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A STRATEGY FOR INTELLIGENT PLATFORM POWER MANAGEMENT WITHIN GROUND COMBAT VEHICLES

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ABSTRACT

As new subsystems are integrated onto existing ground combat vehicle platforms for capability enhancement purposes, the demand for electrical power output increases. In many cases these enhancements exhaust the available output power reserves and leads to performance capability plateau for some of the existing power systems. This increased power demand may sometimes cause the vehicle's generator to become fully loaded, causing any energy shortfalls to be covered by the battery storage system. When a high percentage of system power is routinely provided by the battery system without optimized battery management, the result is degraded battery capacity that leads to frequent battery replacement. This paper addresses specific limitations of ground combat vehicle power systems related to insufficient power output capacity and deficient battery management practices. Additionally, the paper will discuss concepts that enhance battery management capability and extend the operational life of automotive batteries by applying active battery charge management methods.

INTRODUCTION

The demand for intelligent power management strategies within commercial vehicles has seen an increase due to the rising cost of petroleum based fuel and world community pressures to improve environmental performance by the reduction of carbon dioxide emissions. Many power management strategies, architectures and use cases found in the commercial vehicle arena are applicable to ground combat vehicles (GCVs) with the exception that the operation of GCVs tend to be mission critical and they are expected to perform under rigorous and challenging environmental conditions. Moreover, GCVs are required to provide robust performance and be capable of supporting a variety of electrical loads. The power management controllers present in both GCVs and commercial vehicles strive to optimally distribute electrical power to meet the demands of specific loads using their engine/generator. When the power demand imposed by the loads exceeds the output capacity of engine/generator it is known as fully loaded. The difference (deficit) between the full-load output capacity and the load demand is a shortfall which must be accommodated by the battery system. Routine overloading of the engine/generator resulting in battery system intervention demonstrates a less than optimal power management system design that will shorten the life-span of the battery storage system. Another scenario or use case critical to power management within the GCVs, commercial vehicles and even portable electronics is the optimal usage of battery energy storage when the battery system is the sole provider of the device power. In the case of GCVs this mode of operation is commonly referred to as "silent watch", and may last as long as a few hours. In the case of commercial vehicles this scenario is known as "*you left your lights on*" or "*whose alarm is that*". With respect to portable electronics, *i.e.* cell phones and other mobile devices, complete battery power operation occurs as soon as the device is no longer power-assisted by its charger. Regardless of the technology or use case it is important to maximize the usage of battery energy storage so as to prolong the operational life of the device. The following section will present a brief survey of research and other works related to intelligent power management.

BACKGROUND

As mentioned in the previous section, vehicle states and modes, where efficient and intelligent power management decisions are critical, include *engine/generator overload* conditions and *battery-only* modes of operation. The simplest approach to overcoming the engine/generator overload condition within the GCV arena would be to increase the size/capacity of engine/generator pair. This approach partially solves the problem if the electrical loads remain the same. The disadvantage of the larger and more powerful engine/generator pair is the potential decrease in fuel economy, as well as the potential increases in weight and space that could affect mobility performance and cost. Another approach would be to utilize more power efficient loads that fit within the existing power budget made available by the current engine/generator pair. However, a bulk of military and GCV equipment/loads operate at 28VDC and they assume that their power demands are always going to be met. So typically these devices are not designed to be power efficient or operate in a low-power regime. To meet design constraints, such that GCV's engine/generator and electrical loads remain at the same levels of efficiency, while improving the GCV's fuel economy and battery storage reliability, requires an intelligent platform power management strategy.

U.S. Military Vehicle Hybridization

A majority of applicable works/technology related to possible design improvements for GCV power management systems is rooted in the design concepts associated with commercial HEVs (Hybrid Electric Vehicles). According to the Deloitte study [1], the DoD (Department of Defense) is exploring several energy projects (*e.g.* tactical power and generation) for tactical and in-theater applications. There is also interest in determining the efficacy of commercial hybrid power stations. In recent years due to an increased environmental focus on green energy, green operation and technologies, the U.S. military has been making use of hybrid electric technology in the design of Ground Combat Vehicles. Due to this initiative, companies such as BAE systems and Northrup Grumman have pursued the development of armored personnel carriers, known as *hybrid Ground Combat Vehicles*, that are projected to be 20 percent more fuel-efficient in comparison to conventional diesel-powered models.

HEV Power Management Control Schemes

Power management systems typically found in hybrid electric vehicles primarily focus on improving fuel economy and/or reducing carbon dioxide emissions by interleaving or injecting energy from multiple electric power sources when applicable. Control strategies are central to the design and architecture of HEV power management systems. The algorithms used by the HEV controllers are overwhelmingly implemented using the following design principles: (1) *Rule-Based* control, (2) *Optimization-Based* control or (3) control mechanisms that utilize a combination of rule-based and optimization-based strategies. However, there are some HEV power management controller research efforts that have applied concepts/theories rooted in the areas of Neural Networks, Cognitive Learning and Numerical Methods to the application of optimal controller design for HEV power management systems. These research efforts are presented in [2], [3], [4] and [5]. The next sections will briefly highlight the HEV power systems controller work that is based on rule-based and optimization-based control schemes.

Rule-Based Control

Rule-based (RB) control strategies usually depend on modes of operation. The rules for each mode of operation and state change can be based on human experience, mathematical models or heuristics, and may not require *a priori* information or knowledge of a predefined drive cycle. Early energy management strategies for HEVs were designed based on rules for its effectiveness in real time supervisory control of power flow in a hybrid powertrain, which is set up on the basis of heuristics, intuition, and human expertise [6]. Many rule-based control strategies are based on IF·THEN logic and integrated with expert systems. Different RB strategies for power control and energy management may be applied to HEVs. The common RB control strategies include *Thermostat*, *Power Follower* and *Fuzzy* rule-based control.

The *Thermostat Control Strategy* works by limiting the battery SoC (*state of charge*) to a pre-defined region by cycling the engine/generator *on* or *off*. When the battery SoC reaches the upper limit the engine/generator is turned off and the power requests are supplied by the battery storage system. When the battery SoC reaches the lower limit, the engine/generator is turned on and battery storage system begins charging with a predetermined power level set by the controller that runs the engine at its most efficient point [7]. This thermostat RB control strategy is very simple to implement and may use lookup tables. However, it may not be capable of supplying the necessary power demand in all modes of operation. In the *Power Follower Control Strategy*, the rules are designed such that the controller will operate the primary power source (engine/generator) at its most efficient operating points so as to follow the power demand simultaneously while using the battery storage system as an additional (secondary) power source. Using this rule-based power split strategy, the power demand (request) will be distributed between the primary power source and battery given the instantaneous conditions, which include the

SoC status, power demand from the loads, and other sensory data [7]. The power follower rule-based controller determines the amount of power needed drive loads and the power required to charge or discharge the battery according to the current conditions. Optimal points of operation can be determined in advance by reviewing the engine/generator efficiency specifications. The *Fuzzy Control Strategy* closely mimics the manner in which humans make decisions as opposed to other control schemes. Fuzzy control methods have an advantage in the control of complex, nonlinear, multi-domain and time-varying plants/systems having multiple uncertainties. The advantage stems from the fact that Fuzzy rules have the ability to utilize human expertise as a starting point and adapt or evolve based on collected sensory data.

Rule-based control strategies for the use in power/energy management of hybrid electric vehicles have been applied to many traditional four-wheeled Truck vehicles as shown in [8], [9] and [10]. However, rule-based control strategies have also been applied to hybrid controllers found in railway vehicles described in [7] and [11].

Optimization-Based Control

Optimization-Based control strategies are based on optimal control theory. When applied to HEV controllers the goal of optimization-based control strategies is to minimize energy loss or fuel consumption for a specific drive cycle over a given period of time. Using predetermined path or driving cycle information beforehand, optimization-based strategies are able to compute a global optimal solution which for example guarantees minimization of the desired cost function J (fuel consumption, emissions and other) given constraints such as power loads, component inefficiencies and other losses. Optimization-based strategies are complex and require significant computational time to obtain a global optimum solution. Methods used for global optimal control of power/energy management systems primarily include *dynamic programming* (DP) techniques. Dynamic programming (DP) is a technique based on *Bellman's Principle of Optimality*, which asserts that an optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision [12]. Additionally, this principle suggests that for every sub-problem an optimal solution must contribute to the overall policy to find an overall optimal solution. In addition to DP, global optimization methods may utilize *linear programming* (LP), *quadratic programming* (QP), *stochastic dynamic programming* (SDP) and *genetic algorithms* (GA) to approximate optimal solutions in the HEV problem space as discussed in [13], [14].

With varying results, optimization-based control strategies implemented using dynamic programming have been used in a variety of HEV simulation based research [13], [14], [15], [16], [17]. However, due to the required *a priori* or predetermined drive cycle information and significant computational runtimes, these optimization-based control schemes alone, are not suitable for real-time control of HEVs. Power and energy management strategies involving the use of both Rule-Based and Optimization-Based techniques have shown very promising results in the simulation-based and real-time HEV environments [10], [18]. These works utilize global optimized solutions obtained from dynamic programming to generate improved rules for real-time operation.

PROPOSED ENERGY MANAGEMENT STRATEGY

The proposed strategy for intelligent platform power management within ground combat vehicles is categorized as a modified deterministic or rule-based control scheme, similar to the works presented by Banvait *et. al* [9] and Lin *et. al* [18]. The proposed power management strategy focuses on two modes (*Engine-On, Engine-Off*) of vehicle operation in which to enhance engine fuel consumption (*Engine-On*) and improve (extend) the utilization of electric power provided by the battery system during the *Engine-Off* state. This study utilizes an initial test platform (*baseline*) architecture which is used to establish baseline power consumption and operational point of efficiency data related to the power generation equipment. A second test platform (*rule-based energy management*) architecture is used to investigate and observe the behavior of the proposed *rule-based* energy management strategy. The resulting data collected from the proposed rule-based energy management control architecture will be analyzed and compared to the baseline data. Details related to both test platform architectures are discussed in the following sections.

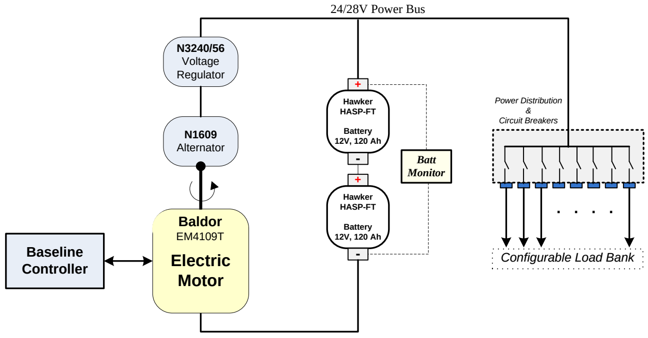

Figure 1: Baseline power management platform.

Baseline Power Management Platform

The baseline power management platform (illustrated by Figure 1) is a very simple/primitive power system that operates manually, *i.e.* no computer control. This power system platform is comprised of a short list of components which include a power supply, battery system, battery monitor and a power distribution unit with circuit breaker capability. In addition, the power distribution ports provide power to a configurable load bank and current measurement sensors (*not shown*). The main purpose of the baseline power system platform is to provide power to loads within the configurable load bank and allow one to measure the current and power draw of various load combinations. Given the simplicity of the baseline setup it is very easy to compare charge and discharge characteristics of various battery technologies with the use of the configurable load bank. Characterizations of battery discharge behavior can be determined by switching the power supply off and using the battery system as the only means of power (*silent watch*). A variety of unique power demand and supply scenarios can be achieved by configuring the load bank to match or exceed the output power of the power supply and/or battery system.

Rule-based Power Management Control Platform

The rule-based power management control platform (depicted in Figure 1) is an automated power system that mimics the high-level power demand/supply control characteristics found in a hybrid vehicle's power management system. The rule-based controller system is comprised of primary and secondary power sources. The primary power source utilizes a configurable power supply, electric motor, alternator and voltage regulator. The secondary power source is a battery. Additional components found in the rule-based controller system include a battery monitor, solid state power controller (SSPC), configurable load bank and controller with sensory devices.

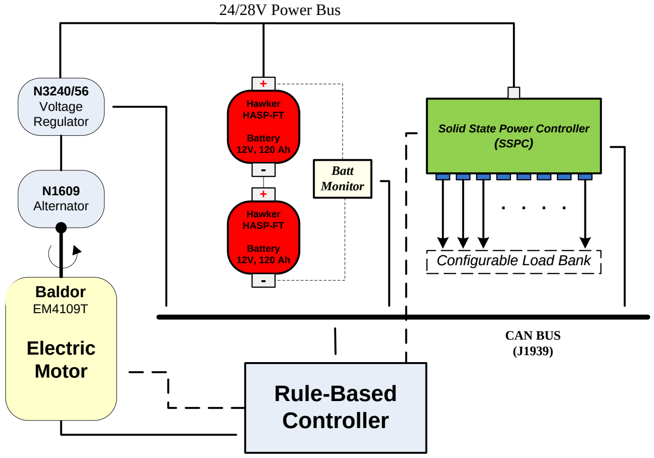

Figure 2: Rule-based power management control platform.

Operationally, the controller utilizes a method of rule-based control known as ***power follower***. This platform, led by a power follower control algorithm, is equipped to automatically adjust the power output of the voltage regulator in response to the power demands generated by the configurable load bank, given the battery's SoC. The controller is able to influence the voltage setpoint of the voltage regulator and set the (*on/off*) state of loads powered via the SSPC, by the use of J1939 CAN Bus messages. The primary power supply system attempts to mimic the operation of a vehicle's power-train, specifically the engine/generator (alternator). This approximation is accomplished by combining a 3-phase AC electric motor with an alternator/regulator pair. Given the motor speed (rpms) necessary to generate a specific output power level at the voltage regulator output terminals to meet the given power demand, a fuel consumption (Gal/Hr) approximation can be obtained for a specific diesel engine (Caterpillar C7) given an rpm to fuel rate relationship. The rpm rate or alternator shaft speed is computed by the N3240/56 voltage regulator and communicated over the CAN Bus at a 1Hz rate. Requests for additional or less power output require an increase/decrease in the alternator speed which is accomplished by sending serial commands to the 3-Phase AC electric motor.

Investigation & Experimentation Description

A physical test bench supporting both baseline and rule-based (optimized) control strategies was realized for this experiment. The major components and materials used to construct the test platform are presented in Table 1

Description	Manufacturer	Model
Electric Motor	Baldor-Reliance	EM4109T
Solid State Power Controller	DDC	RP26200
Alternator	C. E. Niehoff	N1609
Voltage Regulator	C. E. Niehoff	N3240/56
Battery	Hawker	HASP-FT 12V, 120Ah
Battery Monitoring System	Ultra Electronics	BMS MK2
RB Controller	DCS Corporation	Custom Design

Table 1: Test bench material list.

The purpose of the test bench is to provide a controllable test environment that can be used to verify the performance of the proposed rule-based power management control strategy against a very basic (baseline) controller strategy, found on the Stryker vehicle. The test platform is comprised of a few major components normally used in modern ground combat vehicles, as far as the power-train sub-system is concerned. Due to indoor testing constraints an electric motor (Baldor EM4109T) was selected over the preferable diesel engine as a means to provide the system's primary electrical output power. The test bench environment is designed such that each control scheme is operated against a pre-determined event load profile (*on/off events*). The load profiles and speed requests are systematically applied to each controller at the exact same time and with the same initial conditions to provide a fair comparison. The fundamental goals of the study are outlined below.

Design Goals:

(1) Improve fuel efficiency while minimizing the alternator speed during the active battery charge management phase. And, find an optimum SoC point and battery *charging* current that results in an overall power savings during the ***Engine-On*** state.

(2) During the Engine-Off state, determine if the ***Rule-based control algorithm*** with priority-based load shedding will maximize the battery SoC, resulting in an extended battery discharge time. Presumably, this feature will allow the silent watch operation to endure for a longer period of time.

(3) Upon transition to the ***Engine-On*** state, immediately following *silent watch* operation and given that the battery system has enough capacity to start the engine, determine the appropriate charging current that will maximize the SoC in the shortest time period while minimizing engine speed and improving fuel economy.

RESULTS

The experiments are conducted using five test scenarios or use cases, shown in Table 2. The baseline controller as well as the rule-based controller are tested according to each use case in the same manner. The use case (*a time-based load event profile*) describes the vehicle's engine state and electrical power demand over specified time intervals. As an example in use case (2), the engine will start in the OFF state and remain OFF for 7.5 minutes. Next it will enter the ON state and remain on for 10 minutes. Finally, the engine state will change to OFF and remain off for an additional 7.5 minutes. After a total of 25 minutes the load event profile is complete.

Case	***Engine State***			
	ON (min)	*OFF (min)*	*ON (min)*	*OFF (min)*
1	7.5	7.5	-	-
2	-	7.5	10.0	7.5
3	7.5	7.5	7.5	-
4[*]	7.5	7.5	7.5	-
5	-	15.0	5.0	-

Table 2: Use-case scenarios.

For each use-case scenario load profile information (not shown) is applied so as to mimic the demands of the vehicle power system as dictated by the driver/user during the operation of the vehicle. Use-case (4) is a specific test scenario such the rule-base controller disables its ability to perform priority-based load shedding. This test is used to determine the power savings that can be attributed to priority based load shedding.

The active charge battery management scheme applies very conservative and predictable rules for charging the battery. Based on the depletion level or SoC of the battery a recharge current is selected an applied. The implementation used in this study is described below.

Charge Conditions					***I_{CHARGE} (A)***
90	≤	SoC	<	100	0
75	≤	SoC	<	90	5
50	≤	SoC	<	75	20
0	≤	SoC	<	50	100

Table 3: Active charge management policy.

Battery SoC above 90% results in zero recharge current to the battery. When battery SoC exceeds 90%, the fuel economy improvement scheme is applied. During this scheme, alternator speed is reduced and system power demands are partially supplied by the batteries until SoC falls below 90%. During the various charge cycle conditions the rule-based controller determines if loads that qualify (based on priority and SoC) can be shed. The shedding of loads has the benefit of reducing the overall system demand placed on the alternator during recharging and non-recharging conditions. A reduction in system loads will allow a reduction in alternator speed, thus reducing fuel usage. During the active charge management cycle, the voltage regulator setpoint may be adjusted to help facilitate an increase/decrease in current flow.

All five test cases (shown in Table 2) were completed for this study. The corresponding results are shown in Table 4.

Use Case	*Control Strategy*	*Avg. Load*	*Avg. I_Batt*	*Avg. Speed*	*Avg. SOC (%)*	*Discharge Rate (%SOC)/t*	*Charge Rate(%SOC)/t*
1	*Baseline*	87.862	-35.417	80.456	84.722	-31.707	2.273
1	*Rule-Based*	80.724	-80.724	71.469	75.504	-29.545	4.651
2	*Baseline*	96.153	48.712	640.204	62.000	-35.934	9.259
2	*Rule-Based*	96.047	30.252	657.448	47.531	-34.160	48.148
3	*Baseline*	71.182	31.819	806.056	70.845	-26.190	-2.632
3	*Rule-Based*	66.661	5.128	1174.161	76.277	-24.000	18.919
4	*Baseline*	101.972	-44.094	906.905	56.437	-24.000	5.405
4	*Rule-Based*	57.364	19.892	1258.313	70.538	-26.000	27.027
5	*Baseline*	97.650	-55.037	558.548	59.228	-36.782	51.852
5	*Rule-Based*	95.038	-48.265	392.984	56.161	-35.417	70.370

Table 4: Use case test results.

The use case experiments indicated that the rule-based power management strategy in comparison to the baseline controller reduced the average load current by as much as 12.9% and improved the battery charge rate (+SOC/t) of 33.8% compared to the baseline charge rate of 13.2% percent *state-of-charge* per unit time. Additionally, it was found that the rule-based controller had a reduced discharge rate (-SOC/t) in the engine-off state of 29.8% vs. 30.9% percent *state-of-charge* per unit time. The average speed of the rule-based controller was found to somewhat higher than the baseline control configuration.

FUTURE WORK

The experimental setup implemented for this research effort provides an initial basis for the study of *rule-based* power management control schemes in ground combat vehicles. There are many possible directions in which this body of work could progress. These future objectives include the application of real mission data collected from a terrain exercise. Another future improvement would be the consideration of optimal control theory and/or dynamic programming methods for the development of a power management controller.

CONCLUSION

This paper investigates the use of rule-based control strategies for the development and implementation of a power management system specific to ground combat vehicles. A test bench comprised of hardware and control software was developed to assist with this research effort. A rule-based control strategy was designed to enhance or optimize basic vehicle and engine control variables such as *fuel economy*, *battery state-of-charge* and *speed*. Data was collected and measured as a means to compare the behavior and performance of the rule-based controller versus the baseline control strategy for this specific test setup. The improvements achieved by the rule-based or optimized controller were in the areas of %SOC, reduced average load current and improved charge time. Additionally, the rule-based controller presented an improved (lower) discharge rate during the engine off state.

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