_f	Desired final SOC level
SOE	State of energy
v	Vehicle velocity
V_{act}	Actual vehicle velocity
V_{C-full}	Voltage of the ultracapacitor at full charge
V_d	Desired vehicle velocity
V_t	Terminal voltage of battery
α	Slope of the road
δ	Rotational inertia factor
η_t	Transmission efficiency
η_m	Traction motor efficiency

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Last but not least, I want to thank my parents in China. Thanks for everything you have done for me.

Chapter 1

Introduction

In this section, we provide a brief review of vehicle system architecture and power management strategy for hybrid electric vehicle, which is the main topic in this thesis. In section 1.1, the hybrid electric vehicle concept and development is discussed. In section 1.2, vehicle power system is reviewed. In section 1.3, the requirement and development of military vehicle power system are reviewed. In section 1.4, we provide a brief review of four most commonly used hybrid vehicle control strategies.

1.1 Hybrid electric vehicle

Conventional vehicles have typically relied on internal combustion engines and petroleum fuels. The underlying idea in a combustion engine is that an reaction between the petroleum fuel and the air in the engine produces heat which is then converted into mechanical power. However, the reaction between fuel and air also produces other combustion products such as nitrogen oxide and carbon monoxides which are harmful to human beings and the environment. In addition, using an internal combustion engine alone as the power plant in vehicles also has other disadvantages such as: (1) poor fuel efficiency due to failing to match engine efficiency map with real operation, and (2) failing to fully utilize the vehicle kinetic energy during braking, especially when operating in urban area. As a result, the concept of hybrid electric drive train has been introduced and studied to overcome the disadvantages of conventional vehicles in the past two decades.

1.1.1 Concept of hybrid electric drive train

The power train of vehicle is required to (1) produce sufficient power to meet vehicle operation demands; (2) carry enough energy on board to support vehicle operation to a sufficient range; (3) be efficient, and (4) emit few environmental pollutants [1]. A vehicle may have more than one power train and the power train is defined as the combination of energy source and power source, such as diesel engine and chemical battery. The vehicle that has two or more power trains in the electric drive train is called an hybrid electric vehicle [1]. The hybrid electric drive train normally consists two power trains. In order to fully utilize vehicle kinetic energy, such as the braking energy dissipated in the form of heat, the hybrid electric drive train provides a power train which allows energy to flow bidirectionally. The other can be bidirectional or unidirectional. A typical hybrid electric drive train consisting two power trains is shown in Fig. 1.1. The operation modes of a hybrid drive train can be categorized as: (1) Energy source 1 alone delivers its power to the load through energy converter 1;

(2) Energy source 1 alone delivers its power to the load through energy converter 2;

(3) Both of the energy sources deliver their power to the load through energy converters simultaneously;

(4) Energy source 2 obtains power from the load;

(5) Energy source 2 obtains power from energy source 1;

(6) Energy source 2 obtains power from both the load and energy source 1;

(7) Energy source 1 delivers power to load and supply energy source 1 simultaneously;

(8) Both energy source 1 and energy source 2 deliver their power to load simultaneously;

(9) Energy source 1 deliver its power to the load while the load delivers part of the power to power train 2.

The flexible operation modes and configurations in a hybrid vehicle drive train make it possible to optimize vehicle performance, efficiency and emissions with proper control. The key point to increase vehicle overall fuel efficiency is to operate each power train in its most

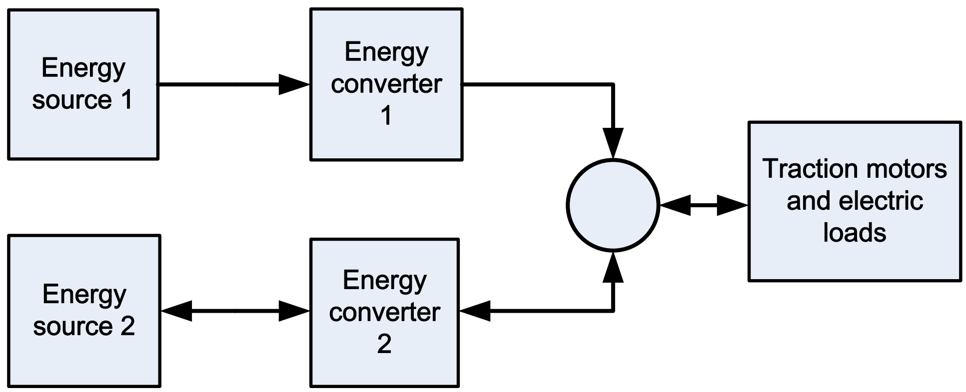

Figure 1.1: Architecture of a typical Hybrid Electric Vehicle

efficient region.

1.1.2 Architecture of hybrid electric drive trains

The hybrid electric vehicles are presently classified into four types, series hybrid, parallel hybrid, series-parallel hybrid and complex hybrid [1]. In a hybrid electric vehicle, there are only two kinds of energy flowing in the drive train: electrical energy and mechanical energy. Based on the coupling of electrical or mechanical energy, the classification of hybrid electric vehicle can be also categorized into two types: electrical coupling drive train and mechanical coupling drive train. Next, we provide a brief introduction of the three commonly used hybrid electric drive trains-series hybrid, parallel hybrid and series-parallel hybrid.

Fig. 1.2 illustrates the architecture of series hybrid electric drive train. The key feature of this type of drive train is that two electrical power sources are added together to supply load through an electrical converter. The engine/generator serves as the primary power source to supply the load or battery. The battery serves as an energy bumper which is used to deliver power or absorb power from an electric motor through a bidirectional electrical converter. The electrical converter serves as an electrical coupler to control the power flows among generator, battery and electric motor.

Fig. 1.3 illustrates the architecture of parallel hybrid electric drive train. The key feature of this type of drive train is that two mechanical power sources are connected through a

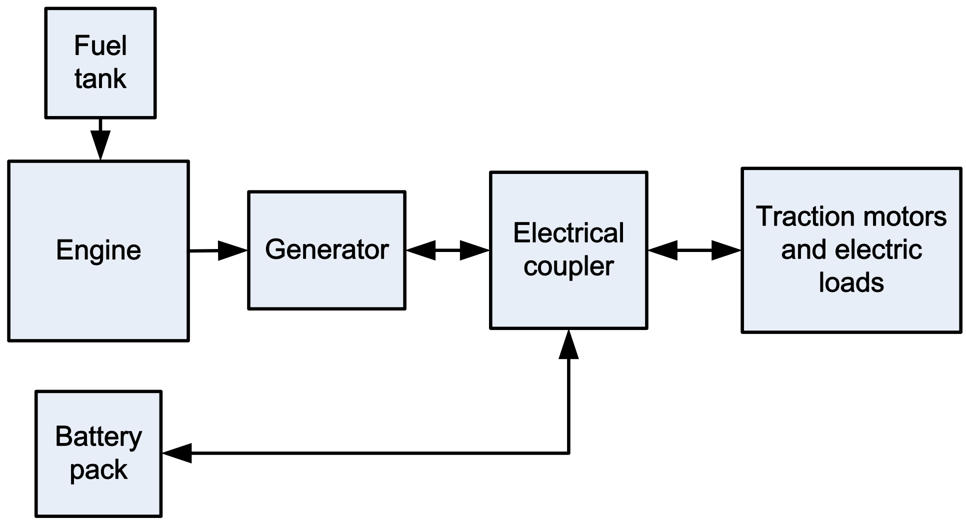

Figure 1.2: Architecture of Series Hybrid Electric Drive Train

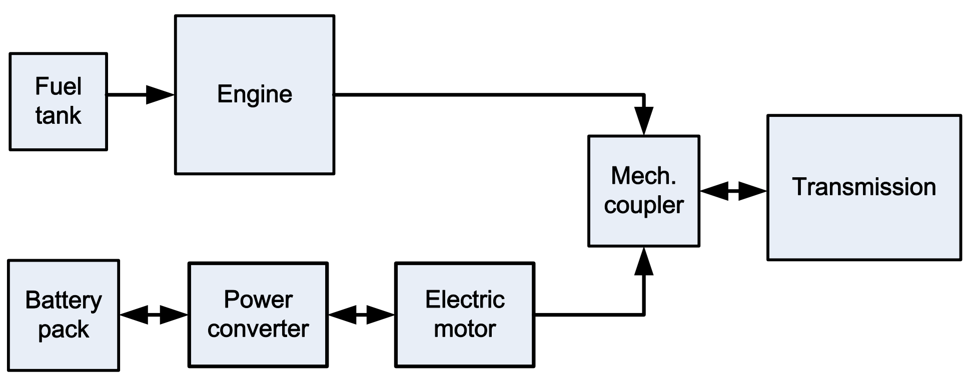

Figure 1.3: Architecture of Parallel Hybrid Electric Drive Train

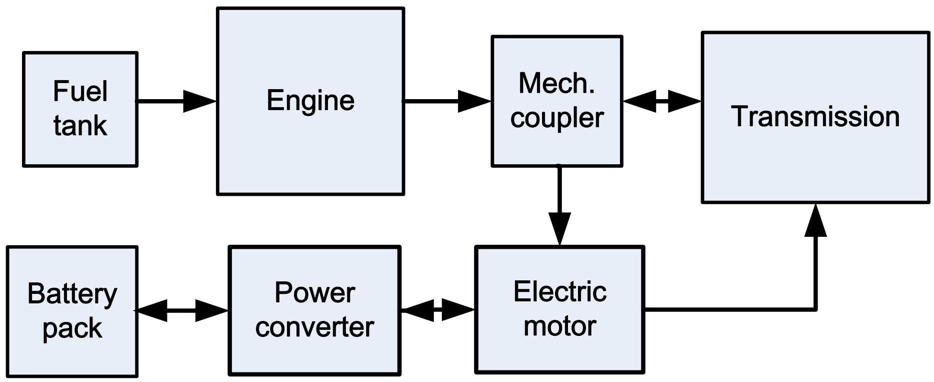

Figure 1.4: Architecture of Series-parallel Hybrid Electric Drive Train

mechanical coupler to propel the vehicle. The engine serves as the primary power source, and the battery pack and electric motor together serves as the secondary power source. The power flows in this type of drive train are controlled by engine and electric motor.

Fig. 1.4 illustrates the architecture of series-parallel hybrid electric drive train. The key feature of this type of drive train is that this type of drive train employs both electric and mechanical couplers which can be considered as a combination of series hybrid and parallel hybrid drive trains. The advantage of this type of drive train is that it provides more operation modes. However, the disadvantages are complicated structure and higher cost [1].

1.2 Commercial vehicle power system

The evolution of vehicle power system in voltage level and power has increased significantly during the past few decades. For commercial vehicles, initially a vehicle incorporated with 6 volts system is used in the early 1950's. In the mid 1950's, the system voltage level was changed to 12 volts due to the increasing use in electrical loads, such as lamps and ignition system. In the past two decades, with the development of power electronics technology, the hydraulically and mechanically controlled system were replaced by power electronics based electrical applications such power steering and electrically controlled suspension [7].

The increasing use of electrical loads in vehicle system has led better vehicle performance and reliability. However, the trend also leads to an exponential increase in power requirement for vehicle electrical loads. In addition, the higher voltage level reduces the energy loss during power distribution in vehicle system. To meet the increasing power needs and reduce power losses during power distribution, the current vehicle power system is in transition to a 42-volt system and employs dual-voltage architecture [22]. The benefits a dual-voltage architecture can provide include the ability to benefit all vehicle electrical loads from higher voltage and maintain the currently manufactured loads operated at low level voltage [7]. Additionally, due to the different characteristics of each load, the dual-voltage level architecture is able to meet all different operation requirements from those loads.

1.3 Military vehicle power system

In contrast to commercial vehicles, military vehicles are required to: (1) be more fuel efficiency; (2) provide robust performance, and (3) have the ability to support a variety of electrical loads. Although the needs in military vehicles are different from commercial vehicles, the needs to have a reliable power system to meet all loads requirements are the same.

The power requirements of commercial vehicles are well studied in the literature [22]-[25]. For military vehicles, there are several platforms, namely: (1) Light armored vehicle (LAV); (2) High mobility multipurpose wheeled vehicle (HMMWV); (3) Family of medium tactical vehicle (FMTV), and (4) Unmanned ground vehicle (UGV). The electrical specifications of these vehicle are shown in Table 1.1. From Table 1.1 we can see that military power system follows a similar trend as commercial vehicles. Due to the higher power requirement and the complexity of military vehicle electrical loads, military vehicles are normally based on 14/28 volts system architecture. With the increasing use of electrical loads in military vehicles, such as weapon and protection systems, the industry is trying to switch current system to 42 volts system. As a result, 14/28/42 three level power system will be used in future military

Table 1.1: Electrical specifications for military vehicles [22-25]

Type	Voltage level	Current level
LAV	28 volts dc	245/280 amps
HMMWV	14/28 volts dc	100 amps
FMTV	14/28 volts dc	100 amps
UGV	28 volts dc	650 amps

vehicle power system. The advantages of switching to 42 volts system architecture includes: (1) reduce wiring harness size [7]; (2) improve power system efficiency, and (3) meet higher power demand from high energy weapon and protection system.

The electrical loads added to the military power system also result in a trend toward the development of the hybrid power sources combination in vehicle electric drive train architecture. In the modern military vehicles, due to the huge power requirement from vehicle auxiliary equipment, significant amount of energy is needed to support vehicle electrical loads. Additionally, high energy weapon and protection system have became more and more common for their potential to improve vehicle survivability and lethality. Conventional power sources, such as engine and battery fail to meet the demanding requirement. Therefore, special designed power sources such as the ultracapacitor and fuel cell are used to fulfill the requirements of these special loads.

1.4 Hybrid electric vehicle power management methods development

Due to the use of hybrid drive train architecture and electric devices, hybrid electric vehicles have the potential to improve fuel efficiency in comparison to conventional vehicles. The additional energy source and electric devices provide a freedom since each time index the total power required is supplied of one of the energy sources or their combination. Therefore, solving the power management problem involves finding out the most efficient power spilt between the on-board energy sources.

The main objective of a power management strategy is to minimize fuel consumption and emissions over a driving cycle without compromising the vehicle performance [27]. During the development of hybrid electric vehicles, many control strategies have been proposed [30].In the following sections, we provide a brief introduction of classification of power management methods based on the technique used. References [1] and [15] present heuristic methods such as thermostat and power follower control strategies. These kind of methods do not involve explicit optimization; instead, the methods are implemented with rules and algorithms based on engineering intuition [26]. These control strategies have a simple logic algorithm and require little computation time. However, the results may be far from optimal. Similar control methods, such as fuzzy logic [33-34], are also part of this category. In references [2], [3], [14], [16] and [17], electric power is translated into an equivalent amount of fuel rate (in order to calculate the overall fuel cost), and an optimization problem is formulated to determine the proper split between the engine power and battery power through steady-state efficiency maps. In this control strategy, developing the efficiency maps is a challenge. Another control strategy considers the vehicular system as a dynamic system as references [4], [18], [28] and [29] formulate an optimization problem with respect to a time horizon, using dynamic programming to solve it. Compared to the first two methods, results obtained from the third method are more accurate under transient conditions. However, the third method requires heavy computation, and is not practical for real time applications. The detailed introduction will be provided in the following sections.

1.4.1 Thermostat control strategy

The thermostat control strategy is also called engine on-off control strategy in references [1] and [15]. In this control strategy, the operation of the engine/generator is completely controlled by the SOC of the battery pack. Depending on the SOC of the battery pack, the engine/generator turns on and off, and operates with a fixed power at its most efficient point. When the SOC the of battery pack reaches its upper limit, the engine/generator is turned off and the vehicle is propelled only by the battery pack. On the other hand, when the SOC reaches the lower limit, the engine/generator is turned on to propel the vehicle and charge the battery pack if possible. According to its characteristic, this method is preferable for a long time driving on a highway at constant speed [7].

1.4.2 Max SOC control strategy

The objective of this control strategy is to meet the power demand from the mission profile while maintaining the SOC of the battery pack at a relatively high level [7]. This control strategy is fit for vehicles in which performance (speed, acceleration, gradeability, etc.) is the first concern [1]. The high SOC level guarantees high performance of the vehicle at all times and fits the demands of military vehicles. Max SOC control strategy works as follows: according to the power request and vehicle status, if the power request for traction is greater than the power that the engine/generator can produce, the battery pack assists the engine/generator. In case the power request for traction is less than the power produced by the engine/generator (when it's operating within its most efficient region), the following conditions apply: If SOC of the battery pack is below its upper limit, power from the engine/generator propels the vehicle and the rest charges the battery pack. If the SOC of the battery pack is at its upper limit, the engine/generator produces the required power and the battery pack is set at idle. A negative power request indicates that brake control is required to decelerate the vehicle. In this case, if the required braking power is greater than the braking power the motor can produce, the electric motor produces its maximum braking power (maximum regenerative braking power) and the friction brake produces the remaining. If the required braking power is less than the maximum braking power the motor can produce, the motor produces the required braking power. The regenerative braking power can be used to charge the battery pack for future use.

1.4.3 Instantaneous equivalent consumption minimization strategy

The original concept of equivalent fuel consumption was proposed by Paganelli et al [31] for an instantaneous optimization energy management strategy [3] and [26]. Further, this control strategy was developed by several authors [14], [27] and [32]. In a series hybrid vehicles, both the engine/generator and the battery pack supply energy to support vehicle operation. The electrical energy consumption of the battery is transformed into an equivalent fuel consumption to make the two comparable. If some energy is drawn from the battery at the current sample time, the battery will have to be recharged to maintain the SOC in the future. First, a function is defined to reflect the equivalent fuel consumption rate over the test cycle. Within the constraints, an optimization problem is formulated aim at minimizing the equivalent fuel consumption at each time index over the whole driving cycle. The optimal power spilt between engine/generator and assistant power sources (battery, fuel cell and ultracapacitor) can be obtained which results in the minimum fuel use. It should be noticed that this control strategy can not be implemented on real-time control because of the whole driving cycle has to be known a priori [17]. However, the problem can be reduced to a local one by minimizing the equivalent fuel consumption rate at each time to avoid the drawback. The advantages of this control strategy is that the results are near optimal. However, this control strategy requires the steady state engine efficiency map which is a challenge for a generalized solution.

1.4.4 Dynamic programming

As an powerful tool to solve the general dynamic optimization problem using dynamic programming technique in hybrid vehicle power management problem has been widely studied. The concept of this control strategy is that a cost function is defined which reflects the user's preference. Through solving an optimization problem with respect to the time horizon, the optimal results can be obtained. The dynamic programming technique basically is based on

Bellman's principle of optimality: An optimal control policy has the property that no matter what the previous decisions have been, the remaining decisions must constitute an optimal policy with regard to the state resulting from these previous decisions [35]. The optimal policy can be obtained by first solving a one stage sub-problem which involves only the last stage, and then gradually extending the problem by solving last two stages, then last three stage until all the stages in the dynamic system have been solved. In this way, the recursive equations can be solved backward to find the optimal results [4]. The main advantages of this control strategy is that it is easy to handle all the constraints and nonlinearity of the problem while obtaining a globally optimal solution [21]. It can be used as a good tool to test, design and analyze hybrid electric vehicle system and control strategies. For a more detailed description of dynamic programming, see References [36] and [37].

1.5 Thesis overview

In this thesis, the main objective is to model a hybrid military vehicle with three power sources (engine, battery pack, pulse power source modules) and propose an effective power management [27] solution which considers traction, non-traction electrical loads and pulsed power load needs. The operation and performance of the military vehicle and its subsystems are analyzed and tested on different mission profiles. Additionally, the improvement in fuel efficiency and controllable battery SOC ability is demonstrated. We solve the power management problem as a linear quadratic regulator (LQR) in conjunction with a rule-based approach. The optimal power management solution over a mission specific profile is obtained by minimizing a defined cost function. Under the proposed power management strategy, all military vehicle needs are met while: (1) minimizing the power drawn from the engine; (2) maintaining a desired battery SOC level at the end of the mission for offloading power; (3) having the capability to supply pulsed power loads, and (4) load scheduling based on different power requirement and operation modes. The system performance under different combinations of power sources and control strategies is evaluated, and the operation of pulsed power loads are also quantified. Significant fuel efficiency improvement, a desired final SOC level and the capability to meet all needs are achieved through employing the proposed optimal control strategy.

This thesis is organized as follows: In Section 2, the vehicle structure model and subsystems including vehicle drive train configuration, battery model, pulse power sources module and pulsed power load are introduced. In Section 3, we first introduce the optimal control problem introduction and formulation of the power management strategy for traction, followed by the power management strategy for non-traction electrical loads. In Section 4, the simulation results of optimal control strategy are shown. Finally, the conclusion and future work are discussed in Section 5.

1.6 Key contributions

This section describes in detail, the key contributions of our thesis.

- *We build a series hybrid drive train with three power sources combination.* In chapter 2, we introduce the drive train configuration and parameters of each power source.

- *We build a two-bus power system with switches connected to each electrical loads.* In order to ensure military vehicle system reliability, a two-bus power system is used to ensure redundancy and reliability. Priorities are also assigned to each electrical load due to different mission requirements. If part of the system is damaged, by controlling the status of the switches, critical loads are powered while loads with low priority can be shed to maintain the energy balance.

- *We take the pulsed power weapon load into consideration.* To better evaluated the system performance and the efficacy of the proposed approach, a pulsed power weapon load is taken into consideration in the simulation. ETC gun is used as the pulsed power weapon load. We introduce the operating principle and parameters of a modeled ETC gun in chapter 2. Additionally, due to the different operation requirements of ETC gun, a specially designed PPS module is needed to supply it. Therefore, a weapon PPS module to supply an ETC gun is introduced.

- *We propose an optimal control based algorithm in conjunction with rule-based control strategy.* In order to achieve the listed objectives:

    1. improve fuel efficiency,
    2. control battery SOC,
    3. meet all traction, non-traction and pulsed power load requirements,
    4. perform load scheduling when energy saving is needed.

    An optimal control based algorithm in conjunction with rule-based control strategy is proposed for all the objectives list above. For the power management strategy for traction, we formulate an optimization problem and apply the LQR approach to control the operation of engine and battery pack. For the operation of ultracapacitor, the Charge-sustaining strategy is used which the SOE of ultracapacitor may fluctuate but on average is maintained at a certain level during the mission [1].

- *We propose a rule-based control strategy for non-traction loads power management.* We first assign priorities to all non-traction electrical loads based on different mission requirements. When load scheduling is needed to save energy, the loads with low or middle priority will be shed depending on the power requirement.

- *We compare the fuel efficiency for single power source, dual power sources and three power sources combination.* We obtain the simulation results of fuel efficiency under two mission specific profiles when different power sources combinations are employed. The results confirm that three power sources combination are better in fuel efficiency and are able to reduce the max engine output power.

- *We show that our proposed approach is effective in achieving better fuel efficiency, controllable battery SOC as presented.* In order for that, we compared the simulation results of fuel efficiency and final battery SOC under our proposed approach with the Thermostat control strategy and Max SOC control strategy. The results show that our approach successfully reduce the power drawn from engine while maintaining the desired SOC level. However, the other two commonly used control strategies fail to achieve the same results.

- *We demonstrate the system performance when ETC gun is in use* We simulate the system performance under two mission specific profiles when ETC gun is in use. The simulation results show that the proposed approach successfully enable the military vehicle meet all traction, non-traction and pulsed power load needs while achieving better fuel efficiency and desired battery SOC and ultracapacitor SOE.

- *We demonstrate the load scheduling ability of the proposed approach.* In order to accomplish that, we tested the vehicle performance when engine is not able to produce its max power.

Chapter 2

System Architecture

In this section, a military vehicle system architecture is introduced with special emphasis on the drive train structure and its subsystems.

2.1 Series hybrid electric vehicle system

The hybrid electric vehicle drive trains are usually categorized into three main types: series, parallel and series-parallel configuration [1]. Parallel and series-parallel configurations are typically used in passenger vehicles because of their compact design, while series configuration is used in large vehicles that have large available space for packaging of the drive train. Compared to parallel configuration, series configuration has the advantages of simple structure and control [5]. Therefore, in this thesis we focus on a series drive train for an off-road military vehicle model.

We consider three electrical power sources in a series hybrid drive train. The engine/generator serves as the main power source. A battery pack and a PPS module are used as secondary power sources and feed the electrical power plant (electric motor) that propels the vehicle and supports electrical loads within the vehicle [1]. Fig. 2.1 illustrates the structure of the series hybrid drive train considered in the work. Table 2.1 illustrates the basic vehicle parameters used in this research. The engine/generator converts chemical energy from fuel to mechanical energy through a diesel engine, and the mechanical energy is then converted into electric energy through a generator. The battery pack and traction

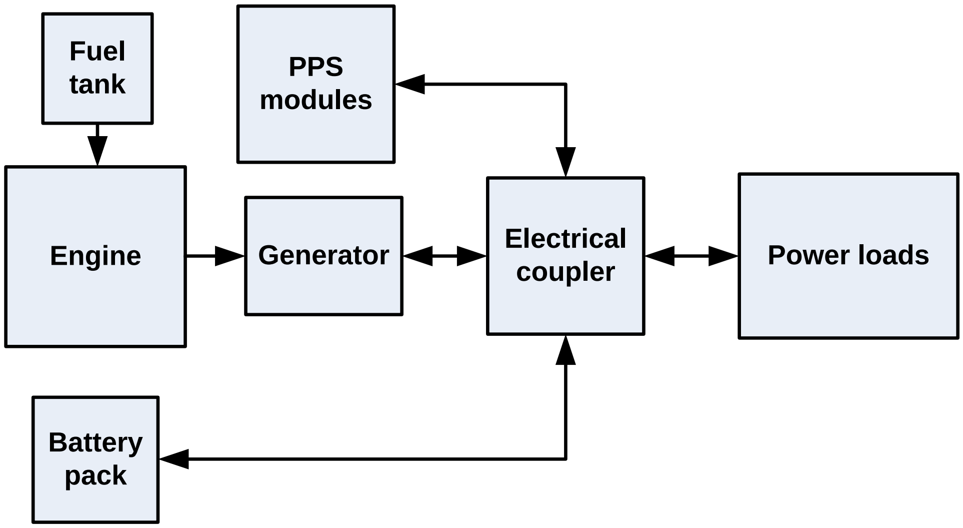

Figure 2.1: Architecture of Hybrid Military Vehicle Drive Train

Table 2.1: Basic vehicle parameters [38]

Diesel Engine	600 hp
DC Motor	Maxim Power: 80 kW
Battery pack	Capacity: 50 Ah/25 modules
Traction PPS module	Stored energy: 1200 kJ
Vehicle weight	10,000 kg

PPS module charge and discharge power according to total power requirements. The output of the engine/generator is connected to a DC power bus through a controllable electronic converter (rectifier). The battery pack and traction PPS module connect to the same DC power bus through two controllable, bidirectional power electronic converters. The ultracapacitor is chosen to be the energy storage device to form the traction PPS module because of its high efficiency, high specific power and long life time [1]. In addition, another specially designed PPS module is incorporated in the drive train to fulfill the needs of a pulsed power weapon system. Details of the weapon system and the weapon PPS module used in this thesis are provided in section 2.3 of this chapter.

2.2 Power system model

Over the past several decades, a variety of power loads have been added to the vehicle power system in order to provide better performance and safer driving conditions. Military vehicles have many demanding requirements such as the need to climb hills, sharp acceleration and high reliability. Therefore, it is necessary to build a power system that ensures survivability while maintaining performance. In this thesis, we focus on a six-drive-wheel heavy duty military vehicle and 2-bus power system for its reliability [6]. The vehicle power system architecture is shown in Fig. 2.2. The voltage levels of two buses are 300 volts DC. The buses supply power to six traction motors and all non-traction loads. We assume that there are a total of eighteen non-traction power load categories, such as water heater, lights, communication systems and engine controller. According to their relative importance to the vehicle operation and mission, we categorize the loads into six vital loads, six semi-vital loads and six non-vital loads [7]. Within each load group, we add switches that can be closed or opened to deliver power to the vital loads, in case of faults or other contingencies. Among the six vital loads, there is one pulsed power weapon load which we will introduce later in this chapter. In this thesis, we assume that during the mission, all non-traction loads are operating at the rated power. The rated power of each load are shown in Table 2.2. The total power required for vehicle operation is the sum of the power requests from traction motors and non-traction electrical loads. However, the strategies for power management for traction and non-traction loads is different. For example, the power required for traction is a direct function of the mission velocity profile. However, the power drawn by non-traction loads can be minimized by selectively powering the most relevant loads for a specific mode of operation within a mission. Additionally, by controlling switches, we can deliver power to critical loads even in the case of faults.

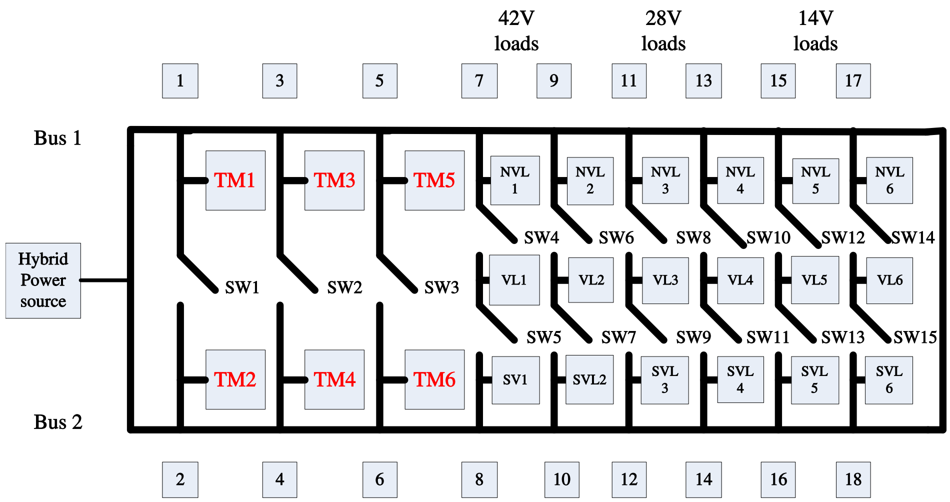

Figure 2.2: Two-bus power system

Table 2.2: Rated power of the non-traction electrical loads [7]

Load	Rated Power (W)
Vital Load	3000
Semi-vital Load	1500
Non-vital Load	900

2.3 Pulsed power weapon load and weapon PPS module

Besides conventional electrical loads, pulsed power loads, such as missile systems, air defence systems and gun systems, are gaining more interest in military vehicles. In these applications, ETC technology offers increased lethality for the military vehicle and is widely used in military vehicles. Many experiments with medium and large-caliber guns have been performed at Rheinmetall within the German R&D ETC-Program [9]. In this thesis, a medium-caliber ETC gun system with electrical energy of 2 kJ for one shot and a repetition rate of 20 shots/s is assumed to be installed in the military vehicle. Additionally, taking into account the efficiencies of all the subsystems and components of the ETC gun system, an electrical power of 60 kW is necessary to supply the weapon system [10]. Due to the characteristic of short duration and high energy magnitude of this pulsed power weapon load, the

Table 2.3: Basic parameters of weapon PPS module and capacitor [10], [11]

Stored Energy	400 kJ	100 kJ
Charge Voltage	20-30 kV	20-30 kV
Charge Time	5 s	5 s
Maximum Discharge Current	30 kA	10 kA
Pulse Duration	2 ms	2 ms

electric energy for this electric weapon system has to be provided by a specially designed weapon PPS system. Unlike the traction PPS module used to supply the traction power, the requirement of the weapon PPS module for the ETC gun system is quite different. The role of traction PPS module is to supply power during peak load time and reduce power drawn form the engine. Based on the characteristic of the ETC gun, a specially designed weapon PPS module is needed to fulfill the power requirement of this pulsed power load. The electrical requirements of the medium-caliber ETC gun system include not only the energy released during shooting, but also temperature compensation and energy loss related to component efficiency. In order to fulfill the electrical requirements of ETC gun system and provide sufficient flexibility to meet all different requirements due to temperature effects, a design of one discharge module is selected to form the weapon PPS module. The energy contained in the weapon PPS module is 400 kJ and four identical ultracapacitors are used in this module. Table 2.3 illustrates basic parameters of the weapon PPS module and the ultracapacitor employed in the module [11]. When the ETC gun is in use, the weapon PPS module supplies the required energy. When the ETC gun is out of service, the engine or the combination of engine and battery with or without traction PPS module charges the weapon PPS module. This ensures that the weapon PPS module contains enough energy for future operations of the ETC gun.

In this thesis, the analytic simulation of ETC gun system and weapon PPS module is based on the following assumptions [10], [12]:

(1) weapon PPS module charging efficiency is 90%;

(2) ETC gun charger efficiency is 75%;

(3) pulsed power module efficiency 88%;

(4) no transients in ETC gun charger;

(5) the operation of ETC gun is random with the possibility of active use of ETC gun is 0.1;

(6) the operation of ETC gun is as follows: 20 evenly spaced shots in 1 second (i.e, each shot takes 2 ms, and, the ETC gun system takes 48 ms to get ready for the next shot).

2.4 Vehicle dynamic and subsystem model

In discrete-time format, a simplified vehicle model can be used to analyze vehicle movement, battery and PPS module performance. We are concerned with four state variables: the vehicle speed, battery SOC, traction PPS module SOE and weapon PPS module SOE. Four control vectors are of interest: power drawn from the engine, power from the battery pack, power from the traction PPS module and power from the weapon PPS module. The simplified models of vehicle operation and subsystems are described below:

2.4.1 General vehicle dynamics

To operate a while on the road, the driving power on the vehicle wheels can be expressed as [1]:

$$P_{req\_traction} = \frac{v}{\eta_t \eta_m}[Mg\cos\alpha(c+dv) + 0.5\rho_a C_D A_f v^2 + Mg\sin\alpha + M\delta\frac{dv}{dt}] \tag{2.1}$$

where, $P_{req\_traction}$ is the power required from traction motors; v is the vehicle speed; η_t is the transmission efficiency; η_m is the efficiency of traction motor; M is the mass weight of the vehicle; g is the gravity; δ is the rotational inertia factor, α is the slope of the road; c and d are constant representing the vehicle rolling resistance; ρ_a is the air mass density; C_D is the aerodynamic drag force; A_f is the front area of the vehicle. In this work, we consider a fixed value of 90% for transmission efficiency and traction motor efficiency [1]. For $P_{req\_traction} > 0$, the vehicle wheels accept power from power sources that propel the vehicle forward, when

Table 2.4: Basic vehicle parameters used in this paper [7][38][40][41]

Item	Symbol	Value
Vehicle Mass	M	10,000kg
Transmission efficiency	η_t	90%
Traction motor efficiency	η_m	90%
Gravity	g	9.81m/s^2
Air mass density	ρ_a	1.205kg/m^3
Aerodynamic drag force	C_D	1.17
Vehicle front area	A_f	6.25m^2
Rotational inertia factor	δ	1.05
Vehicle rolling resistance c	c	0.0138
Vehicle rolling resistance d	d	0.000918
Battery capacity	Q	1250Ah
Battery cell ohm resistance	R_{ohm}	0.002
Battery terminal voltage	V_t	300V
Traction PPS module capacity	E_{C-full}	1200kJ
Traction PPS module terminal voltage	V_{C-full}	300V

$P_{req\_traction} < 0$, the driving power is zero and the braking and kinetic energy of vehicle mass is dissipated by brake system and also can be absorbed by regenerative braking which can be used to charge the battery pack. The basic vehicle parameters used in this paper is shown in Table 2.4.

The total power required by the vehicle consists of two parts, power for traction and non-traction loads. Non-traction loads include conventional electrical loads such as water heater, lights, communication systems and pulsed power load as ETC gun system. In this thesis, we aim to improve fuel economy by primarily focusing on the power required for traction and modeling the non-traction power requirement as a time series model. In a series hybrid drive train configuration, three power sources are connected to electrical converters to supply traction power requirement and conventional non-traction loads [16]. Additionally, if the ETC gun is in operation, the special designed weapon PPS module is used to fulfill this power requirement. Therefore, for every time index k:

$$P_{req\_total}(k) = P_{req\_traction}(k) + P_{req\_nontraction} \tag{2.2}$$

$$P_{req\_total}(k) = P_{eng}(k) + P_{bat}(k) + P_{tPPS}(k) + P_{wPPS}(k) \tag{2.3}$$

where, P_{req_total} is the power requirement for both traction motors and non-traction electrical loads; $P_{req\_nontraction}$ is the power requirement of non-traction electrical loads; $P_eng(k)$ is the engine output power; $P_{bat}(k)$ is the power charged or discharged from the battery pack; $P_{tPPS}(k)$ is the equivalent power charged or discharged from the traction PPS module, and $P_{wPPS}(k)$ is the equivalent power charged or discharged from the weapon PPS module.

Based on equation 2.1, 2.2 and 2.3, the dynamics of the state variable $v(k)$ can be discretized as:

$$v(k+1) = v(k) + \frac{\eta_t \eta_m P_{req\_traction}(k)}{M\delta v(k)} - \frac{0.5\rho_a C_D A_f v(k)^2}{M\delta} - \frac{g\cos\alpha[c + dv(k)] - g\sin\alpha}{\delta} \tag{2.4}$$

where $v(k)$ is the vehicle speed at time index k and $P_{req\_traction(k)}$ is the power required for traction at time index k.

2.4.2 Battery

There are many battery models, including the RC model, the internal resistance model and the lead-acid model. In this thesis, the internal resistance model is used and the battery is simulated as an electrical equivalence model. The charging or discharging power of battery is determined by its terminal voltage and charging or discharging current, which also represent the battery SOC. Based on the relationship between battery SOC, power of battery, terminal voltage and charging or discharging current, the battery model can be rewritten into discrete form in which only two variables are concerned: power of the battery and battery SOC. And the power of battery is only related to the battery SOC. The continuous time terminal voltage of the battery is given as [7],[16]:

$$V_t = 2 + 0.03SOC - I_L(R_{ch} + R_{ohm}) \tag{2.5}$$

where, V_t is the terminal voltage of battery; I_L is the battery charge or discharge current (positive in charging and negative in discharging); R_{ohm} is the battery cell ohm resistance with the value of 0.002; R_{ch} is the battery cell chemical resistance as a function of SOC [7].

$$Rch = \begin{cases} k_1 e^(k_2(1 - SOC)), & \text{when discharging} \\ k_1 e^(k_2(SOC)), & \text{when charging} \end{cases} \tag{2.6}$$

where, $k_1 = 4.5 \times 10^6$; $k_2 = 8.8$. The relationship between battery SOC at time t and current can be expressed as:

$$SOC(t) = SOC_0 - \frac{1}{Q}\int_0^t I_L dt \tag{2.7}$$

where, SOC_0 is the initial SOC at time $t = 0$; Q is the battery capacity in Ampere-hour. From equation (2.7), we obtain the discrete time state equation of battery as a function of SOC:

$$SOC(k+1) = SOC(k) - \frac{P_{bat}(k)}{QV_t(k)} \tag{2.8}$$

The basic battery parameters used in this paper is shown in Table 2.4.

2.4.3 PPS module

The ultracapacitor is selected to form the traction and weapon PPS modules for its high efficiency, high energy density, long lifetime and low cost. To represent the performance of an ultracapacitor, an electrical equivalent model is used in this thesis. In this model, terminal voltages during discharge and charge with different current rates can be used to represent the relationship between ultracapacitor output power and the SOE of an ultracapacitor. The equivalent output power of ultracapacitor is only related to SOE of the ultracapacitor and can be expressed as [1],[7]:

$$i_C = i_L + i_P \tag{2.9}$$

$$i_L = \frac{V_C - V_t}{R_s} \tag{2.10}$$

$$i_P = \frac{V_C}{R_p} \tag{2.11}$$

$$V_C = V_{C0} + \frac{1}{E_{c-full}} \int_0^t i_C dt \tag{2.12}$$

$$SOE = \frac{E_c}{E_{c-full}} = \frac{{V_C}^2}{{V_{C-full}}^2} \tag{2.13}$$

where i_C is the current from the ideal ultracapacitor; i_L is the output power of the ultracapacitor; i_P is the leakage current; V_C is the voltage of the ideal ultracapacitor; V_t is the terminal voltage of the ultracapacitor; R_s is the series resistance; R_p is the dielectric leakage resistance; E_c is the instantaneous energy stored in the ultracapacitor; E_{C-full} is the energy stored in the ultracapacitor at full charge; V_{C-full} is the voltage of the ultracapacitor at full charge. The output power of the ultracapacitor can be expressed as:

$$P_{PPS} = V_t i_L \tag{2.14}$$

The discrete time state equation of ultracapacitor as a function of SOE can be described as [1]:

$$SOE(k+1) = SOE(k) - \frac{P_{PPS}(k)}{E_{c-full}} \tag{2.15}$$

where $SOE(k)$ is the SOE of ultracapacitor at time index k; $P_{PPS}(k)$ is the equivalent instantaneous power output of ultracapacitor; E_{C-full} is the full energy stored of the ultracapacitor in kJ. The basic ultracapacitor parameters used in this paper is shown in Table 2.4.

In the next section, we propose a power management solution for hybrid military vehicle. First, we focus on traction requirements and propose an optimal control based power management to minimize the power drawn from the engine while maintaining a desired level of battery SOC. Next, a power management strategy is proposed for military vehicle non-traction electrical loads.

2.5 Summary

This chapter provides an introduction of the system components we analyzed in this thesis. First, a two bus power system architecture is presented for improved reliability and flexibility, followed by the introduction of non-traction electrical loads and pulsed power weapon load (ETC gun system) in military vehicle system. Next, we introduced the vehicle general dynamic equation and its subsystem models (battery and ultracapacitor models) used in this thesis.

Chapter 3

Hybrid military vehicle power management problem

The objective of this work is to present a power management solution for hybrid military vehicle to improve fuel efficiency by minimizing the power drawn from the engine while satisfying mission specific requirements related to a desired velocity profile and final battery SOC. Based on an optimal control strategy, we formulate an optimal control problem, the solution of which enables us to determine the minimum power from the engine and the charging and discharging strategy for the battery pack and PPS modules. Specifically, we linearize the underlying system dynamics and employ a dynamic programming approach to solve the resulting LQR problem. In the following subsections, we first introduce our proposed optimal control strategy. Next, the power management strategy for non-traction electrical loads is introduced. Finally, we present a mathematical formulation of optimal control problem and a approach to solve the optimal control problem is discussed.

3.1 Proposed optimal control strategy

Our proposed method is an optimal control based algorithm in conjunction with rule-based control strategy. In this control strategy, engine/generator, battery pack and two PPS modules are combined together to supply power to meet all power requirements of the vehicle. Additionally, the boundary constraints of battery SOC, PPS modules SOE, engine output power, battery pack and PPS modules output power are set to ensure the algorithm is not breaking the limit of power plants and energy storage devices [14]. The proposed optimal control strategy developed in this research is shown in Fig. 3.1. The algorithm first examines if the pulsed power weapon system is operating. If yes, the weapon PPS module is used to supply power to the weapon and we proceed to the second step. If no, the algorithm directly proceeds to the second step. It is important to note that after the operation of ETC gun, the combination of power sources will charge the weapon PPS module back to desired SOE level as soon as possible. In the second step, the total power required from traction motors and non-traction electrical loads is compared with a predetermined power threshold. If the total power requirement for traction motors and non-traction loads exceeds that threshold and the discharge action of traction PPS module will not pass its boundary constraints, the traction PPS module discharges and supplies power. The exact power threshold is based on the characteristic of the engine used and the desire to prevent drawing excessive power from the engine which can in turn affect its efficiency. If in the traction PPS module, the SOE level is higher than what is needed to supply the traction needs, then it is used to supply power, otherwise, it is set at idle. In the third step, the LQR approach is applied to determine the actions of engine and battery pack. A cost function is minimized which leads to the least power drawn from the engine while ensuring the final SOC level of the battery pack is within the constraints set for offloading power applications.

3.2 Power management strategy for vehicle non-traction electrical loads

For military vehicle, non-traction electrical loads in military vehicle, such as radar, weapon system and protection system have became more and more important for increased safety and lethality. Therefore, the power needed to supply those non-traction electrical loads has increased significantly. However, when a military vehicle is on a mission, it is hard

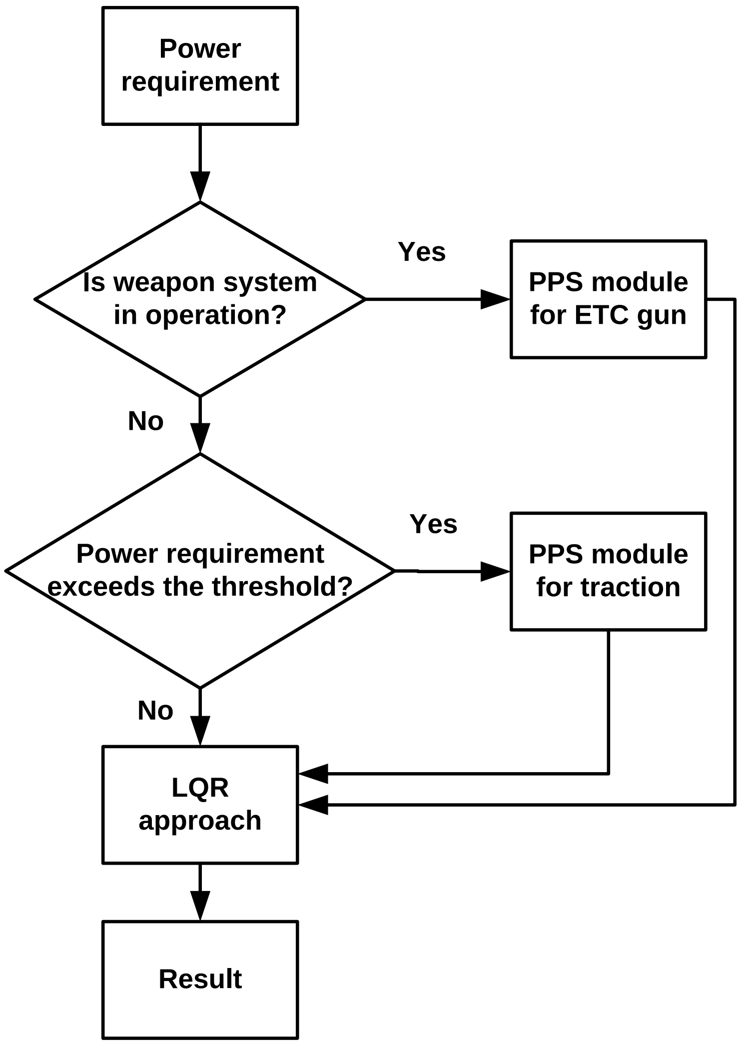

Figure 3.1: Optimal control strategy flow chart

to provide the vehicle with additional supply. For example, when a military vehicle is in a battle, it is important for the vehicle to employ an effective power management strategy that ensure the vehicle have enough energy to complete the mission under all kinds of situation. Therefore, there is a need to develop an effective power management solution for military vehicle non-traction electrical loads.

Due to the different power requirements of military vehicles, the operation of military vehicles can be categorized into several operation modes, such as combat, silent watch, cruising and maintenance modes. For example, in combat mode, all protection and weapon systems need to be ready for any operation to ensure that the vehicle is able to complete the mission. While in maintenance mode, these high power weapon and protection loads can be turned off to save energy. Therefore, based on the different operation modes during the mission, we can set priorities for all the non-traction electrical loads in different operation modes. When military vehicle power sources are not able to supply all the power requirements or have a need to save energy for future operation, those loads with low priority in certain operation modes can be shed, while those loads with high priority are always powered to make sure the vehicle can still operate to complete the mission. In this work, according to the possible military vehicle operations [7], we define five operation modes and set priorities for all the non-traction electrical loads in each operation mode. We prioritize the loads with H, M and L which indicates high priority, middle priority and low priority, respectively. The priorities for all non-traction loads in each operation mode are shown in Table.3.1.

In the real operation of military vehicles, electrical loads in the vehicle power system are not always operated at their rated power or just turned off. To certain loads, it may take quite a long time to activate. Therefore, during the battle, it's not wise to turn off some critical loads in the vehicle system such as protection and weapon systems. However, always keeping the high power electrical loads on may consume too much energy which may affect the vehicle's future operation. Therefore, we propose a three-level power paradigm (on, off and low power modes) in this work. Low power level is like a stand by mode of

Table 3.1: Operation modes and non-traction electrical loads priorities [7]

Load number	Combat	Cruise	Maintenance	Planning	Fording
Load 1	H	M	L	L	L
Load 2	H	L	M	L	L
Load 3	L	L	L	L	L
Load 4	H	L	L	M	H
Load 5	H	L	M	M	L
Load 6	L	L	L	L	L
Load 7	H	L	L	M	H
Load 8	M	L	L	L	L
Load 9	M	L	L	L	L
Load 10	H	L	L	L	L
Load 11	L	L	M	M	L
Load 12	L	L	L	L	L
Load 13	M	L	L	M	H
Load 14	L	L	M	L	L
Load 15	L	L	L	L	L
Load 16	H	L	L	L	H
Load 17	M	M	M	L	L
Load 18	M	L	L	L	L

the non-traction electrical loads in the system. In this mode, the load in low power mode will not consume much power compared to the on mode and is able to activate very quickly if necessary. The non-traction electrical loads with low and middle priority can operate at three different power level and shift among the three-level paradigm: (1) on mode indicates that the electrical load is operating at its rated power; (2) off mode means the electrical load is turned off and consumes no power, and (3) low power mode means that the electrical loads are operating at 30% of their rated power. We assume that the loads with high priority must be always in the on mode. In addition, at the beginning all the non-traction electrical loads are in the on mode which means they are all operating at their rating power. When the vehicle is not able to supply all the power required and load-scheduling is needed to save energy, total power required for traction and non-traction loads are calculated and compared with the available power from the hybrid power sources first. Based on the power shortage of all electrical loads, the power management solution will find out the optimal load scheduling result under a mix modes mission profile (more than one mode in the whole mission, battle, fleeting, etc. The power level can switch among the three-level paradigm) which ensures the vehicle can operate normally. However, if we turn off all the loads with low and middle priority and hybrid power sources are still no be able supply the required power, then we have to slow down the vehicle since the remaining loads with high priority are critical to the vehicle operation and can not be shed.

3.2.1 Optimal control theory

The main objective of a optimal control problem is to guarantee the dynamic system to attain the desired performance. The attractive part of contribution optimal control theory is that it offers an analytical approach to solve design problems. In an optimal control problem, first we consider the system as discrete and given as [11]:

$$x(k+1) = f_k(x_k, u_k) \tag{3.1}$$

$$x_0 = x_{initial} \tag{3.2}$$

where $x(k)$ is the state of the system at kth stage; x_0 is the initial state of the system. The function $f_k(x_k, u_k)$ describes the evolution of the state of system, as a linear function of both the state of system $x(k)$ and control vector $u(k)$. It is noted that control vector $u(k)$ can be chosen by system designer's preference. Since the objective of the optimal control problem is to make the system attain a certain state, a cost function is usually defined as J which reflect the system designer's preference. The cost function J is given as [11]:

$$J = L(x_K) + \sum_{k=0}^{K-1} V_k(x_k, u_k) \tag{3.3}$$

where $L(x_K)$ represents the function of final state of the system; V_K is the running function which depends on both the system state and control vector.

In optimal control theory, the objective is to find the sequence of optimal control vectors u_k (k=0,1,...,K-1) that results in the minimum cost function J. Nothing that the system model represented by equation 3.1 is a set of equality conditions. Therefore, optimal control problem can be solved as an constrained optimization problem by solving Lagrange multiplier to establish optimality conditions. The scalar Hamiltonian is usually defined as [11]:

$$H(k) = V_k(x_k, u_k) + \lambda^T(k+1) f_k(x(k), u(k)) \tag{3.4}$$

We can derive the optimality conditions by applying KKT conditions to the Hamiltonian [11] [20]:

$$x(k+1) = f_k(x_k, u_k) \tag{3.5}$$

$$x_0 = x_{initial} \tag{3.6}$$

$$\lambda_k = \bigtriangledown_{x_k}^T f_k(x_k, u_k)\lambda(k+1) + \bigtriangledown_{x_k}^T V_k \tag{3.7}$$

$$\lambda_K = \bigtriangledown_{x_K}^T L \tag{3.8}$$

$$0 = \bigtriangledown_{u_k} V_k + \lambda_{k+1}^T \bigtriangledown_{u_k} f_k(x_k, u_k) \tag{3.9}$$

where λ_k is the k-th Lagrangian multiplier and $\bigtriangledown_x L$ is the differential of L with respect to x.

The elements in the hybrid vehicle power management problem can be mapped into the optimal control problem. The vehicle dynamic and subsystem state space equations can be considered as an system. The states of vehicle and battery pack operation, x_k, depends on the control actions which correspond to the control vector, u_k. When a control vector, u_k, is applied to the system, the system state x_k changes according to the system evolution function f_k. In addition, to reflect the objectives of this power management problem which are minimize the power drawn from the engine, meet the traction requirements and control battery pack SOC level at the end of the mission, the cost function J can be designed to reflect all these requirements.

In the next section, we introduce a specific type of optimal control problem - the LQR. This hybrid electric vehicle power management problem is modeled as an LQR problem,

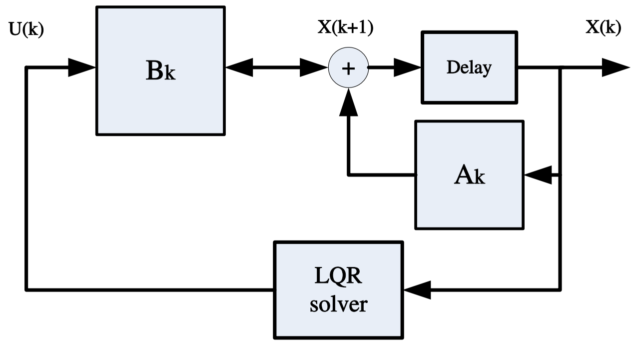

Figure 3.2: LQR problem block diagram

the system states, control vector design and the process to obtain optimal solution will be discussed in the following section.

3.2.2 LQR formulation

The LQR problem is a very well-studied problem in optimal control theory. Based on the state space equation we derived from vehicle dynamic and its subsystem models, we model the control problem as an LQR problem. In a LQR problem, the system evolution function corresponds to:

$$x(k+1) = A(k)x(k) + B(k)u(k) \tag{3.10}$$

$$x_0 = x_{initial} \tag{3.11}$$

where, $A(k)$ and $B(k)$ are matrices of appropriate dimension; $x(k)$ is the state of the system at kth stage; x_0 is the initial state of the system. The function describes the evolution of the state of system, as a linear function of both the state of system $x(k)$ and control vector $u(k)$. The objective of an optimal control problem is to determine the control inputs required for the system to reach a desired state. The block diagram of LQR problem is shown in Fig. 3.2. A cost function J is usually defined as quadratic function and corresponds to [8]:

$$J = x^T(K)Q(K)x(K) + \sum_{k=0}^{K-1}[x^T(k)Q(k)x(k) + u^T(k)R(k)u(k)] \tag{3.12}$$

where, $Q(K)$, $Q(k)$ and $R(k)$ are weighting matrices of appropriate dimension. In general, $Q(K)$ and $Q(k)$ are chosen to be positive semi-definite, while $R(k)$ is chosen to be positive definite. The LQR problem is well-studied in optimal control problem, due to its linearity of system state evolution equations and the convexity of cost function which mean the KKT conditions in LQR problem are both sufficient and necessary of optimality [8][19]. For all these advantages, it is desirable to solve the optimal control problem as an LQR problem.

In this work, we propose an approach to solve an hybrid electric vehicle power management problem using LQR formulation. From the objective we mentioned in previous section, the objectives we want to achieve are: (1) minimum power drawn from the engine for improved fuel efficiency; (2) certain battery SOC for offloading power, and (3) vehicle to meet the traction requirements according to mission specific profile. Therefore, in this optimal control problem, we want to minimize: (1) the errors between the actual speed the vehicle and the desired speed; (2) deviation between SOC at the end of mission and desired SOC for corresponding power needed, and (3) the power drawn from the engine. Therefore, we design a modified state of the system $x(k)$ and control vector $u(k)$ as two 2-dimensional vectors:

$$x(k) = \begin{bmatrix} V_{act}(k) - V_d(k) \\ SOC(k) - SOC_f \end{bmatrix} \tag{3.13}$$

$$u(k) = \begin{bmatrix} P_{eng}(k) \\ P_{bat}(k) \end{bmatrix} \tag{3.14}$$

where, V_{act} is the actual speed of the vehicle; V_d is desired speed specified in the mission profile; $SOC(k)$ is the actual SOC at each time step k, and SOC_f is defined as the desired SOC at the end of mission. It is necessary to mention that in a LQR problem, the system state evolution function should be linear in respect to both x_k and u_k. To construct the linear system state evolution function which is equivalent to an LQR problem formulation, we need to apply Taylor-series to linearize the original system state space equations which can be mapped into an LQR formulation. During the optimization, constraints are needed to ensure the operation of engine, battery and ultracapacitor is safe. The constraints of the optimization problem are defined and given as:

$$P_{eng-min} \leq P_{eng} \leq P_{eng-max} \tag{3.15}$$

$$P_{bat-min} \leq P_{bat} \leq P_{bat-max} \tag{3.16}$$

$$P_{tPPS-min} \leq P_{tPPS} \leq P_{tPPS-max} \tag{3.17}$$

$$P_{tPPS-min} \leq P_{tPPS} \leq P_{tPPS-max} \tag{3.18}$$

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{3.19}$$

$$SOE_{min} \leq SOE \leq SOE_{max} \tag{3.20}$$

$$\tag{3.21}$$

where SOC_{min} and SOC_{max} are set to be 0.4 and 0.7 respectively; SOE_{min} and SOE_{max} are set to be 0 and 1.0 respectively. To achieve our objectives in this power management problem, we choose Q and R matrices as:

$$Q(K) = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix} \tag{3.22}$$

$$Q(k) = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix} \tag{3.23}$$

$$R(k) = \begin{bmatrix} 10 & -1 \\ -1 & 0 \end{bmatrix} \tag{3.24}$$

where, α and β are positive weighting factors, $\alpha = 500,000$ is used to assure battery SOC will return to the desired SOC at the end of mission [8] and $\beta = 1,000$ is used to assure speed requirement is met. For the $Q(k)$ corresponding to state variables, we want to minimize the errors between the actual speed of the vehicle and the desired speed but we don't care about the SOC changes during the mission, thus we choose to use 10 and 0 to form the diagonal matrix similar to $Q(K)$. For $R(k)$ which correspond to control vector, according to our interest that only minimize the power drawn from engine, the matrix is determined as shown in equation 3.15, 3.16 and 3.17.

To solve the LQR problem, first we define the Hamiltonian function as:

$$H(k) = J + \sum_{k=0}^{K-1} \lambda^T(k+1)[A(k)x(k) + B(k)u(k)] \tag{3.25}$$

Then, applying the KKT conditions, we obtain the sequence of optimal control vectors. The KKT conditions and the solution of LQR correspond to [8]:

$$0 = \frac{\partial H(k)}{\partial u(k)} = 2u^T(k)R(k) + \lambda^T(k)B(k) \tag{3.26}$$

$$u(k) = -\frac{1}{2}R^{-1}(k)B^T(k)\lambda(k+1) \tag{3.27}$$

$$\lambda(k) = \frac{\partial H(k)}{\partial x(k)} = A^T(k)\lambda(k+1) + 2Q(k)x(k) \tag{3.28}$$

$$\begin{aligned} P(k) =& Q(k) + A^T(k)P(k+1)[I + B(k)R^{-1}(k)B^T(k)P(k+1)]^{-1}A(k) \\ & P(K) = Q(K) \end{aligned} \tag{3.29}$$

$$u(k) = -[R(k) + B^T(k)P(k+1)B(k)]^{-1}B^T(k)P(k+1)A(k)x(k) \tag{3.30}$$

The above equations show the process to obtain the optimal control actions for this power management problem. In the next section, analysis and results are provided and discussed.

3.3 Summary

In this chapter, we first presented our proposed optimal control based algorithm in conjunction with rule-based control strategy, the core part in our analysis. Next, we provided an introduction of the power management strategy for non-traction electrical loads in the vehicle system, we also define the priorities of each load based on different operation modes. Further more, the optimal control theory is introduced in order to solve the power management problem. Additionally, LQR formulation and solution are presented which is used to solve the optimal control problem we focus on in this analysis.

Chapter 4

Analysis and results

In this section, the fuel efficiency of the engine, the variations of battery pack SOC and PPS modules SOE under proposed optimal power based algorithm combined with ruled-based control strategy are analyzed. Additionally, the proposed approach is compared with the Thermostat control strategy and Max SOC control strategy.

4.1 Mission profile

The mission profile considered in this work includes two velocity profile that sets for the traction requirements and two electrical loads profiles (power requirements of electrical loads with and without ETC gun system) which we will discuss in the following section. Fig.4.1 illustrates the two velocity profiles used in this thesis. The sample time is selected to be one second.

In the following sections, first the advantages of the three power sources combination in hybrid military vehicle drivetrain on fuel efficiency and ability to control SOC will be demonstrated. Next, the advantage of our proposed optimal control based power management solution over two other widely used control strategies (Thermostat control strategy and Max SOC control strategy) will be presented. In addition, the system performance will be tested when non-traction electrical loads and pulsed power weapon load are considered. Finally, optimal load scheduling ability of the studied hybrid military vehicle system under proposed optimal control based power management solution will be demonstrated. Accord-

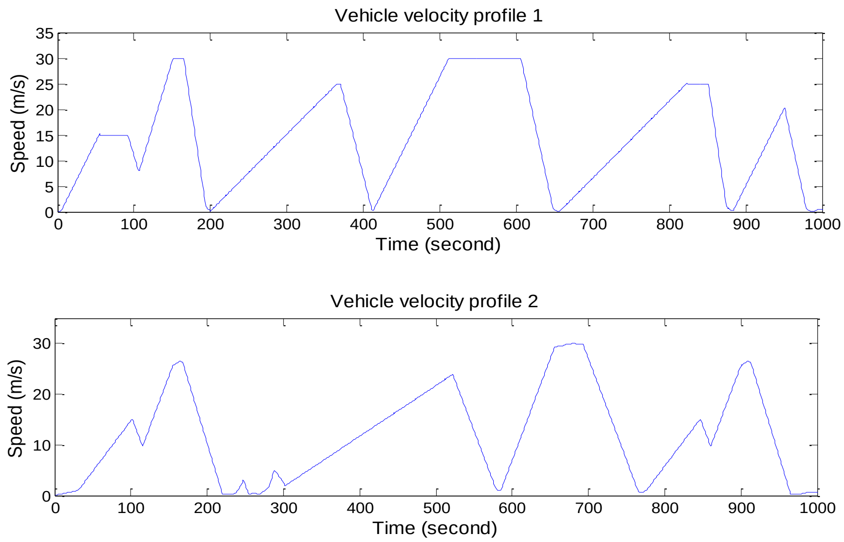

Figure 4.1: Velocity profile

ing to the characteristics of battery and ultracapacitor used in this thesis, the charging and discharging efficiencies of battery and ultracapacitor are all set to 90%; the battery SOC variation range is chosen to be between 0.4 and 0.7 [14]; the initial SOC is set to be 0.6, and the initial SOE is set to be 0.8.

4.2 Advantage of three power sources combination

In the section, we consider the case that ETC gun is not in use during the mission (The mission profile used in the simulation includes only the velocity profile and conventional electrical loads power requirement which is simulated as a constant, the operation of ETC gun system is not considered in this simulation). We investigate the advantage of three power sources combinations over two power sources combination. Within this framework, the engine output power under three different combinations of power sources (engine alone, engine and battery pack with and without traction PPS module) are simulated and analyzed.

Typically, a combination of engine and battery pack is used as the hybrid power source for commercial and military hybrid electric vehicles. In this thesis, the performance of three

Table 4.1: Fuel efficiency comparison under three power sources combinations in mission 1

Power sources combination	Avg. engine power
Engine	105.9
Engine and battery	101.7 kW
Engine, battery and ultracapacitor	101.8 kW
Power sources combination	Max engine power
Engine	484.8
Engine and battery	484.8 kW
Engine, battery and ultracapacitor	394.8 kW

power sources combination (engine, battery pack and traction PPS module) is investigated first. A simulation to test the benefit of three power sources over two power sources is presented under the proposed approach . Fig. 4.2, Fig. 4.3, Table 4.1 and Table 4.2 illustrate the results of this simulation. The red solid line represents the actual output power from engine, and the dotted line represents the total power required for traction and non-traction loads. From Fig. 4.2, Fig. 4.3 , Table 4.1 and Table 4.2, we can see that, despite no significant difference between the average engine output power under three different combinations, the combination of three power sources achieves the least max output power from engine compared to the other two combinations. According to the characteristic of engine, the engine size is determined by the max engine output power. Additionally, the higher the engine output power is, the lower the engine efficiency [1]. Thus, based on the same simulation platform, a lower max engine output power is desirable to reduce the engine size and improve engine efficiency. Besides, the engine output power curve shows that the three power sources combination significantly reduces the engine output power when the total power requirement is extremely high compared to the other combinations. Based on the simulation results, the three power sources combination is able to improve the fuel economy significantly compared to the other two combinations.

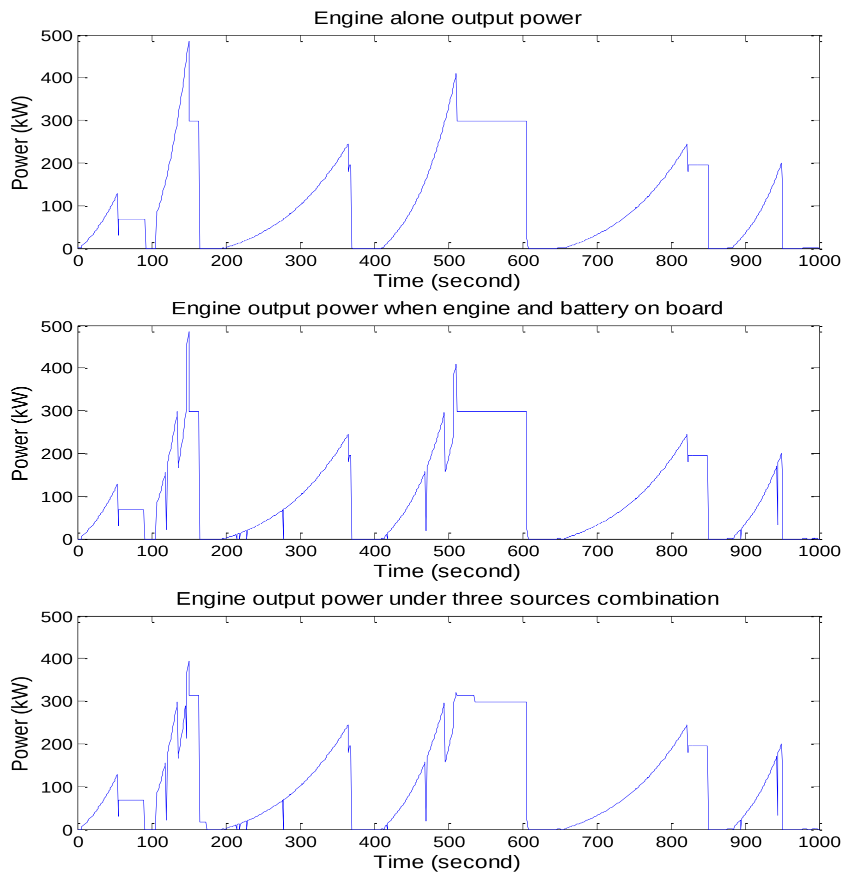

Figure 4.2: Power from engine under three power source combinations in mission 1

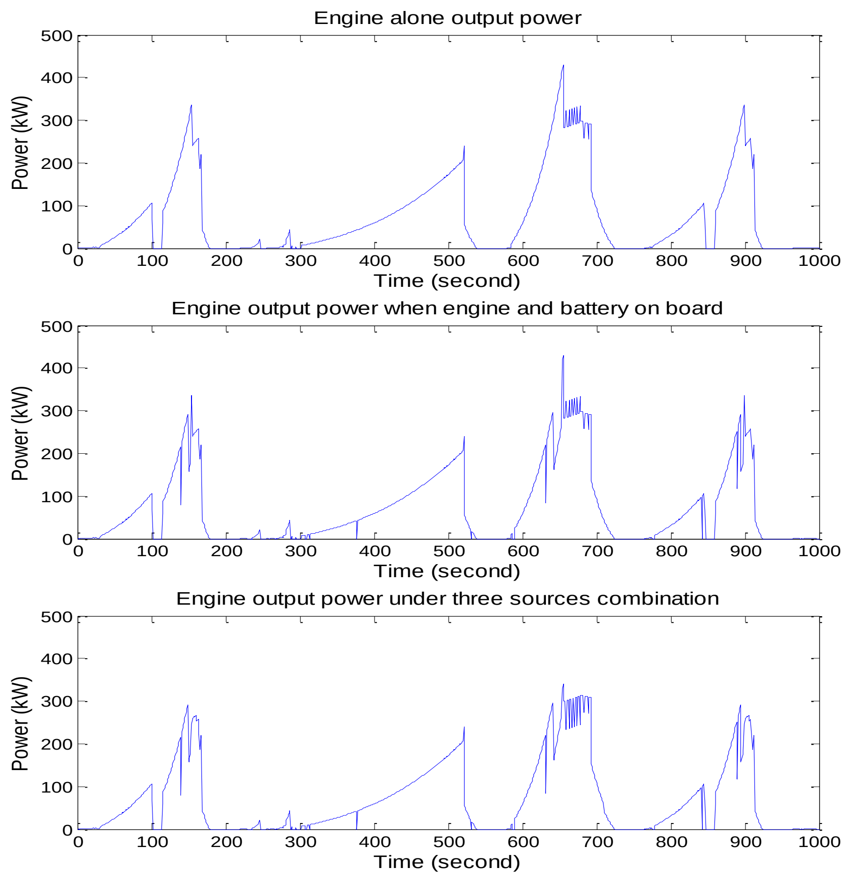

Figure 4.3: Power from engine under three power source combinations in mission 2

Table 4.2: Fuel efficiency comparison under three power sources combinations in mission 2

Power sources combination	Avg. engine power	Max engine power
Engine	72.9 kW	430.7 kW
Engine and battery	69.4 kW	430.7 kW
Engine, battery and traction PPS module	69.5 kW	340.7 kW

4.3 Advantage of the proposed approach

Next, we compare the system performance under three different control strategies. In the test cases, we only consider the traction needs without non-traction electrical loads and pulsed power weapon load. Fig.4.4 and Fig.4.5 present the total power required and engine output power under three different control strategies in mission 1 and mission 2. Fig.4.6 and Fig.4.7 present final battery SOC level under three different control strategies in mission 1 and mission 2. Namely, (1) thermostat control strategy; (2) max SOC control strategy, and (3) the proposed optimal control strategy. The solid lines represent the actual engine output power, and the dotted lines represent the total power required for traction and non-traction loads. Table 4.3 illustrates the average engine output power under the three different control strategies. From Fig.4.4 Fig.4.5 and Table 4.3 we can see that, the thermostat control strategy tends to make the engine operate at its most efficient point. However, the average engine output power is much higher compared to the other two control strategies in both missions. The engine output curves of max SOC control strategy and the proposed approach are very similar, from an engine efficiency stand point. However, the proposed optimal control strategy uses less power from the engine. Thus, our proposed approach achieves the best fuel economy, followed by max SOC control strategy and thermostat control strategy.

Battery end of life (EOL)is defined by USABC as the condition when battery is on longer capable of meeting power and energy targets [43]. Battery cycle life is the number of deep discharge cycle the battery can under-go before it reaches the EOL conditions [44]. From the aspect of protecting battery, it is desired to avoid deep charge of battery SOC. Under

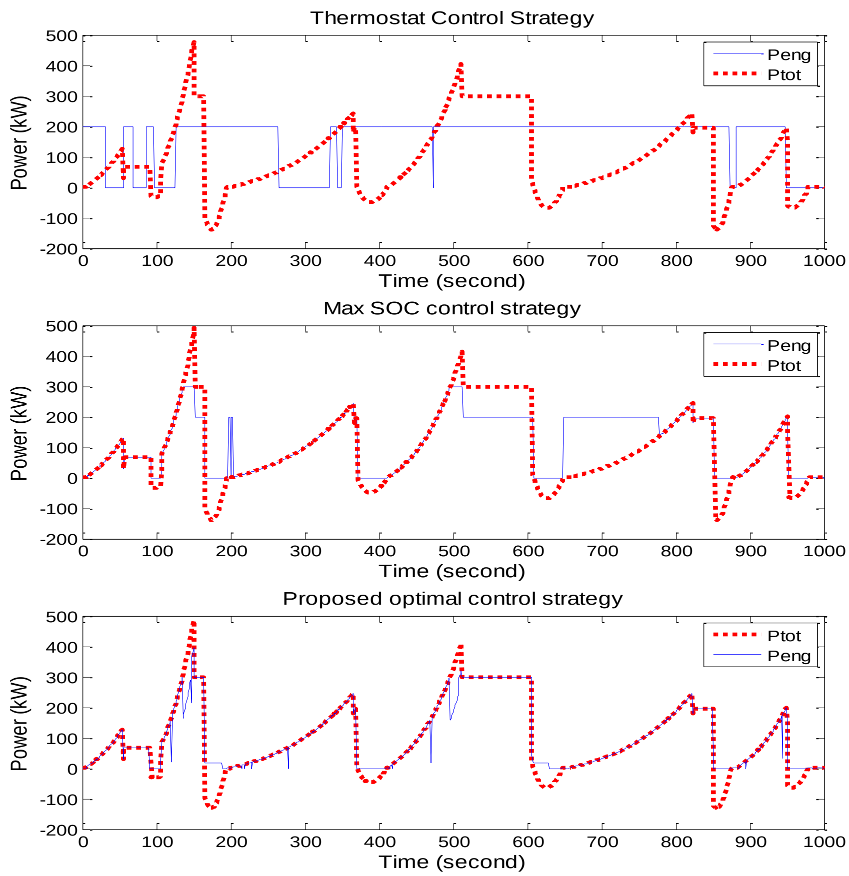

Figure 4.4: Fuel efficiency comparison under three control strategies in mission 1

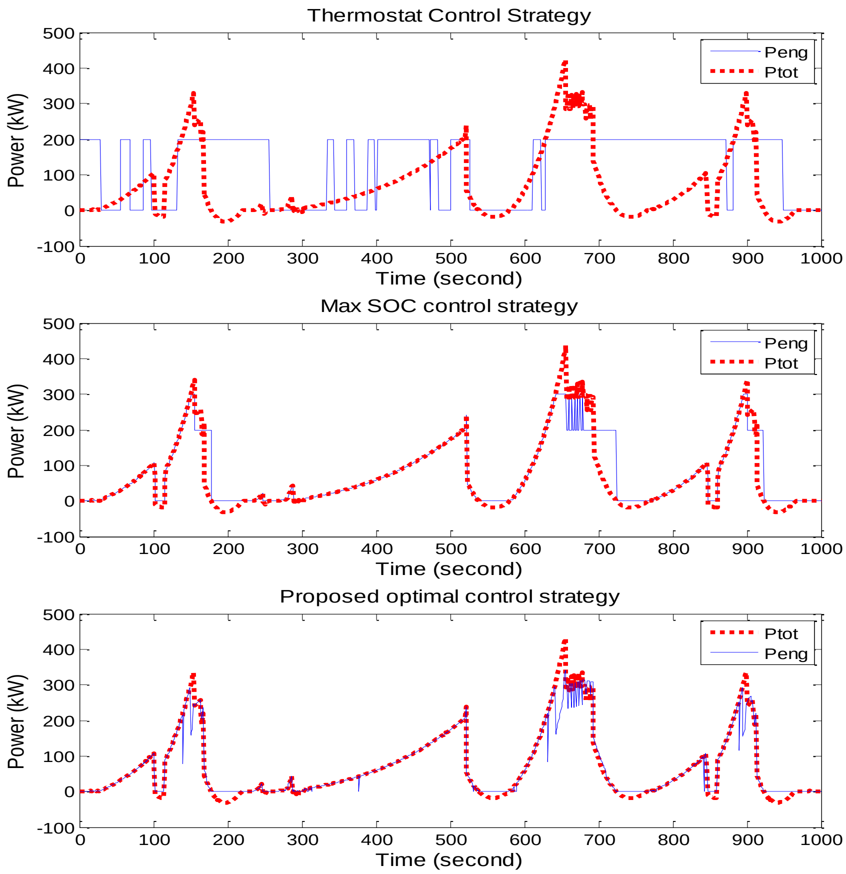

Figure 4.5: Fuel efficiency comparison under three control strategies in mission 2

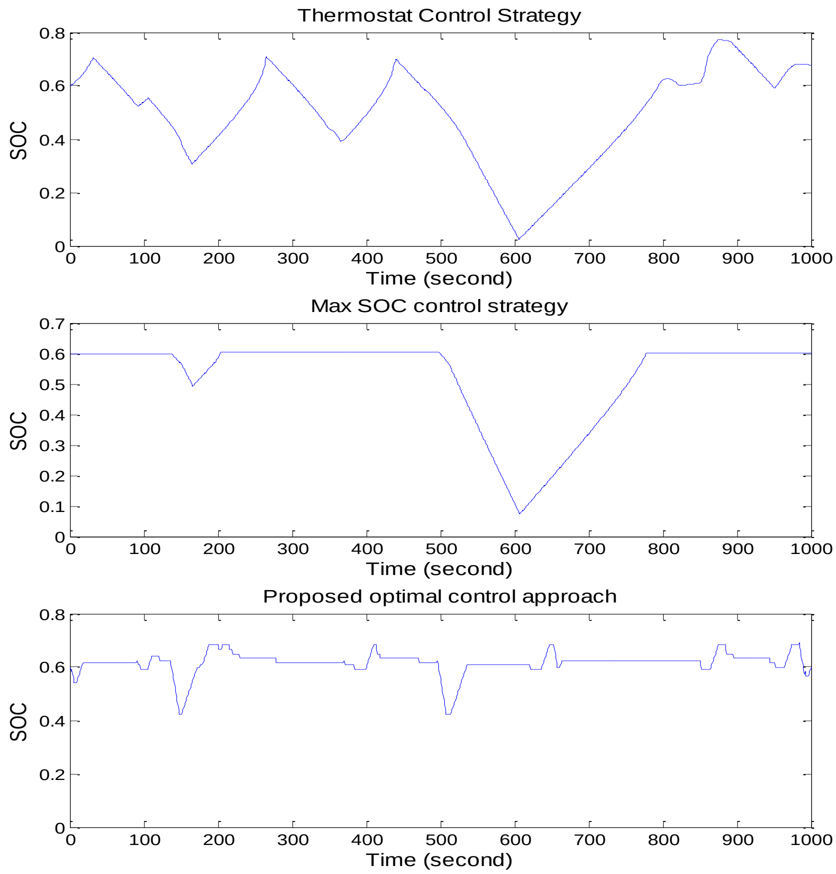

Figure 4.6: SOC comparison under three control strategies in mission 1

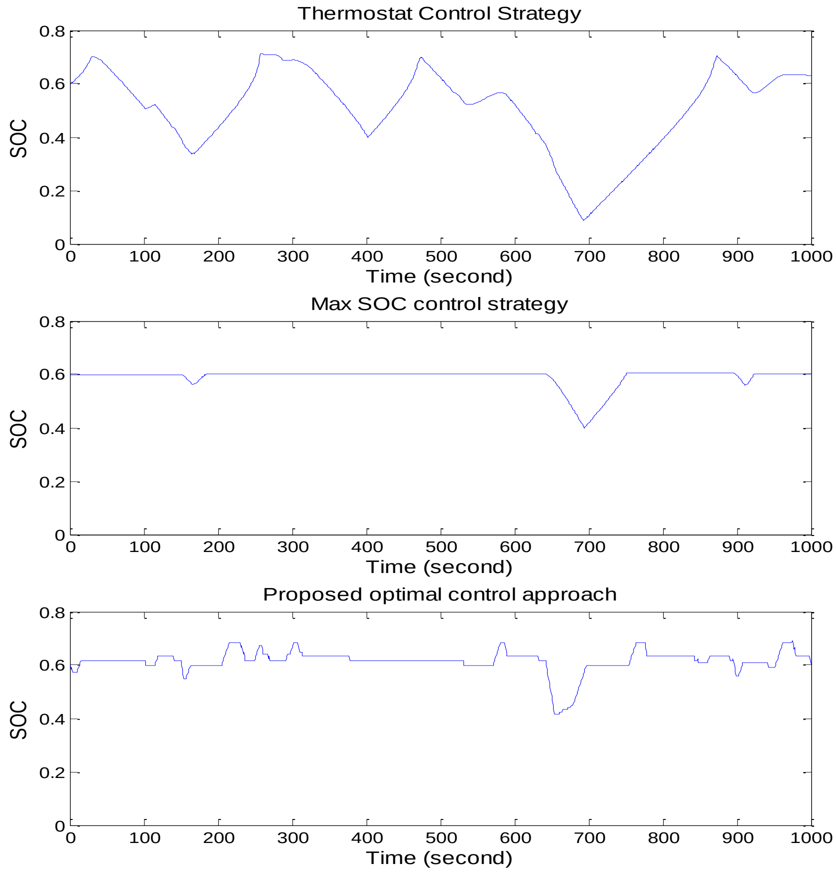

Figure 4.7: SOC comparison under three control strategies in mission 2

Table 4.3: Fuel efficiency comparison under three power source combinations

Control strategy	Avg. engine power in mission 1
Thermostat control strategy	128.0 kW
Max SOC control strategy	114.5 kW
Optimal control strategy	105.7 kW
Control strategy	Avg. engine power in mission 2
Thermostat control strategy	99.0 kW
Max SOC control strategy	76.0 kW
Optimal control strategy	73.0 kW

the condition that the traction power needs are satisfied, a good control strategy should also have the following characteristics: (1) the final battery SOC should be restored to its target level which leads to a highly efficient battery and ensures that the battery pack always has enough energy to meet offloading power needs; (2) high charging and discharging currents that reduce efficiency and battery life should be avoided [42], and (3) avoid deep discharge to increase battery life. Under the specific mission profiles, the battery variations under different control strategies are simulated. The results are shown in Table 4.4, Fig.4.6 and Fig.4.7. In our proposed control strategy, once we specify the initial SOC and the desired final SOC, the optimal control policy will find a way to minimize the power from the engine while bringing the final SOC close to the desired value. However, the other two control strategies are not able to control the final SOC. In this paper, we specify the initial SOC in all three different control strategies all be 0.6, and the desired final SOC is chosen to be 0.6 as well for a fair comparison of three control strategies. Table 4.4 illustrates the final SOC of three different control strategies. From Table 4.4 we can see that the final SOC of our proposed approach and max SOC control strategy return to the desired value. For thermostat control strategy, the final SOC reaches 0.6296. For max SOC control strategy, the final SOC is very close to the desired value. However, since both thermostat control strategy and max SOC control strategy are purely rule-based, the final SOC largely depends on the mission profile. This implies that the final SOC level may change in different missions. That is, these control strategies are not able to control the final state SOC level. In mission,

Table 4.4: Battery SOC variation

Control strategy	Final SOC in mission 1	SOC variation in mission 1
Thermostat control strategy	0.6296	0.7467
Max SOC control strategy	0.6001	0.5265
Proposed control strategy	0.6000	0.2834
Control strategy	Final SOC in mission 2	SOC variation in mission 2
Thermostat control strategy	0.6345	0.6234
Max SOC control strategy	0.6002	0.4961
Proposed control strategy	0.6000	0.2667

the simulation results show that the final SOC of thermostat control strategy and max SOC control strategy is 0.6345 and 0.6002, respectively. In addition, from the simulation results shown in Table 4.4, Fig.4.6 and Fig.4.7, we can see that only our proposed approach is capable to avoid deep discharge which is better for battery life. Therefore, the ability to maintain the desired SOC level at the end of different missions while protecting battery life is demonstrated, our proposed optimal control strategy is capable of providing good fuel efficiency while controlling the final SOC under all mission profiles.

4.4 System performance when ETC gun is in operation

Next, we evaluate the proposed optimal control strategy while considering both traction and non-traction loads including the ETC gun. In our proposed approach, a traction PPS module is used to supply power when it is needed. In our proposed optimal control strategy, we tend to use the traction PPS module as little as possible and charge it back to the pre-set SOE level as soon as possible. This ensures that the traction PPS module always has enough energy to meet unexpected mission requirements. We use the PPS module primarily to reduce the peak power. The power from engine, the SOC variation of battery pack, and the SOE variations of two PPS modules are obtained and analyzed. The results are shown in Fig. 4.8, Fig. 4.9 and Table 4.5. From Fig. 4.8 Fig. 4.9 and Table 4.5 we can see that the final states of SOC and SOE all return to the initial value we set.

Table 4.5: Optimal results when ETC gun is in operation

	Mission 1	Mission 2
Max power required	496.1kW	464.1kW
Average engine output power	139.5kW	107.8kW
Max engine output power	398.7kW	373.1kW
Final SOC	0.6000	0.6000
Final SOE of PPS module for traction	0.8000	0.8000
Final SOE of PPS module for ETC gun	0.8000	0.8000

The proposed approach effectively reduces the engine output power. The capability of the proposed approach to effectively improve fuel economy, maintain the SOC and SOE levels is demonstrated. According to different mission requirements and military vehicle parameters, this power management strategy can be modified and used as an helpful tool to improve fuel economy and enable power offloading.

4.5 Optimal load scheduling analysis

In previous studied cases, we assume that all non-traction electrical loads are operating at their rated power which is simulated as an constant. However, in the real operation of the military vehicles, sometime the engine may not be able to operated at its full capability. Therefore, an effective power management solution for non-traction electrical loads is necessary to save energy and enable the military vehicle to complete the mission. The non-traction electrical loads with low or middle priority can be shed according to the operation status and power requirement of the military vehicle. Using the power management strategy for non-traction electrical loads we introduced in the previous chapter, in this section we analyze the performance of vehicle system and load scheduling results when engine is not able to work at its full capability. We analyze engine output power and non-traction loads scheduling results in the mission when engine is producing from 100% to 50% of its max power. In addition, it is necessary to demonstrate the load scheduling strategy is helpful to improve vehicle performance compared to non load scheduling results. Therefore, we also analyze the vehicle performance without load scheduling. The simulation results when

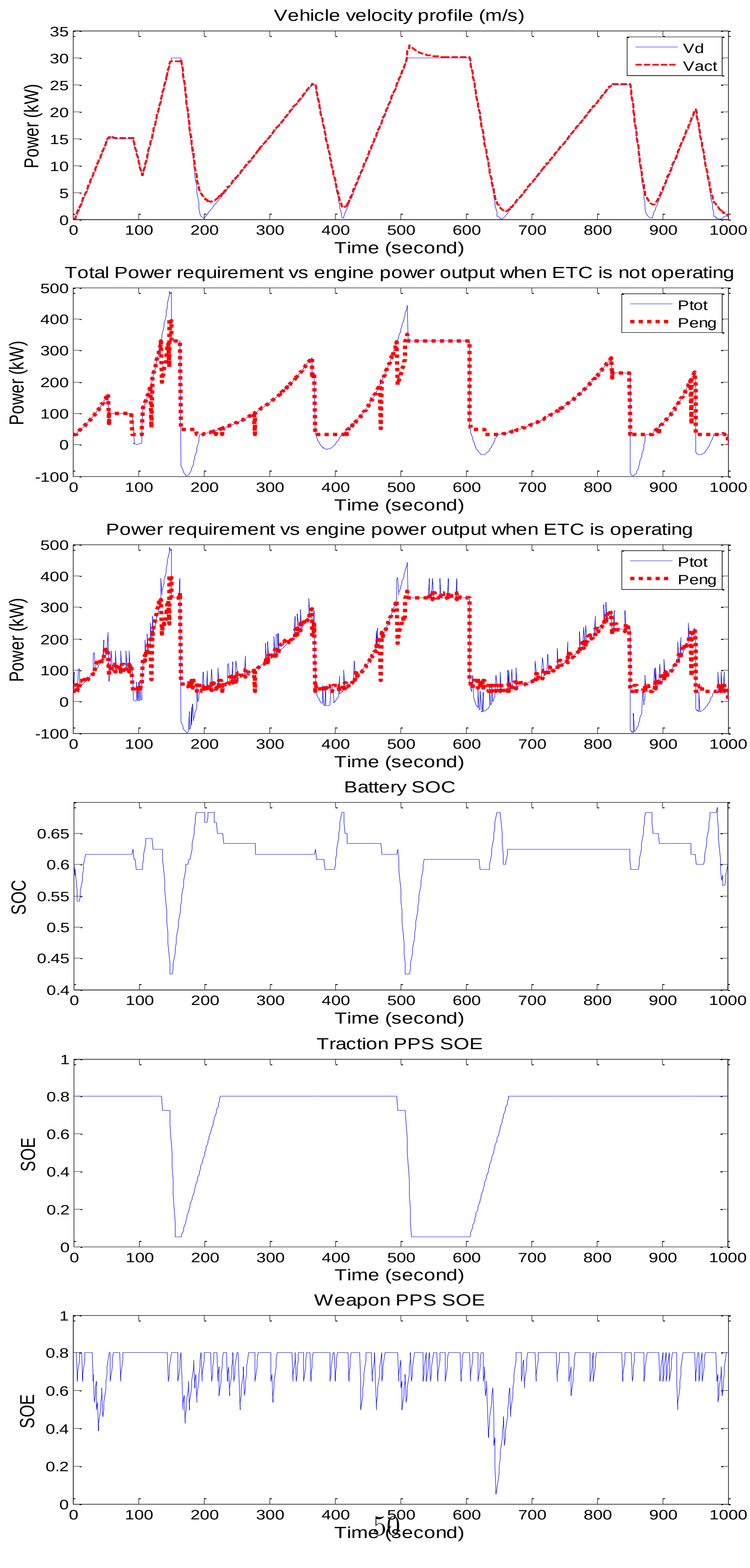

Figure 4.8: Optimal results when ETC gun is in operation in mission 1

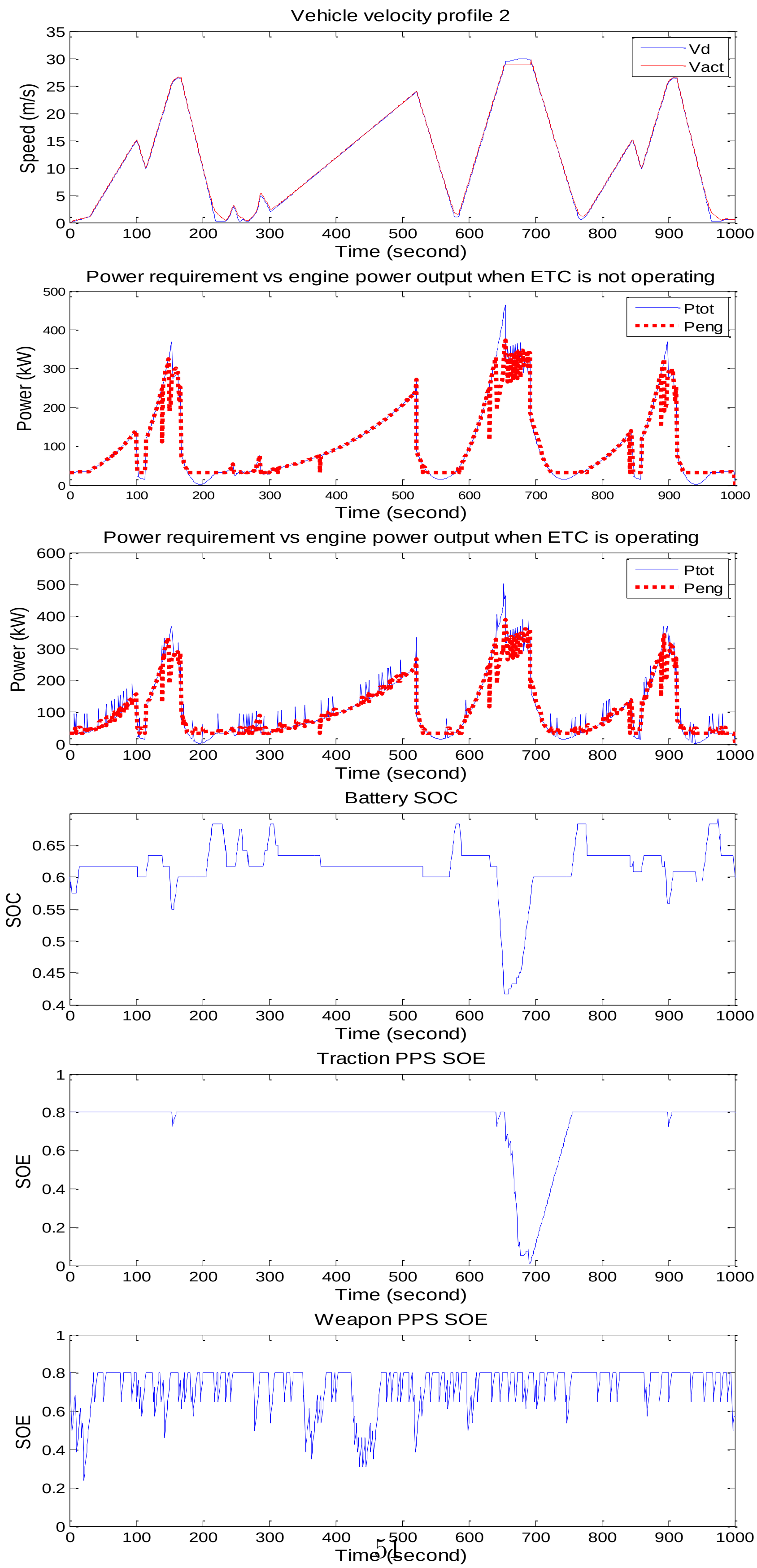

Figure 4.9: Optimal results when ETC gun is in operation in mission 2

engine is producing 100%, 70% and 50% are shown from up to down in respectively Fig. 4.10, Fig. 4.12, Fig. 4.11 and Fig. 4.13. In Fig. 4.10 and Fig. 4.12, we plot the desired vehicle velocity vs achieved velocity with or without load scheduling. The desired vehicle velocity from mission profiles which are represented by blue solid line, the achieved velocity when load scheduling is performed is represented by red solid line and the achieved velocity when load scheduling is not performed is represented by black dotted line. To compare the advantage of load scheduling over vehicle performance without load scheduling, we plot them as three groups. The upper one represents the desired vehicle speed vs achieved vehicle speed with load scheduling. The lower one represents the desired vehicle speed vs achieved vehicle speed without load scheduling. Fig. 4.11 and Fig. 4.13 illustrate the plot of engine output power and load scheduling results of non-traction electrical loads. The blue solid line represents the total power requirement of both traction needs and non-traction needs, the red solid line represents the actually engine output power and green solid line represents the power requirement of non-traction electrical loads during the mission.

From the simulation results which are shown in Fig. 4.10 and Fig. 4.12 we can see that when the engine is able producing more than 70% of its max power, the actually velocity the vehicle achieved match the desired velocity profile perfectly. However, when then engine is not able to produce more than 70% of its max power, the difference between achieved velocity and desired velocity becomes obvious with the decreasing of engine capability. In addition, the simulation results clearly show that with load scheduling, the vehicle can achieve better performance in terms of match the vehicle velocity profile better. Therefore, the advantage of load scheduling is demonstrated. From Fig. 4.11 and Fig. 4.13 we can see similar results. When engine is producing more than 80% of its max power, almost all loads are operating at their rated power. With the decreasing of engine max output power, more non-traction electrical loads are shed. From the simulation results we are able to find out what is requirement of the engine and battery pack size in a certain mission,and if the engine is not able to producing its max power and energy need to save for future operation, how the non-traction electrical loads can be managed and how fast the vehicle can operate. The system model and power management solution can be used to determine engine and battery size based on different mission requirements, and can be used as a tool to test vehicle performance under different situation.

4.6 Summary

In this chapter, we first analyzed the advantages of the three power sources combination over two power sources combination and single power source drive train. Based on the velocity profiles we designed in this study, simulation results are obtained and analyzed. Form the simulation results we can see that three power sources combination have the ability to reduce max engine output power and average engine output power, which results in the reduced size of engine and better fuel efficiency. Next, we compared the fuel efficiency and final battery SOC of our propose approach with two other control strategies. The simulation results showed that our approach achieved better fuel efficiency and maintain the battery SOC at our desired level, while the other two control strategies failed to achieve the same results. Then we tested the system performance under our proposed power management strategy when pulsed power weapon load (ETC) is in used in the military vehicle system. The simulation results demonstrated that our proposed approach is able to improve fuel efficiency and control battery SOC while fulfilling all traction, non-traction and pulsed power load needs. Finally, we tested the analyzed military vehicle potential limitation when engine is not able to produce its max power Optimal load scheduling is performed when load shedding is needed to save energy. From the simulation results we can see that, our proposed approach successfully achieved our desired objectives: (1) fuel efficiency is improved; (2) battery SOC is maintained, and (3) optimal load scheduling is performed when load shedding is needed.

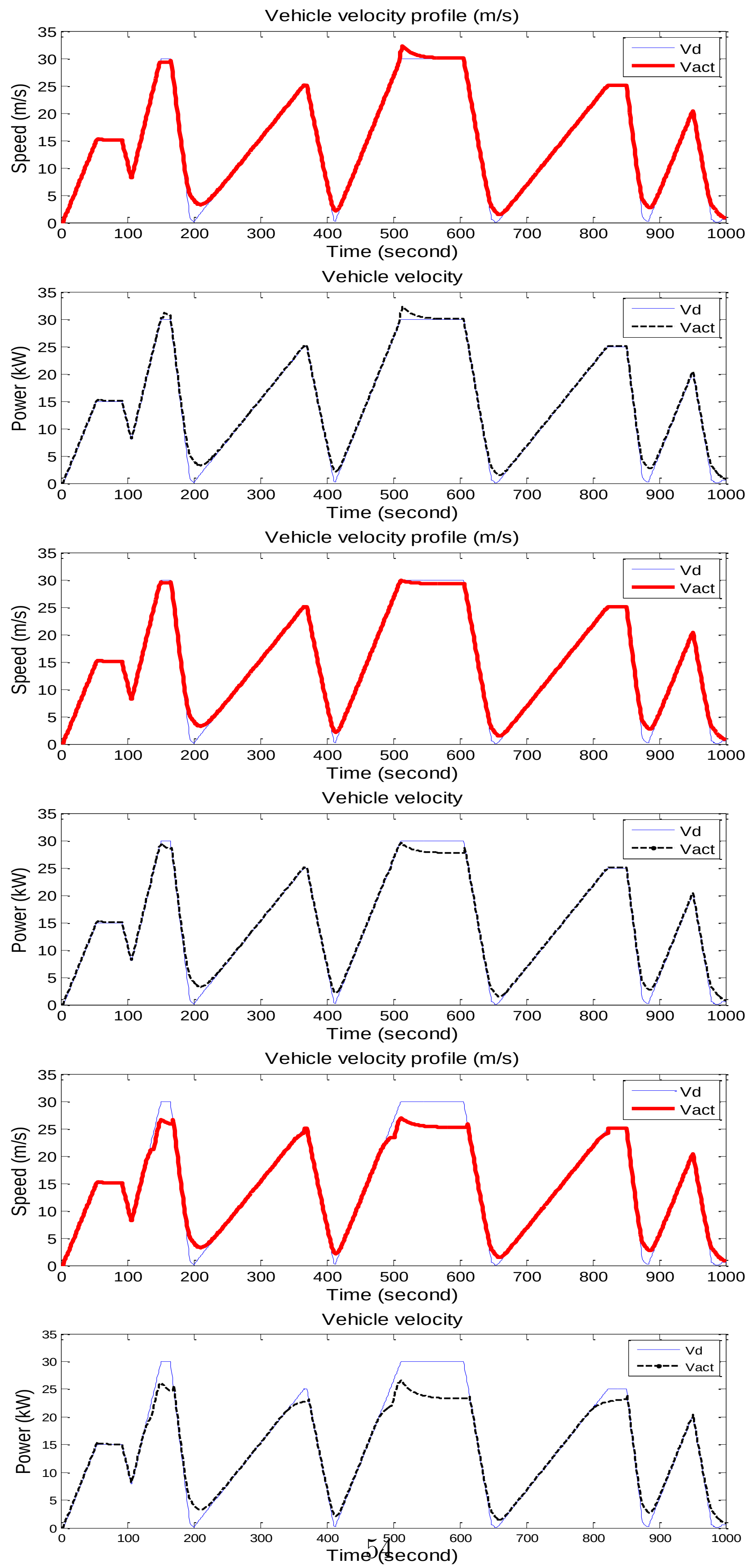

Figure 4.10: Desired vehicle velocity vs achieved vehicle velocity in mission 1

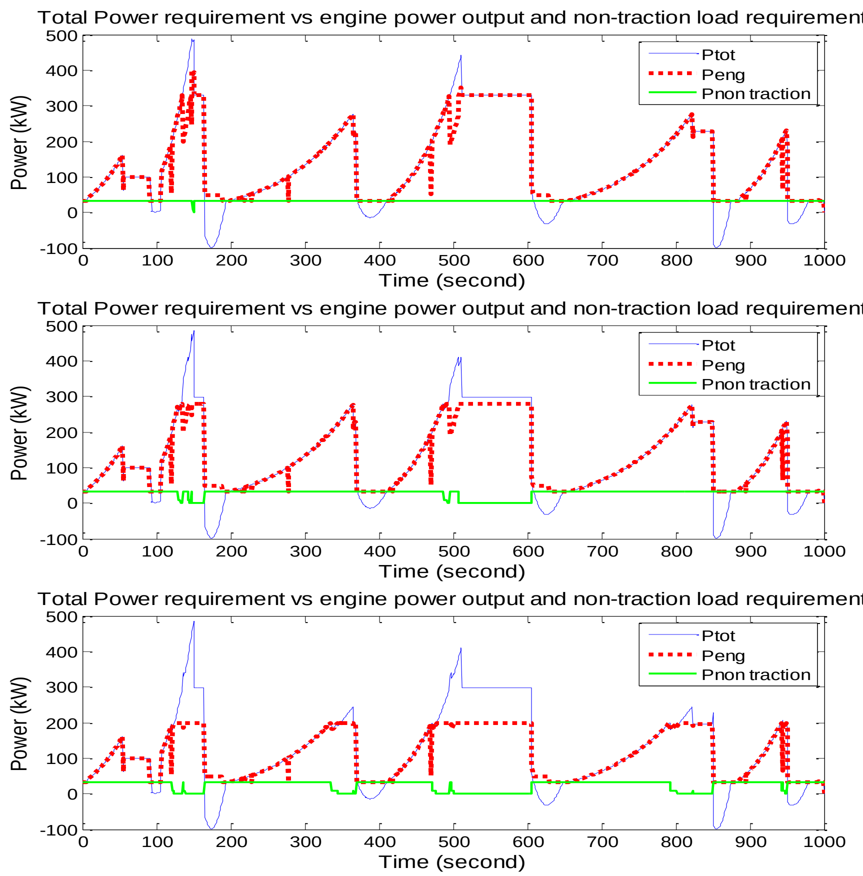

Figure 4.11: Total power requirement vs engine output power and non-traction loads power requirement in mission 1

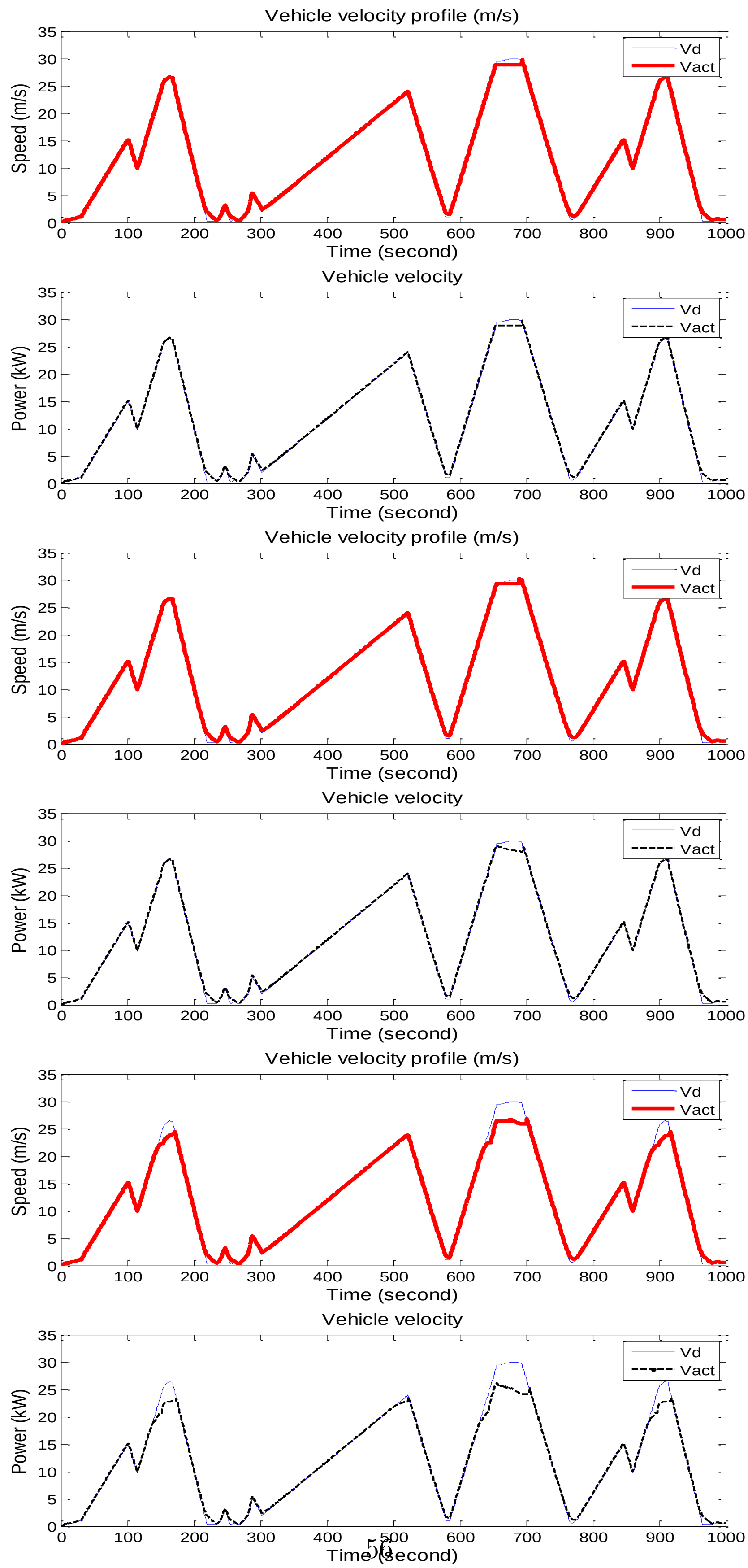

Figure 4.12: Desired vehicle velocity vs achieved vehicle velocity in mission 2

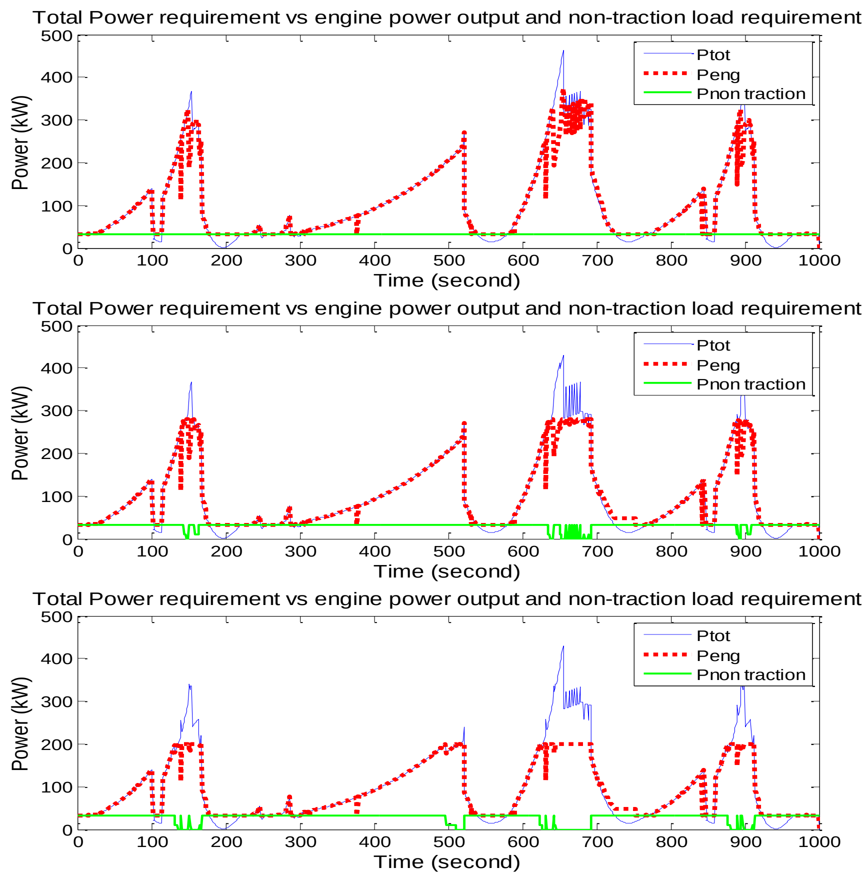

Figure 4.13: Total power requirement vs engine output power and non-traction loads power requirement in mission 2

Chapter 5

Conclusions and future work

So far, we have already analyzed the improvement in fuel efficiency, the controllable final battery SOC, the ability to support both non-traction electrical loads and pulsed power weapon load under different control strategies in Chapter 4. In this chapter, we provide a concise summary of the key contribution and possible future work.

5.1 Summary of key contributions

Sufficient energy is particularly critical to military vehicles in mission. It is necessary for military vehicles to posses an reliable system architecture, a variety of non-traction electrical loads to improve vehicle performance and an effective power management strategy to optimize energy use in vehicle. In this thesis, to achieve the objectives of improving fuel efficiency, controlling battery SOC and providing robust performance, an optimal control based algorithm in conjunction with rule-based control strategy, and a reliable two-bus vehicle power system architecture with three power sources (engine/generator, battery and ultracapacitor) series hybrid electric drive train are presented.

First we analyzed the advantages of three power sources combination over two or single power sources drive train. From the simulation results it is obvious that three power sources combination is able to significantly reduce the max power output from engine which is helpful to reduce engine size in the vehicle design, at the same time improve fuel efficiency. Next, we analyzed the system performance under three different control strategies. From the simulation results, our proposed approach is demonstrated to achieve better fuel efficiency and controllable battery SOC compared to other approaches. Next, we focus on the test of system performance when pulsed power weapon load is in use. With the combination of three power sources (engine/generator, battery pack, traction and weapon PPS modules), all traction, non-traction and pulsed power needs are met while the abilities to improve engine efficiency and control battery SOC are maintained. Therefore, the capability of the proposed power management strategy to react to different mission requirements is demonstrated, vehicle performance and offloading power requirements are satisfied, better fuel efficiency is achieved as well. Finally, we performed optimal load scheduling of non-traction electric loads and tested the potential limitation of the studied military vehicle model. We analyzed the vehicle performance when engine is not able to operated at its full capacity. With the decreasing of engine max output power, first the optimal load scheduling algorithm automatically shed those loads with low or middle priorities. When all the loads with low and middle priorities have been shed, the vehicle reduce its speed to ensure major components of the military vehicle can still operate normally. This test and power management solution is capable to figure out the potential limitation of military vehicle under all possible situations, and provide suggestion to the design of military vehicle components.

The approach and analysis presented in this thesis successfully achieve the objectives of improving fuel efficiency, controlling battery SOC and meeting all loads requirements. It provides a tool for further investigation to improve military vehicle performance and survivability.

5.2 Future work

One possible extension of this work is to make the operation of ultracapacitor also controlled by the optimal control algorithm rather than a rule-based algorithm. This extension may be able to further improve fuel efficiency. Additionally, we can also include the capability to control the ultracapacitor SOE at the end of the mission.

Moreover, to further save energy and improve military vehicle survivability, switches can be added into the system. An optimal configuration problem can be formulated to control the statues of switched in the system if faults occur to the system. If part of the system is damaged and unable to supply power to electrical loads, through controlling the statues of the switched those loads with high priority can be powered while lower priority loads are shed. It is desired to create an automated power system and optimal control reconfiguration solutions can be obtained that enable survivability during faults or failures (due to component failure or battle damage). In addition, comprehensive performance evaluation can be performed to study the contingency management solutions for various types of faults and failures.

Furthermore, our proposed approach can be compared with other control strategies such as instantaneous equivalent minimization strategy. Through the comparison, the advantages of our approach can be further demonstrated while the disadvantages of our proposed approach can be found. The main drawback of our proposed approach is the complexity of LQR solution, it is desirable to find ways to reduce the calculation process of our approach.

Bibliography

[1] M. Ehsani et al, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles-Fundamental, Theory and Design,* Baca Ranton, FL: CRC Press, 2005.

[2] C. Kim et al, *"Fuel Economy Optimization for Parallel Hybrid Vehicles with CVT,"* in SAE, Paper no. 1999-01-1148.

[3] G. Paganelli et al, *"A General Formulation for the Instantaneous Control of the Power Split in Charge Sustaining Hybrid Electric Vehicles,"* in Proc. of 5^{th} Int. Symp. of Advanced Veh. Control, Ann Arbor, MI, 2000.

[4] C. C. Lin et al, *"Energy Management Strategy for a Parallel Hybrid Electric Truck,"* Proc. of the 2011 Amer. Control Conf., Arlington, VA, Jun. 2000, pp. 2878-2883.

[5] M. A. Marsrur et al, *"42-Volt Electric Power System for Military Vehicles-Comparison with Commercial Automotive System,"* Proc. of Veh. Technol. Conf., 2002.

[6] L. Boulon et al, *"Simulation Model of a Military HEV with a High Redundant Architecture,"* IEEE Trans. Veh. Technol., vol. 59, no. 6, Jul. 2002.

[7] M. A. Lipscomb, *"A Versatile Tool for the Design and Verification of Military Vehicle Power System,"* M.S. thesis, Dept. Elect. Eng.,Texas A&M Univ., College Station, TX, Aug. 2005.

[8] M. Mahmoud, and M. Singh, *Discrete System: Analysis, Control and Optimization,* Spring-Verlag, New York, 1984.

[9] Th.H.G.G Weise et al, *"Status and Result of the German RD Program on ETC Technologies,"* IEEE Trans.Mag., vol. 37, pp. 46C51, Jan. 2001.

[10] H.G Wisken, and Th.H.G.G. Haak, *"Capacitive Pulsed Power Supply Systems for ETC Guns,"* IEEE Trans. Mag., vol. 39, no. 1, Jan. 2003.

[11] H.G Wisken et al, *"High Energy Density Capacitors for ETC Gun Applications,"* IEEE Trans. Mag., vol. 37, pp.332C335, Jan. 2001.

[12] S. Fish and E. Redding, *"Prime Power and Pulsed Energy Storage for EM Gun E-quipped Tank Combat Missions,"* IEEE Trans. Mag., vol. 33, Jan. 1997.

[13] S.R Shumway and D.S Stoffer, *Time Series Analysis and Its Applications,* Springer-Verlag, New York, 2000.

[14] C. Musardo et al, *"A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management,"* Proc. of the 44th IEEE Conf. on Decision and Control, and the European Control Conf. 2005, Seville, Spain, Dec. 12-15, 2005.

[15] N. Jalil et al, *"A Rule-Based Energy Management Strategy for a Series Hybrid Vehicle,"* Proc. of the Amer. Control Conf., Albuquerque, NM, Jun. 1997.

[16] L. Serrao et al, *"A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles,"* J. Dynamic Syst., Measurement, and Control, vol. 133, May. 2011.

[17] P. Pisu, and G. Rizzoni, *"A Supervisory Control Strategy for Series Hybrid Electric Vehicles with Two Energy Storage Systems,"* 2005 IEEE Veh. Power and Propulsion Conf., Sep. 7-9, 2005.

[18] J. Kang et al, *"Dynamic Optimization of Lean Burn Engine Aftertreatment,"* ASME J. Dynamic Syst. Measurement and Controls, vol. 123, no. 2, pp. 153-160, Jun. 2001.

[19] S. Boyd and L. Vandenberghe, *Convex Optimization,* Cambridge University Press, 2004.

[20] A. Sage and C. White, *Optimum System Control,* Princton-Hall, 1997.

[21] D. P. Bertsekas, *Dynamic Programming and Optimal Control,* Athena scientific, 1995.

[22] *"Transitioning to 42-Volt Electrical System,"* SAE SP-1556,2000.

[23] P. Nicastri and H. Huang, *"42 V Powernet: Providing the Vehicle Electrical Power for the 21st Century,"* SAE 2000 paper#2000-01-3050.

[24] *"42 Volt technology,"* SAE SP-1619,2001.

[25] *"42 Volt technology,"* SAE SP-1661,2002.

[26] L. Serrao et al, *"A Comparative Analysis of Energy Powermanagement Strategies for Hybrid Electric Vehicles,"* Trans. of the ASME J. of Dynamic Syst., Measurement, and Control, vol. 133, May 2011.

[27] A. Sciarretta and L. Guzzella, *"Control of Hybrid Electric Vehicles,"* IEEE Control Syst., Mag., 27(2), pp. 60-70, 2007.

[28] A. Braham et al, *"Optimal Energy Management in Series Hybrid Electric Vehicles,"* Proc. of the 2000 Amer. Control Conf., vol. 1, pp. 60-64.

[29] O. Sundstrom et al, *"On Implementation of Dynamic Programming for Optimal Control Problem with Final State Constraints,"* Oil Gas Sci. Technol., 65(1), pp. 91-102.

[30] F. Salmasi, *"Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison and Future Trend,"* IEEE Tran. Veh. Technol., 56(5), pp. 2393-2404.

[31] G. Paganelli et al, *"General Supervisory Control Policy for the Energy Optimization of Charge-Sustaining Hybrid Electric Vehicles,"* JASE Rev., 22(4), pp. 511-518.

[32] B. Gu, and G. Rizzoni, *"An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management Based on Driving Pattern Recognization,"* Proc. of the 2006 ASME Int. Mech. Eng. Congr. and Exposition.

[33] M. Salman et al, *"Control Strategies for Parallel Hybrid Vehicles,"* Proc. of the 2000 Amer. Control Conf., Vol. 1, pp. 524-528.

[34] X. He et al, *"Energy Management Strategies for a Hybrid Electric Vehicle,"* Proc. of the 2005 IEEE Vehicle Power and Propulsion Conf., pp. 536-540.

[35] F. Lewis and V. Syrmos, *Optimal Control,* Wiley-Interscience, New York, 1995.

[36] L. Serrao, *"A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles,"* PhD Thesis, The Ohio State University, Columbus, OH, 2009.

[37] O. Sundstrom and L. Guzzella, *"A Generic Dynamic Programming Matlab Function,"* Proc. of the 18th IEEE Int. Conf. on Control Applications, pp. 1625-1630.

[38] Oshkosh Dfense, *"Medium Tactical Vechicle Replacement,"* Internet: http://www.oshkoshdefense.com/products/6/mtvr#lit, Apr. 22, 2012.

[39] B. Lu et al, *"Optimal Control Based Power Management in Hybrid Military Vehicle"* Proc. of the 2012 IEEE Int. Elect. Vehicle Conf., 2012.

[40] Y. Gao and M. Ehsani, *"Parametric Design of the Traction Motor and Energy Storage for Series Hybrid Off-Road and Military Vehicles"* IEEE Trans. Power Electron., vol. 21, no.3, May, 2006.

[41] M. Ehsani et al, *"Application of Electrically Peaking Hybrid (ELPH) Propulsion System to a Full-Size Passenger Car with Simulated Design Verification"* IEEE Trans. Veh. Technol., vol. 48, no.6, Nov., 1999.

[42] M. Ehsani, *"Electrical System Architectures for Military Vehicles"* Advanced Vehicle Systems and Motor Drives Research Programs.

[43] US Department of Energy Vehicle Technologies Program, *"Battery Test Manual for Plug-In Hybrid Electric Vehicles"* Rev 0, March, 2008.

[44] N. Shidore et al, *"Trade-off between PHEV Fuel Efficiency and Estimated Battery Cycle Life with Cost Analysis"* 2009 IEEE Vehicle Power and Propulsion Conf., Dearborn, MI, Sep. 2009.