Modeling of a Series Hybrid Electric High-Mobility Multipurpose Wheeled Vehicle

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***Abstract*—In an effort to reduce fuel costs and gas emissions, the U.S. Army is looking into replacing their diesel high-mobility multipurpose wheeled vehicle (HMMWV) with hybrid electric vehicles. The aim of this paper is to present the simulation of the series hybrid electric HMMWV based on a multidomain model using Ansoft Simplorer. Emphasis is placed on the vehicle's transient response to desired speeds dictated by drive cycles based on an urban dynamometer driving schedule and SAE J227a Schedule D. Also included in this paper were the vehicle's responses to hill climbing up to 60% grade.**

***Index Terms*—High-mobility multipurpose wheeled vehicle (HMMWV), hybrid electric vehicle (HEV), modeling, simplorer, simulation.**

I. Introduction

HYBRID ELECTRIC vehicles (HEVs) are increasingly gaining popularity due to their high fuel efficiency. The U.S. military, especially the U.S. Army, is interested in HEVs as a solution in reducing fuel costs. Currently, the U.S. Army has approximately 250 000 vehicles that consume about 200 million gallons of fuel per year for an estimated cost of $3.5B annually [1]. In addition, the cost of fuel can be as much as $400 per gallon when transported into the battlefield [2]. Initiatives to achieve 30% reduction in yearly fuel consumption will lead to a vast amount of savings for the Army.

One unique feature of HEVs is their capability to run in silent mode. The conventional heavy-duty trucks, such as the high-mobility multipurpose wheeled vehicle (HMMWV), use diesel engines that are very noisy. By using the battery in the hybrid system, the vehicle can run silently for an estimated range of about 24 mi [3]. This feature is a desirable and powerful tool in military applications.

Another reason for the Army's interest in HEVs is the HEVs' capability to supply auxiliary power. The battery in HEVs is estimated to supply up to 150 kW of power for many uses [4]. The HEV may be used to supply power to command centers and missile-defense shelters when needed. It can also be used to run weapon systems. This feature reduces the need for and cost of portable generators that need to be transported into the battlefield [5].

The demand for HEVs is expected to increase in the future. The hybrid electric HMMWV (HE-HMMWV) is one of the early HEV models being funded and developed by the U.S. Army in response to that anticipated future demand. The U.S. Army, together with the Department of Defense, is working on the Future Combat Systems program, whose goal is to eventually transform 10% of the HMMWV fleet into HEVs [1] and reduce fuel consumption by 75% [4].

Several papers have presented the modeling and simulation of the HE-HMMWV and HEVs in general [6]–[9]. Bargar *et al.* used the PNGV Systems Analysis Toolkit to simulate the HE-HMMWV based on component manufacturers' specifications to predict vehicle performance in the Federal Urban Drive Cycle [6]. The study showed significant fuel economy improvement by the HE-HMMWV (17 mi/gal) over the conventional HMMWV (11 mi/gal). Fish *et al.* developed a mathematical model of the HE-HMMWV using MATLAB/Simulink to predict the vehicle's and other similar vehicles' performances in hill-climbing conditions [7]. Onoda and Emadi simulated different electric and HEV configurations using the power electronics simulation (PSIM) software. This paper validated PSIM's capabilities in combining electrical, mechanical, and thermal systems of a vehicle [8]. Butler *et al.* developed a simulation package based on MATLAB/Simulink that simulated EVs, HEVs, and conventional vehicles [9].

This paper is focused on simulating the dynamic/transient response of the HE-HMMWV using Ansoft's Simplorer with focuses on the transient response to drive cycles, acceleration (step response), and hill climbing.[1] Simplorer is a multidomain simulation software capable of simulating an electric motor, power electronics components, and a vehicle model. The SAE J227a Schedule D and urban dynamometer driving schedule (UDDS) are used to predict the transient response of the vehicle. Acceleration and hill-climbing capability of up to 60% grade are presented.

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Color versions of one or more of the figures in the paper are available online at http://ieeexplore.ieee.org.

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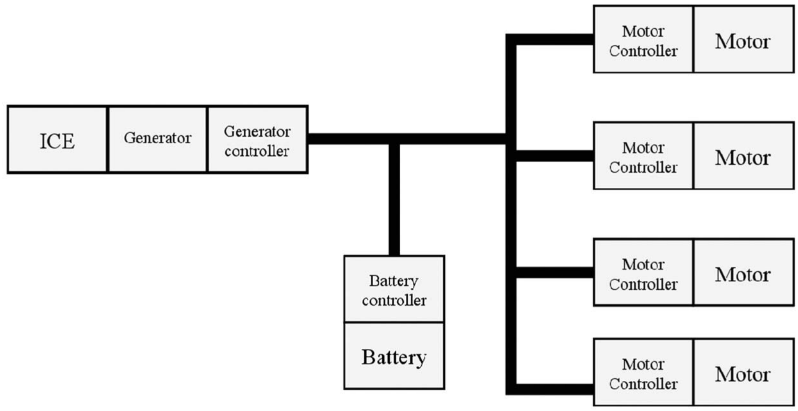


Fig. 1. Block diagram of a series HE-HMMWV.

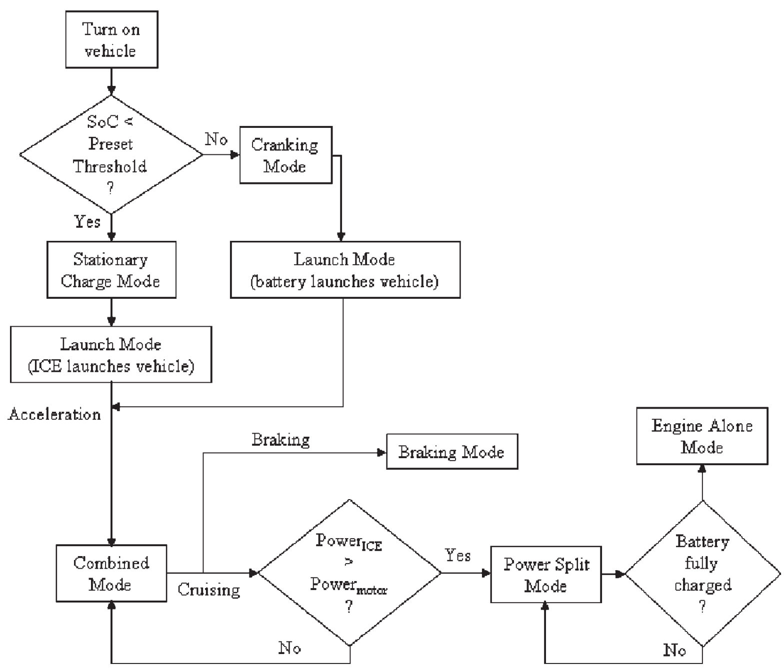


Fig. 2. Control strategy of the HE-HMMWV.

II. HE-HMMWV Specifications

The HE-HMMWV prototype that the U.S. Army and its contractors have built is a series HEV consisting of four permanent-magnet (PM) motors with one on each wheel, an internal combustion engine (ICE), a generator coupled to the ICE, and a battery pack. The ICE drives the generator to charge the battery pack. The battery then provides power to the electrical motors on each wheel. The rated vehicle top speed is 80 mi/h with a gross vehicle weight of 4136 kg [10]. The specifications of the components are the following.

1) ICE: The vehicle uses water-cooled 1.9-L diesel engine, which is directly coupled to the generator.
2) Generator: The generator is rated at 2000 r/min, 55-kW continuous power, and 75-kW peak power.
3) Battery: The traction battery pack is air-cooled Li-Ion battery. It consists of 14 modules of Li-Ion battery and connected in series/parallel configuration to provide 300 VDC, 150-kW peak power, and 80 Ah capacity. These batteries are monitored by a battery management and equalization system.
4) Electric motor: The four drive motors are liquid-cooled PM motors. Each motor directly drives a 5.43 : 1 gear set. The motors are independently controlled, and each drives a single wheel. The motors have a continuous rating of 55 kW and a peak rating of 75 kW. The controller/inverter units for each motor are located above the rear wheel wells.

III. Vehicle Operating Modes

The configuration of the vehicle is shown in Fig. 1. The four wheel motors are located on each of the axles to eliminate the need for transmission and differential. The system is capable of operating in seven different modes. The control strategy is shown in Fig. 2.

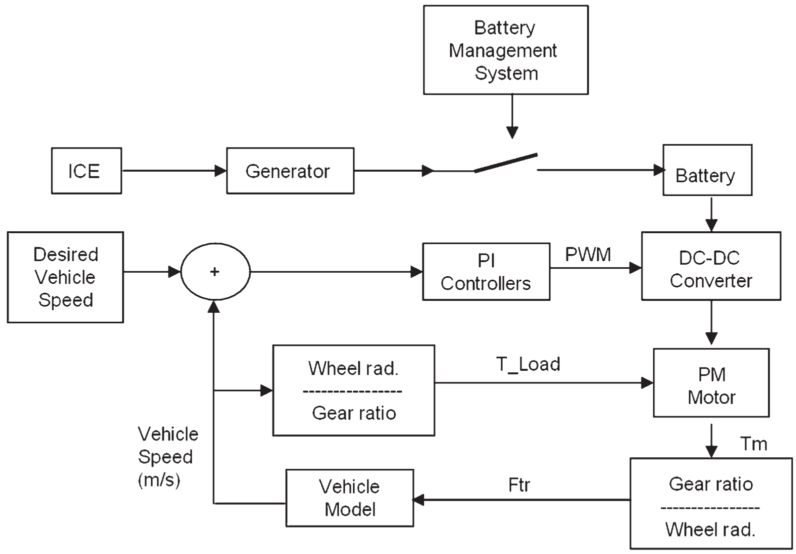


Fig. 3. Block diagram of the vehicle system as simulated in Simplorer.

A. Stationary Charge

When the driver activates the vehicle, the system checks for the battery/cap state-of-charge (SoC). If the SoC is below a certain preset threshold, the engine is started, and the battery is charged.

B. Cranking

The generator can be used to start the engine. Further, if a diesel engine is used, the generator may be designed to fit in the flywheel of the engine.

C. Launch

When the battery SoC is above a preset threshold, the motors start the vehicle with power supplied by the battery. If the SoC is below a preset threshold, then the engine is started, and the vehicle is launched using the engine only. Energy is not provided by the battery.

D. Combined Mode

During acceleration or hill climbing, the battery/ and the IEC/Generator both provide power to the wheel motors.

E. Power Split Mode

During cruising, when the engine provides more than the vehicle need, part of the energy is used to charge the battery while delivering power to the wheel motors.

F. Engine Alone Mode

During cruising, when the battery is fully charged, the ICE/Generator provides energy directly to the wheel motors.

G. Braking Mode

The kinetic energy is recovered and used to charge the battery. Mechanical braking is necessary during hard braking or when the battery is already fully charged.

IV. Modeling of the Vehicle System

The simulation model consists of the following major components: PM motor, proportional-integrator (PI) controllers, dc–dc converter, battery and battery management system, ICE/Generator, and the drive cycle or desired speed as shown in Fig. 3.

A. Vehicle Model

The vehicle model is based on Newton's second law of motion. The total tractive force is

$$\begin{aligned} F_{\mathrm{TR}} &= F_{\mathrm{gxT}} + F_{\mathrm{roll}} + F_{\mathrm{ad}} + ma \\ &= mg\sin(\beta) + mg(C_0 + C_1\nu_{\mathrm{xT}})^{*}\mathrm{sgn}(\nu_{\mathrm{xT}}) \\ &\quad + 0.5\rho C_{\mathrm{D}} A_{\mathrm{F}}(\nu_{\mathrm{xT}} + \nu_0)^2\ {}^{*}\mathrm{sgn}(\nu_{\mathrm{xT}}) + ma \end{aligned} \tag{1}$$

where F_{TR} is the tractive force, F_{gxT} is the gravitational force, F_{roll} is the rolling resistance force, and F_{AD} is the aerodynamic drag force of the vehicle. β is the grade angle, m is the mass, and $g = 9.81$ m/s^2. C_0 and C_1 are the rolling resistance coefficients. ν_{xT} is the vehicle speed. ρ is the air density, C_{D} is aerodynamic drag coefficient, A_{F} is the equivalent frontal area of the vehicle, and ν_0 is the head wind velocity [11].

B. Battery and Battery Management

The battery was simulated using a capacitor in series with an internal resistance and a battery management system that

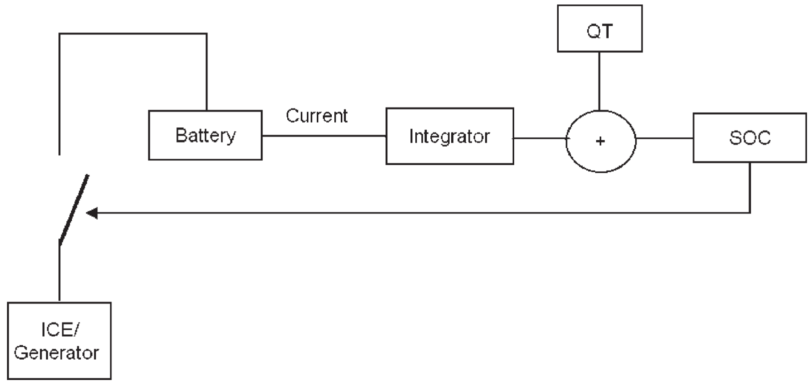


Fig. 4. Battery and the battery management system. The ICE/Generator is turned on or off depending on the vehicles' control strategy.

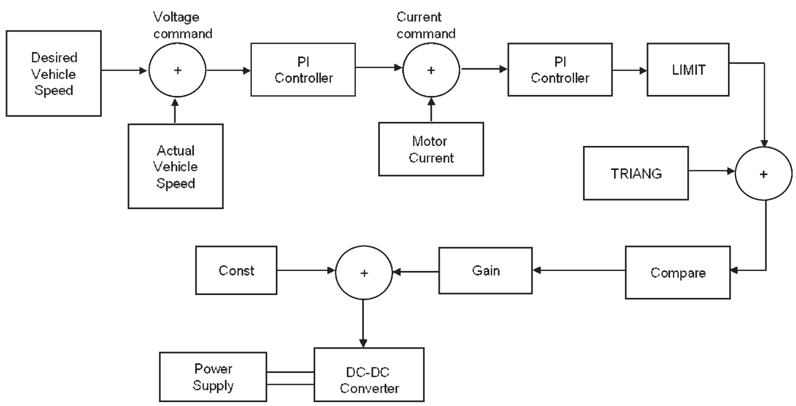


Fig. 5. Motor control design. The control of the drive motor uses two PI controllers, which control the dc–dc converter. One PI controller regulates the voltage of the motor while another controls the current of the motor.

monitors the SoC of the battery, as shown in Fig. 4. The following equations are used to calculate the SoC [11]:

$$Q_{\mathrm{T}} = CV \tag{2}$$

$$\mathrm{SoC} = \left(Q_{\mathrm{T}} - \int_0^t i(\tau)d\tau\right) / Q_{\mathrm{T}} \tag{3}$$

where Q_{T} is the theoretical capacity of the battery, C is the capacitance, V is the battery voltage, and i is the output current of the battery.

C. ICE

The ICE is used to operate the generator. The ICE model is run at only one speed at its maximum efficiency range. The following equation is used in simulating the engine:

$$\frac{T_{\mathrm{e}}}{T_{\mathrm{e_{desired}}}} = \frac{1}{1+\tau_s s} \tag{4}$$

where T_{e} is the engine torque, and τ_s is the engine constant.

D. Generator

The generator is used to charge the battery. The current used to charge the battery is

$$I = (V_{\mathrm{gen}} - V_{\mathrm{bat}})/R_{\mathrm{bat}} \tag{5}$$

where V_{gen} is the generator output voltage, V_{bat} is the battery voltage, and R_{bat} is the battery's internal resistance.

E. Motor

A mathematic model of the PM motor can be expressed using the following equations:

$$V_a = E + L\frac{di_a}{dt} + i_a R_a \tag{6}$$

$$E = k\Phi\omega \tag{7}$$

where V_a is the input voltage, E is the back EMF, L is the armature inductance, i_a is the armature current, R_a is the armature resistance, k is motor constant, Φ is the flux, and ω is the motor speed.

F. DC/DC Converter

A dc–dc converter is used to operate the motor and to achieve regenerative braking. The switching of the converter is controlled by pulse width modulation signals from the PI controllers, as shown in Fig. 5.

G. PI Controllers

Two PI controllers are used to control the dc–dc converter switches such that the actual vehicle speed follows the desired

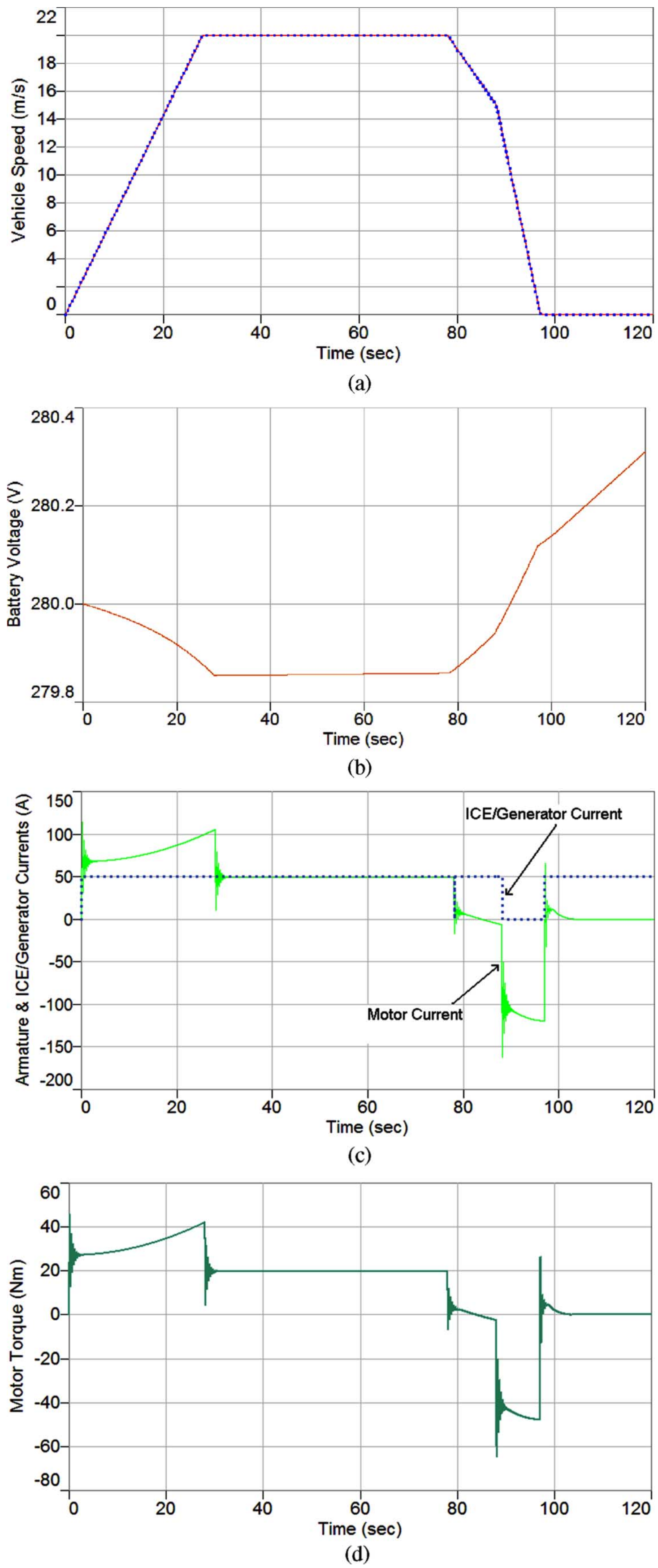
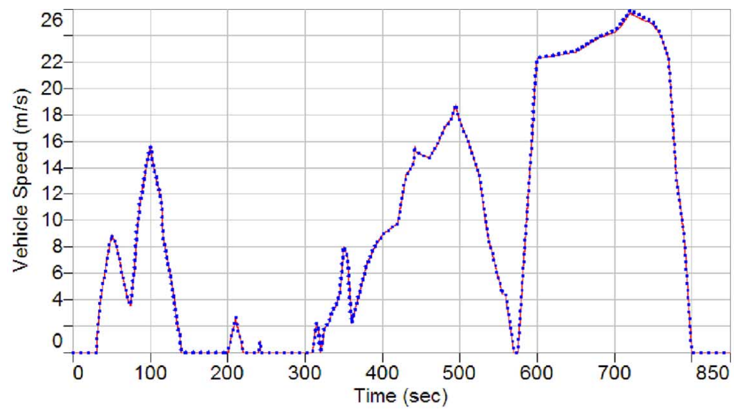


Fig. 6. (a) Simulation results for SAE drive cycle. The dotted curve is the driving cycle based on the SAE J227a Schedule D drive cycle, while the solid curve is the actual vehicle speed. (b) Battery voltage of the HEV model for the modified SAE J227a Schedule D drive cycle. (c) Current. The solid curve shows the armature current, while the dotted curve shows the current supplied by the ICE/generator to charge the battery. (d) Motor torque.



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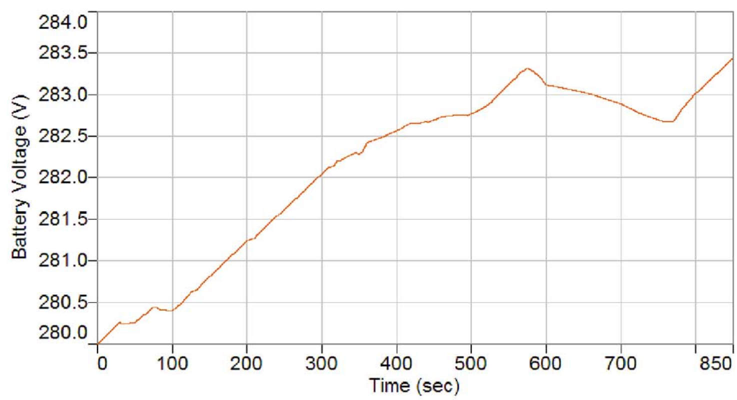

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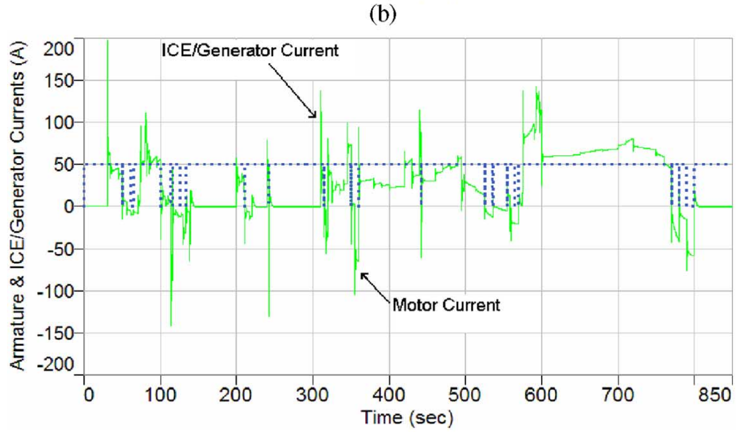

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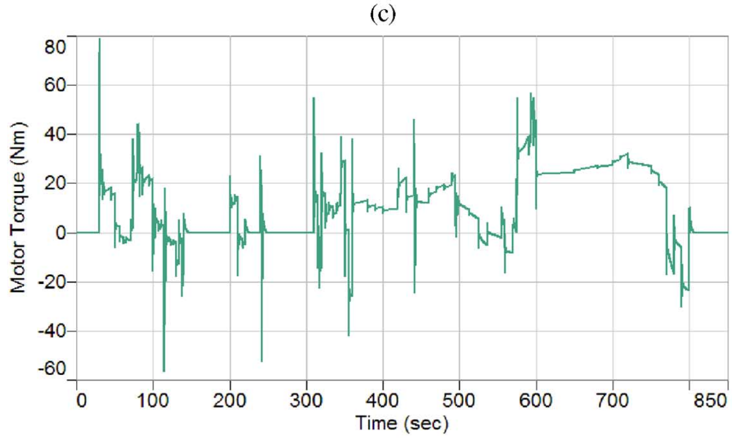


(d)

Fig. 7. (a) Simulation results for the modified UDDS drive cycle. The dotted curve is the driving cycle based on the UDDS drive cycle, while the solid curve is the actual vehicle speed. (b) Battery voltage of the HEV model for the modified UDDS drive cycle. (c) Current. The solid curve shows the armature current, while the dotted curve shows the current supplied by the ICE/generator to charge the battery. (d) Motor torque.

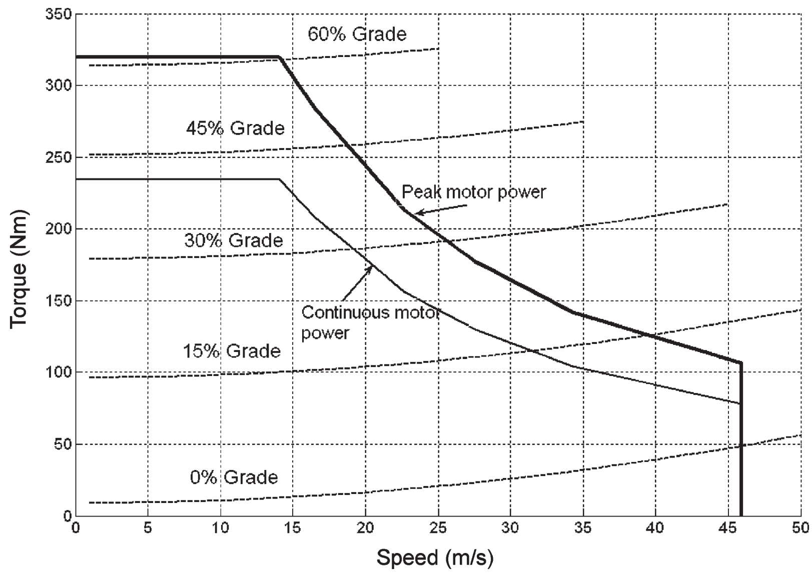


Fig. 8. Gradability at different speeds when motor is operated with continuous power and with peak power.

vehicle speed. One PI controls the input voltage to the motor while another controls the input current of the motor.

H. Driving Cycles

A modified SAE J227a Schedule D [11] standard driving cycle and a modified UDDS driving cycle [12] were used to test the vehicle model.

V. Simulation Results

The vehicle model is implemented in Simplorer simulation package. In the model setup, the battery is charged using the ICE/generator whenever the battery SoC is less than 60%. However, during regenerative braking, the ICE/generator is turned off. During launch, when the vehicle speed is less than 9 m/s while the battery SoC is larger than 60%, the engine is turned off. During acceleration, if the vehicle speed is greater than 26 m/s and the battery is less than 80%, the engine is turned on.

Fig. 6(a) shows the simulation result for the simulated vehicle drive cycle and the desired SAE drive cycle. The simulated vehicle speed closely follows the desired speed during acceleration, constant speed, and braking. The wheel motors provide the braking torque needed to achieve regenerative braking without mechanical brakes.

Fig. 6(b) shows the battery voltage as a result of the modified SAE J227a Schedule D drive cycle. The curve shows a faster consumption of energy when the vehicle accelerates (0 to 27 s) than when the vehicle runs at a constant speed (27 to 78 s). Fig. 6(c) shows the armature current (solid curve) and the ICE/generator current (dotted curve). Combined mode operation occurs at 0 to 28 s. Fig. 6(c) also shows regenerative braking from 78 to 97 s. Fig. 6(d) shows the motor torque.

Fig. 7(a) shows the simulation results for the modified UDDS drive cycle. The dotted curve is the driving cycle based on the UDDS drive cycle, while the solid curve is the simulated vehicle speed. The simulated vehicle speed closely follows the desired speed throughout the drive cycle, during acceleration, and during rapid braking. Fig. 7(b) shows the battery voltage of the HEV model for the modified UDDS drive cycle. Fig. 7(c) shows the armature current (solid curve) and the ICE/generator current (dotted curve). Combined mode operation occurs around 570 to 780 s. Fig. 7(d) shows the motor torque.

Simulations were also conducted with a step function of 40 m/s as the desired driving cycle to determine the vehicle's maximum speed during hill climbing. The battery is set up to start at 300 V and recharged when its SoC drops to 60%.

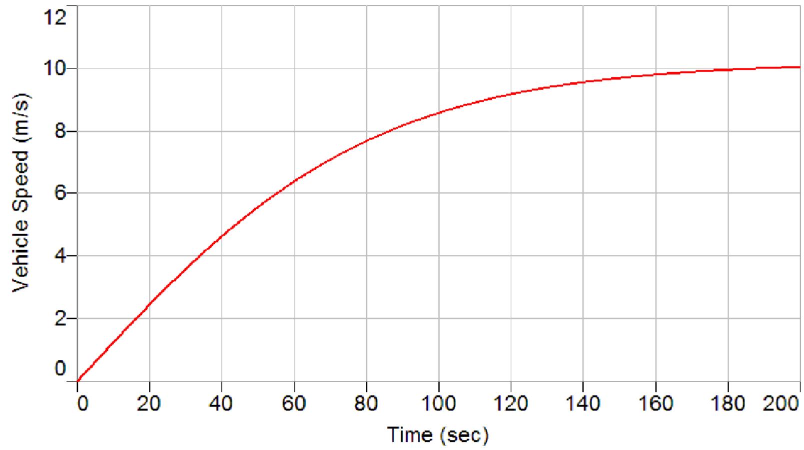
Fig. 8 shows the gradability of the vehicle for climbing different grades with the motor providing continuous power and peak power, respectively. It can be seen that with continuous motor power, the vehicle can achieve 40% gradability. The vehicle is able to achieve 60% gradability with peak motor power. However, since the motors can only operate at peak power for a very short period of time, achieving 60% gradability will not be practical.

Fig. 9 shows hill climbing of the vehicle at 60% grade with peak motor power. It shows that the vehicle is able to achieve a maximum speed of 10 m/s with 60% grade in about 3 s.

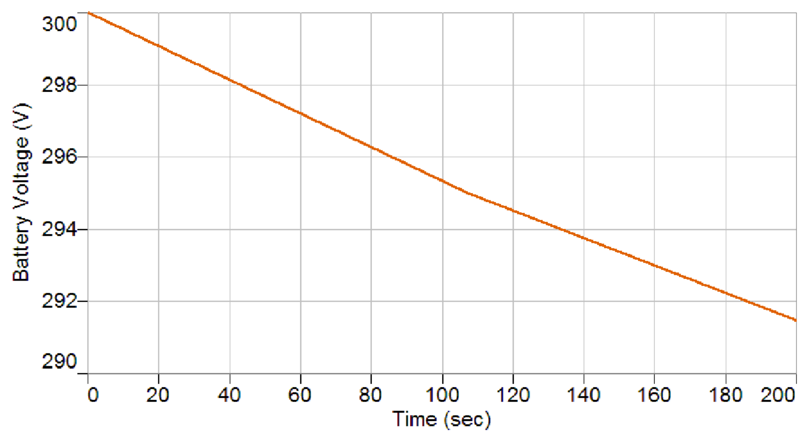
VI. Conclusion

This paper shows that simulations make it possible to reasonably predict the performance of the overall system. Simulations allow engineers to improve designs before building actual prototypes and therefore save costs.

The objective of this paper was to simulate a series HE-HMMWV with focus on transient response and gradability. The simulation model of the vehicle consists of an ICE/generator, a battery, a battery management system, a dc–dc converter,



(a)



(b)

Fig. 9. Step function of 8 m/s is used as the desired speed to simulate the vehicle's response for an incline of 60% grade. (a) Vehicle speed. (b) Battery voltage.

a PM dc motor, PI controllers, and a vehicle model. The ICE/generator charges the battery, which provides power to the PM dc motor. The motor provides the tractive force for the vehicle model. The dc–dc converter regulates the power from the battery to the motor and also charges the battery during braking. The PI controllers supply the switching signals to the dc–dc converter.

The simulation results show that the vehicle speed closely follows the desired speed during slow and fast acceleration, constant speed, and deceleration of the modified SAE J227a Schedule D and UDDS driving cycles. The vehicle only uses the braking torque from the electric motor to brake. The simulation results show that the battery management system performs as specified—the battery charges and discharges when its SoC is between the preset thresholds. The simulations also reveal that the vehicle is capable of running at maximum 10 m/s while climbing an incline with up to 60% grades with the peak motor power. Also, as the incline gets steeper, the number of charge/discharge cycles of the battery increases, as expected.

The series HE-HMMWV was successfully simulated using Ansoft's Simplorer simulation package. The work in this paper may be used as a framework in simulating other similar series HEVs as well as parallel HEVs.

Simplorer is a good simulation tool for electromechanical components that have nonlinear characteristics—components that would otherwise be difficult to model. Simplorer is capable of simulating systems with electrical, mechanical, and thermal characteristics.

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