State of Charge Optimization for Military Hybrid Vehicle Microgrids

Denise M. Rizzo
Mechanical Engineering-Engineering Mechanics
Michigan Technological University
Houghton, Michigan 49931
Email: dmrizzo@mtu.edu

Gordon G. Parker
Mechanical Engineering-Engineering Mechanics
Michigan Technological University
Houghton, Michigan 49931
Email: ggparker@mtu.edu

***Abstract*—One of the barriers to fielding a military hybrid vehicle is the absence of a holistic view of a vehicle's energy. This paper introduces the concept of treating a military vehicle as a microgrid and utilizing energy optimization methods from stationary microgrids, namely battery state of charge (SOC) optimization. This analysis illuminates the comprehensive benefits of military hybrid vehicles with respect to operational energy, which includes propulsion power, electric power for government furnished equipment (GFE), silent watch capability, and vehicle-to-grid (V2G) mobile energy exchange and storage. V2G is especially important in a military setting, where vehicles may be deployed to assist or replace an energy source, therefore common optimization methods become increasingly important and advantageous. It is shown that optimizing SOC can lead to fuel economy improvements over a drive cycle. In addition, the optimal SOC profile determination is explored to allow for expansion and more complex drive cycles. [Unclassified. Distribution Statement A. Approved for public release.]**

I. INTRODUCTION

Militaries worldwide are interested in realizing the potential energy savings associated with hybrid vehicles. "Fossil fuel accounts for 30 to 80 percent of the load in convoys into Afghanistan, bringing costs as well as risk. While the military buys gas for just over $1 a gallon, getting that gallon to some forward operating bases costs $400," according to Gen. James T. Conway, the commandant of the U.S. Marine Corps [1]. In fact, the U.S. Army has been researching hybrid vehicles since 1943 [2]. However, from observing the literature, it appears that the U.S. and other countries are far away from realizing a hybrid ground vehicle.

There are very few, if any, military hybrid hardware related publications, and many of the papers overlook some of the basic requirements of military ground vehicles, such as 60% grade ability and fording. Furthermore, a standard or universally accepted military duty cycle for measuring fuel economy does not exist nor does the research focus on a particular technology. A detailed survey of military hybrid vehicle research to date that details the challenges and reasoning of why a military hybrid vehicle has yet to be fielded can be found in [3].

It is important to note that there are other potential payoffs associated with military hybrid vehicles. The first benefit is the ability to idle and possibly move without the noise and thermal signatures of an internal combustion engine [2]. Another benefit is the increased available onboard electrical power; not only can a hybrid system, such as an engine with an integrated starter generator, provide more electrical power than the typical alternator, but this power can be converted, conditioned and delivered in any form to and from any load. Some examples included charging the soldier's battery powered equipment or delivering power back into an electrical grid. Additionally, new military vehicles are demanding an excess of 50kW of electrical power [4], which can only be provided with an advanced onboard power unit or a hybrid system. Quantifying these capabilities from an operational energy standpoint could help governments understand the benefits of military hybrid vehicles.

Electric power delivery is especially important to the U.S. Army, because their reliance on electrical power is greater than ever and the loss of battlefield electricity imposes a significant loss of capability and operational performance [5]. To ensure power and energy security, as well as reduce overall energy use, the concept of a microgrid has been introduced [6], [7]. A microgrid is defined as an aggregation of consumers and sources operating as a single system. It can connect to other grids or be operated as an island. Additionally, emerging vehicle-to-grid (V2G) technology has been shown to have the ability to support the microgrid as a source, but also a storage device for excess energy [8]. From a military standpoint, there is also an added benefit of temporary connectivity or network capability, which could be useful in a temporary peacekeeping or military operation.

To date, the V2G capability that comes along with a military hybrid has lacked quantifiable value, making it difficult to perform a cost / benefit analysis when trade studies are conducted. Additionally, there are many challenges related to controls and optimization for hybrid vehicles serving in a V2G capacity that need to be explored.

This paper will introduce the concept of regarding a military hybrid vehicle as a microgrid and utilizing battery state of charge (SOC) optimization to minimize energy use in a military scenario. A proof of concept will show how optimizing SOC over a drive cycle can reduce fuel usage. The conclusion and future work will address expandability challenges and next steps.

II. OBJECTIVE AND SCOPE

The overall objective is to quantify and understand the complete benefits of a military hybrid vehicle with respect to operational energy. This includes taking into account:

- Propulsion power requirements
- Electrical power requirements for government furnished equipment (GFE)
- Silent watch - defined as the ability to idle and move without the noise and thermal signatures of an internal combustion engine
- Mobile energy exchange
- Mobile energy storage

Understanding the operational energy of a military hybrid allows for a comprehensive, realistic analysis and therefore the benefit of a military hybrid vehicle to be fully quantified. Additionally, it would introduce and explore the novel use of vehicles as a microgrid that could support a rapid deploying or temporary microgrid.

An unexplored challenge related to this type of analysis will be to coordinate the energy use of the vehicle with stationary microgrids to achieve an overall efficiency. In addition, a military vehicle is used in ways that provide unique challenges, e.g. electrical energy requirements for GFE or idling for lengthy periods of time. This suggests it is beneficial to treat a military hybrid vehicle as a microgrid and utilize energy optimization methods from stationary microgrids, namely SOC optimization. Therefore, the scope of this work will be to detail a process of determining SOC profiles in order to optimize energy use in a military relevant scenario. The next sections will detail this idea and a proof of concept. The future work for full realization on a military hybrid vehicle will be discussed.

III. CONCEPTUAL OVERVIEW

Figure 1 illustrates typical components of a stationary microgrid as originally defined by Lasseter in reference [6]. It is defined by an energy generator, consumer and storage device. As shown in Figure 1, a generator can be any technology that can feed energy to the grid, a consumer is the user of this energy and the storage device stores excess energy when available and provides energy when necessary or optimal. A supervisory control may be used to oversee the energy transfer, thus ensuring that all requirements are met in the most efficient manner possible. Localized control schemes, such as droop control, can also be used to facilitate power flow.

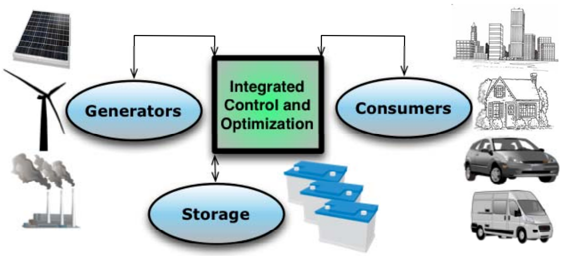

Fig. 1: Overview of a generic stationary microgrid

From a military microgrid perspective, it has been shown that SOC control and design optimization can reduce fuel use from 3 to 30%, due to downsized generators and control of renewable energy with a forward looking energy storage strategy [9]. Peters, et al. [10] used model predictive control to solve the power dispatch problem for a military microgrid using various prediction horizons. This work also determined that limitations in batteries led to energy waste and the design of microgrids would benefit from more effective control and design of the battery system. The effect of the battery resistance was investigated with respect to voltage and frequency regulation and it was determined that an effective inverter based control design should depend on both regulation and the direct current (DC) source characteristics [11]. Lastly, it was illustrated that a range of plug-in hybrid electric vehicle penetration levels can satisfactorily regulate the voltage and frequency of a military microgrid [12]. In all of this work, storage control and design optimization played a large role.

The concept of a microgrid can be applied on any scale, e.g. a large city or a single building, therefore it should also be applicable to a military ground vehicle as shown in Figure 2. It has a source (typically an internal combustion engine) and consumer (i.e. the propulsion requirement or GFE) and storage (usually a battery of some type). Additionally, it's goal is similar to a microgrid – to fulfill power requirements in the most efficient manner possible. Therefore, the supervisory control of the vehicle would benefit from exploiting methods used to optimize stationary microgrid performance, namely the SOC optimization, which has yet to be explored from a vehicle standpoint.

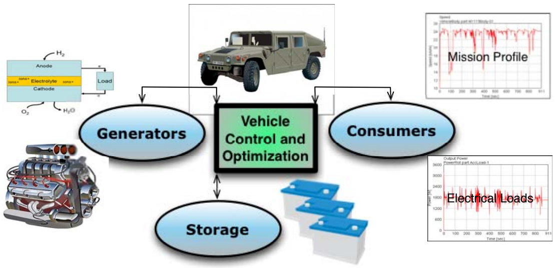

Fig. 2: Overview of a vehicle microgrid

This concept becomes increasingly advantageous when the vehicle has the ability to plug into another microgrid and either absorb or provide power; this is described by the term "vehicle-to-grid (V2G) connectivity." The vehicle now has multiple sources, the engine and the microgrid, and multiple consumers, the propulsion requirements and the microgrid. This capability also allows the military an added security element to temporarily connect microgrids via a hybrid vehicle or utilize the vehicles as the sole source for a microgrid in the event a source was removed or unable to provide enough power.

IV. PROOF OF CONCEPT

As introduced earlier, a vehicle treated as a microgrid can benefit from SOC optimization, which would not only improve energy efficiency, but also allow for interconnection strategies for stationary, rapidly deploying and temporary microgrids. This interconnectivity would not only improve overall operational energy usage, but provide added flexibility in a military scenario. This section will detail the proof of concept showing how SOC optimization can decrease fuel usage over a drive cycle in a hybrid vehicle.

A. Hybrid Model

A state space model defined by equations (1), (2) and (3) of a Toyota Prius$^{\text{TM}}$ hybrid was shown in [13] and [14], where the inputs were defined as motor torque, engine torque and generator torque. The outputs, or states, were defined as the ring gear or motor speed, which is directly related to the vehicle speed, the engine speed and the battery SOC.

$$\begin{aligned}&\dot{w}_r\left(\frac{I_{vp}(R+S)^2}{I_{ep}KR}+\frac{I_{vp}S^2}{I_{gp}KR}\right)=\\&T_m\left(\frac{(R+S)^2}{I_{ep}R}+\frac{S}{I_{gp}R}\right)-\\&C\left(\frac{S^2}{I_{gp}KR}+\frac{(R+S)^2}{I_{ep}KR}\right)+\\&\frac{T_c(R+S)}{I_{ep}}-\frac{ST_g}{I_gp}\end{aligned}\tag{1}$$

$$\begin{aligned}&\dot{w}_e\left((R+S)+\frac{I_{ep}S^2}{I_{gp}(R+S)}+\frac{I_{ep}KR^2}{I_{vp}(R+S)}\right)=\\&T_e\left(\frac{S^2}{I_{gp}(R+S)}+\frac{KR^2}{I_{vp}(R+S)}\right)-\\&\frac{CR}{I_{vp}}-\frac{ST_g}{I_{gp}}+\frac{KRT_m}{I_{vp}}\end{aligned}\tag{2}$$

$$\begin{aligned}&\left(V_{oc}+C_{batt}S\dot{O}C\right)^2=\mathrm{V_{oc}}^2-\\&4R_{batt}\left(\frac{T_m w_r}{{n_m}^k}+\frac{T_g {n_g}^k(w_r-w_e(R+S))}{S}\right)\end{aligned}\tag{3}$$

where:

$$I_{vp}=I_mK+I_rK+\frac{M{R_{tire}}^2}{K}$$

$$I_{gp}=I_c+I_g$$

$$I_{ep}=I_c+I_e$$

$$B=\frac{4R_{batt}}{C_{batt}}$$

$$C=T_{fb}+MR_{tire}f_rg+\frac{0.5C_d{R_{tire}}^3ap{w_r}^2}{K^2}$$

However, for this analysis, the vehicle duty cycle or mission profile is known and the goal is to minimize energy use by optimizing SOC. This can be accomplished by constructing a state space representation detailed in equations (4), (5) and (6). For brevity, the A and B matrices are derived from equations (1), (2) and (3).

$$\vec{x}=A^{-1}B\vec{u}\tag{4}$$

$$\vec{x}=\begin{bmatrix}T_e\\T_m\\T_g\end{bmatrix}\tag{5}$$

$$\vec{u}=\begin{bmatrix}\dot{w}_r\\\dot{w}_e\\S\dot{O}C\end{bmatrix}\tag{6}$$

By solving these equations for the engine, motor and generator torque, the total fuel used over the cycle can be determined. Therefore, using the time dervitative of the ring gear and engine speed, which are derived from the drive cycle, as the input the resultant engine torque can be used to minimize fuel consumption over a drive cycle by optimizing SOC.

B. Optimization Problem

Using the hybrid state space model, the following optimization problem (7) was constructed using the fmincon function [15] in MATLAB®.

$$\begin{gathered}\textit{Objective: } minimize\, J=\sum_{t=1}^{end} f(S\dot{O}C)\\ \textit{subject to } 30\leq SOC\leq 100\end{gathered}\tag{7}$$

A drive cycle, shown in Figure 3, which is a plot of time versus vehicle speed, was used as the basis for the inputs into the model. The ring gear speed is directly related to vehicle speed, the engine speed was determined using a rule based control (strategy shown in Table I) and the generator speed is a function of engine speed.

TABLE I: Rule based desired engine speed

Rule No.	Vehicle Speed Range (mph)	Engine Speed Setpoint (rpm)
1	0-5	500
2	6-15	900
3	16-30	1500
4	30-55	2000

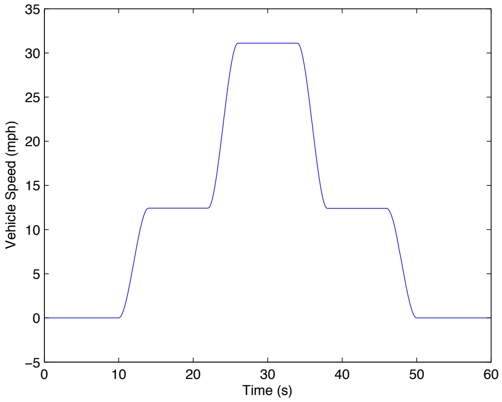

Fig. 3: Proof of concept drive cycle

C. Define Optimization Parameters

The first step was to determine fuel usage for the case of a constant SOC. For this case, only one SOC level was allowed and a constant SOC of 60% was determined to be optimal.This case showed that holding a constant SOC over the input drive cycle will result in a fuel usage of 9.0247 kg.

The next step was to determine if fuel usage can be minimized by optimizing more than one SOC levels. The number of SOC levels and location of SOC breakpoints were determined by the step changes in the drive cycle; more specifically, the number and location of the zero crossing of the second derivative of the vehicle speed, which is the location of the drive cycle inflection point. Once the number of SOC levels and locations were determined, these values were used to optimize fuel usage over the drive cycle using fmincon [15] in MATLAB®.

D. Optimization results

The optimized SOC inputs are shown in Figure 4, which is a plot of desired SOC levels and subsequent rate of change of SOC versus time. These results depict that the desired SOC is decreasing as the vehicle is accelerating and increasing as the vehicle decelerating as expected. These results show a total fuel usage of 8.7952 kg over the drive cycle, which is less than the fuel used for constant SOC case. This illustrates that optimizing SOC over a drive cycle can result in reduced energy consumption by 2.5%.

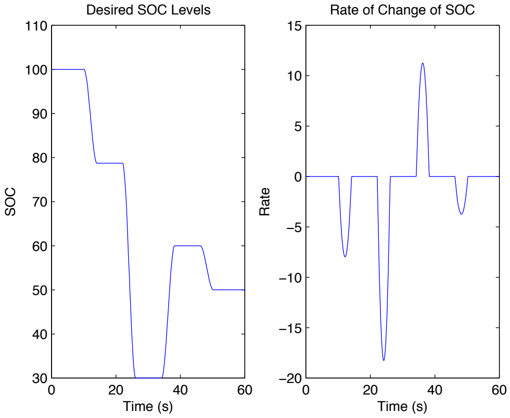

Fig. 4: Optimized SOC inputs

V. CONCLUSION AND FUTURE WORK

The full advantage of a military hybrid vehicle has yet to quantified, especially related to microgrids and V2G capability. A military hybrid vehicle can provide support to a rapidly deploying or temporary grid. It could also be the sole source of a stationary grid in the event that the source was not able to meet the demand or if it was removed.

This paper introduced the concept of regarding a military hybrid vehicle as a micorgrid and utilized stationary microgrid control methods, namely SOC optimization. It was shown through a proof of concept that fuel usage can be minimized by optimizing SOC on a hybrid vehicle over a duty cycle.

While the drive cycle used thus far was justifiable for a proof of concept investigation, it does not represent a realistic military drive cycle. Therefore, the next step will be to integrate a mission profile. Determining the number of necessary SOC levels and the locations of the SOC break points will become increasingly complex with this type of drive cycle. In addition, rule based engine speed determination could also prove to be challenging

The next step is to explore methods of reduced order optimization. The first is proper orthogonal decomposition (POD), also known as principle components analysis, single value decomposition or Karhunen-Loeve transform, dates back to the 1940s for continuous systems [16] and is known for creating a compact representations of complex systems. The second methodology that will be explored is Volterra series, which is a multidimensional combination of a linear convolution and a nonlinear power series [17].

REFERENCES

[1] E. Rosenthal, "U.s. military orders less dependence on fossil fuels," *New York Times*, October 2010.

[2] G. Khalil, "Challenges of hybrid electric vehicles for military applications," Spetember 2009, pp. 1–3.

[3] D. Kramer and G. Parker, "Current state of military hybrid vehicle development," *Int. J. Electric and Hybrid Vehicles*, vol. 3, pp. 369–387, 2011.

[4] D. Desmond, "Power on call how auxiliary power units can extend mission times in the abrams main battle tank," *Accelerate Magazine Energy Efficiency Edition*, pp. 37–38, June-August 20011.

[5] E. Shaffer, D. Massie, and J. Cross, "Power and energy architecture for army advanced energy initiative."

[6] R. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Mekipoulous, R. Yinger, and J.Eto, "Integration of distrubuted energy rsources: The certs microgrid concept," *U.S. Department of Energy and California Energy Commision*, vol. LBNL-50829, 2002.

[7] R. Lasseter and P. Paigi, "Microgrid: A conceptual solution," *IEEE 35th Annual Power Electronics Specialists Conference*, vol. 6, pp. 4285–4290, January 2004.

[8] W. Kempton, J. Tomic, S. Letendre, A. Brooks, and T. Lipman, "Vehicle-to-grid power: Battery, hybrid, and fuel cell vehicles as resources for distributed electric power in california," *Institute for Transportation Studies Report No. UCD-ITS-RR-01-03*, June 2001.

[9] J. Whitefoot, A. Mechtenberg, D. Peters, and P. Papalambros, "Optimal component sizing and forward-looking dispatch of an electrical microgrid for energy storage planning," *Proceedings of the ASME International Design Engineering Technical Conferernce and Computers and Information in Engineering Conference, Paper No. DETC2011-485513*, August 2011.

[10] D. Peters, A. Mechtenberg, J. Whitefoot, and P. Papalambros, "Model predictive control of a microgrid with plug-in vehicles: Error modeling and the role of prediction horizon," *Proceedings of the ASME Dynamic Systems and Control Conference, Paper No. DSCC2011-6030*, November 2011.

[11] T. Ersal, C. Ahn, I. Hiskens, H. Peng, A. Stefanopoulou, and J. Stein, "On the effect of dc source voltage on inverter-based frequency and voltage regulation in a military microgrid," *Proceedings of the2012 American Control Conference (ACC)*, June 2012.

[12] T. Ersal, C. Ahn, I. Hiskens, H. Peng, and J. Stein, "Impact of controlled plug-in evs on microgrids: A military microgrid example," *Proceedings of the Power and Energy Society General Meeting, IEEE*, pp. 1–7, July 2011.

[13] J. Liu, H. Peng, and Z. Filipi, "Modeling and analysis of the toyota hybrid system," *Proceedings of the 2005 IEEE/ASME International Conference of Advanced Intelligent Mechatronics*, July 2005.

[14] J. Liu and H. Peng, "Modeling and control of a power-split hybrid vehicle," *IEEE Transactions on Control Systems Technology*, vol. 16, November 2008.

[15] T. Mathworks, "Fmincon r2012a documentation," http://http://www.mathworks.com/help/toolbox/optim/ug/fmincon.html.

[16] D. Lucia, P. Beran, and W. Silva, "Reduced-order modeling: new approaches for computational physics," *Progress in Aerospace Sciences*, vol. 40, pp. 51–117, 2003.

[17] M. Schetzen, *THe Volterra and Wiener Theories of Nonlinear Systems*. Krieger, 1989.