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Short communication

Hybrid power supplies: A capacitor-assisted battery

Henry A. Catherino [a,*], Joseph F. Burgel [b], Peter L. Shi [c], Andrew Rusek [d], Xiulin Zou [c]

[a] U.S. Army Research Development and Engineering Command, AMSRD-TAR-R/MS 121, Warren, MI 49397-5000, USA
[b] General Motors, North American Engineering, Warren, MI 48090, USA
[c] Department of Mathematical Sciences, Oakland University, Rochester, MI 48063, USA
[d] Electrical and Systems Engineering Department, Oakland University, Rochester, MI 48063, USA

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Abstract

A hybrid electrochemical power supply is a concept that circumvents the need for designing any single power source to meet some extraordinary application requirement. A hybrid allows using components designed for near optimal operation without having to make unnecessary performance sacrifices. In many cases some additional synergistic effects appear. In this study, an electrochemical capacitor was employed as a power assist for a battery. An engine starting load was numerically modeled in the time domain and simulations were carried out. Actual measurements were then taken on the cranking of a diesel engine removed from a 5.0-tonne military truck and cranked in an environmental chamber. The cranking currents delivered by each power source were measured in the accessible current loops. This permitted the model parameters to be identified and, by doing that, studies using the analytical model demonstrated the merit of this hybrid application. The general system response of the battery/capacitor configuration was then modeled as a function of temperature. Doing this revealed electrical the interaction between the hybrid components. This study illustrates another case for advocating hybridized power systems.
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Keywords: Hybrid power sources; Electrochemical capacitors; Batteries; Modeling and simulation

1. Introduction

The notion of a hybrid power system can be illustrated by considering a Ragoni plot. Such a plot is shown in Fig. 1. This plot identifies the ranges of possible operation for various discrete power systems in terms of their specific power and specific energy. Ordinarily, a system can be chosen that would best address a particular power and energy load requirement. An interesting variant is the creation of a hybrid system. Such a system adds some new possibilities to the available discrete power sources. The hybrid system involves marrying a source having a high power density with another having a high energy density. By engineering the match, new possibilities arise that sometimes also provides some synergistic effects. A readily available example would be the hybridization of an air-breathing energy source (e.g., a fuel cell or a metal-air battery) and a high power density source (e.g., a lithium-ion battery or an electrochemical capacitor) [1–3]. In this presentation, the objective shall be the hybridization of a lead-acid battery with an electrochemical capacitor. A general method for modeling the behavior in the time domain will be presented together with empirical studies on the behavior of this hybrid system under a range of thermal environments.

Electrochemical capacitors provide a convenient method for load-leveling the power demands of electric-vehicle propulsion systems [4]. An application having direct commercial significance is using ultracapacitors as a battery assist for vehicle engine starting. The common lead-acid battery used for lighting, starting and ignition in automotive systems is designed to meet the power requirements for engine starting [5]. The primary failure operational discriminator is the inability of the battery to initiate an engine start under ambi-

* Corresponding author. Tel.: +1 586 753 2426; fax: +1 586 574 5054.
E-mail addresses: catherih@tacom.army.mil (H.A. Catherino), joseph.burgel@gm.com (J.F. Burgel), pshi@oakland.edu (P.L. Shi), rusek@oakland.edu (A. Rusek).

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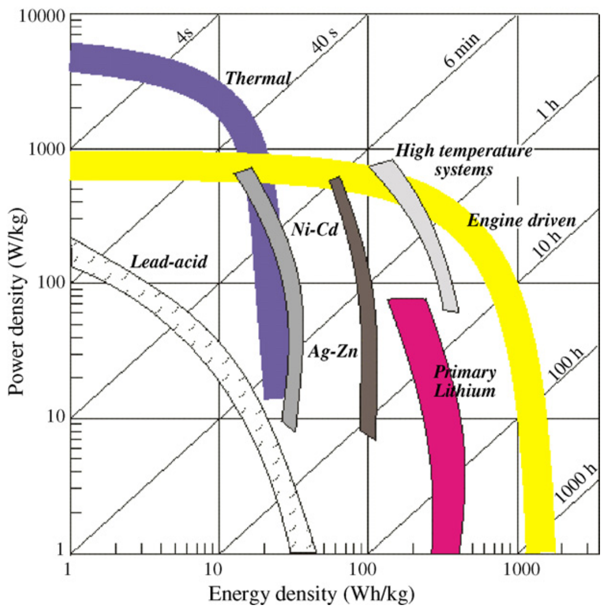

Fig. 1. Ragoni plot of power sources (quoted from naval materials website: http://www.voltaicpower.com/Batteries/spe-power.htm—downloaded January 2003).

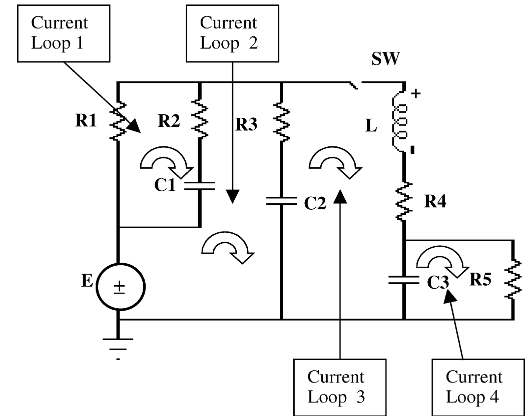

Fig. 2. Equivalent circuit diagram showing current loops for analysis.

ent environmental conditions. Although a number of failure modes can contribute, the operational (i.e., electrical) cause of the failure is that the internal resistance of the battery increases to a point where the battery is no longer able to deliver the power necessary to bring about an engine start. There are a number of internal chemical and physical phenomena that can reflect themselves as an observed increase in internal resistance [6,7]. However, in many cases this battery has much of its energy storage capacity intact. Since this power delivery requirement is of short duration, in the order of seconds, a solution for this problem is the use of an electrochemical capacitor.

The implications inferable from the preceding comments are: (a) extending the service life of the lead-acid battery and (b) improving the low temperature response of the battery so as extend its effective operating range.

Testing performed at the US Army Tank Automotive and Armament Command in Warren, Michigan has shown that the use of ultracapacitors for vehicle starting applications was effective. As a consequence, there existed a need for a quantitative model for sizing components, identifying limits of concept applicability, showing the dynamic interaction between the components and identifying optimal operating points. The discussion that follows describes the measurements made during the testing and the results of the simulation.

2. The mathematical model

A capacitor-assisted engine starting system can be simulated, within linear models, as represented by the circuit diagram shown in Fig. 2. The analysis was presented previously [8].

The battery is represented by an ideal voltage source (E) in series with a resistor (R1) representing the polarization resistance of the battery and a capacitor (C1) and resistor (R2) in parallel to the steady-state polarization resistance representing the net reactance controlling the transient (or high frequency) response of the battery. The interpretation of the physical significance of the circuit elements with respect to the battery operation is beyond the scope of this paper. Suffice it to say that the equivalent circuit for the battery represents an approximation that is adequate for the present discussion.

The electrochemical capacitor is represented by an ideal capacitor (C2) in series with a resistor (R3). The resistance represents the equivalent series resistance of the ultracapacitor. The simulated load corresponding to the starting motor and engine is given as an arrangement of passive components (L, R4, C3 and R5). The circuit response is a good approximation of the starting load for a typical piston engine. In actuality, the real starting load includes a small superimposed sinusoidal response corresponding to the compression strokes of the engine. The simplified load description follows the general response of the load as observed by an oscilloscope. The general response characteristic of the load is that a large current surge is required to accelerate the rotating mass of the engine crankshaft and associated components. As the mass achieves its maximum angular velocity, the load corresponds to that required to overcome the frictional drag associated with this engine rotation. The simulated load considers only the power requirements to bring the engine to a condition where the self-sustaining combustion process can take place.

The steps of the modeling proceed as follows. For the current loops that are identified in Fig. 1, the following set of differential equations result.

- For Loop 1:

$$\mathrm{i1\,R1} + (\mathrm{i1} - \mathrm{i2})\mathrm{R2} + \frac{1}{\mathrm{C1}}\int \mathrm{i1} - \mathrm{i2}\,\mathrm{d}t = 0$$

- For Loop 2:

$$-E + \frac{1}{C1}\int i2 - i1\,dt + (i2 - i1)R2 + (i2 - i3)R3 + \frac{1}{C2}\int i2 - i3\,dt = 0$$

- For Loop 3:

$$\frac{1}{C2}\int i3 - i2\,dt + (i3 - i2)R3 + L\left(\frac{\partial}{\partial t} i3\right) + i3\,R4 + \frac{1}{C3}\int i3 - i4\,dt = 0$$

- For Loop 4:

$$\frac{1}{C3}\int i4 - i3\,dt + i4\,R5 = 0$$

These equations are statements of Kirchoff's law requiring that the sum of the voltages around a loop must equal zero. The signs given the component values adhere to the passive sign convention. Note that although there are only four loops with one of the loop equations (Loop 3) being an integro-differential equation. That equation can be differentiated yielding a second order differential equation. That second order equation can be rewritten as two first-order differential equations. Applying the usual algebraic substitutions and solving for each of the derivatives, the following equations are derived:

$$\frac{\partial}{\partial t} i1 = (C2\,i2\,R3 - C2\,i1\,R3 + C1\,i3\,R2 - C1\,i2\,R2 + R3\,i5\,C1\,C2\,R2)/C2\,C1(R1\,R2 + R1\,R3 + R2\,R3) \quad (1)$$

$$\frac{\partial}{\partial t} i2 = (-C2\,i2\,R1 + C2\,i1\,R1 + C1\,i3\,R1 + C1\,i3\,R2 - C1\,i2\,R1 - C1\,i2\,R2 + R3\,i5\,C1\,C2\,R1 + R3\,i5\,C1\,C2\,R2)/(C2\,C1(R1\,R2 + R1\,R3 + R2\,R3)) \quad (2)$$

$$\frac{\partial}{\partial t} i3 = i5 \quad (3)$$

$$\frac{\partial}{\partial t} i4 = -\frac{i4 - i3}{C3\,R5} \quad (4)$$

$$\frac{\partial}{\partial T} i5 = -(C3\,C1\,R2\,i3\,R1 - C3\,C1\,i2\,R1\,R2 + C2\,C1\,R2\,i3\,R1 + C2\,C1\,i3\,R1\,R3 + C2\,C1\,i3\,R2\,R3 - C2\,C1\,i4\,R1\,R2 - C2\,C1\,i4\,R1\,R3 - C2\,C1\,i4\,R2\,R3 + R3\,C3\,C2\,i2\,R1 - R3\,C3\,C2\,i1\,R1 + R3\,i5\,C2\,C3\,C1\,R1\,R2 + i5\,R4\,C2\,C3\,C1\,R1\,R2 + i5\,R4\,C2\,C3\,C1\,R1\,R3 + i5\,R4\,C2\,C3\,C1\,R2\,R3)/(C2\,C3\,C1(R1\,R2 + R1\,R3 + R2\,R3)L) \quad (5)$$

For the model here, the following initial conditions exist at $t = 0_+$:

$$i1(0) = 0, \quad i2(0) = 0, \quad i3(0) = 0, \quad i4(0) = 0, \quad i5(0) = \frac{E}{L} \quad (6)$$

The assignment of the initial condition to last loop current might be difficult to visualize immediately. Note the relationship given in Eq. (3). The derivative of the current in Loop 3 at $t = 0$ is established (i.e., defined) by the inductor L. Eqs. (1–6) constitute a solvable system of linear differential equations. In this way the circuit response was modeled. The circuit response was modeled in the time domain using an appropriate mathematical analysis package (e.g., Maple).

3. Experimental

A diesel engine was removed from a 5-tonne military truck and mounted inside of an environmental chamber. The engine was not connected to a fuel source. A fully charged battery was connected to the engine starting motor with a 75-Farad electrochemical capacitor (ECOND International, Inc.) in parallel. The battery and capacitor were placed inside of the environmental chamber with the engine. The environmental chamber was stepped between −30 and 110 °F in 20° increments.

After a 24 h cold soak at constant temperature, the battery/capacitor power source was connected to the starting motor for 2 s. Measurements were made of the individual battery current and the capacitor current components delivered to the starting motor. Voltage measurements were made across the engine cranking motor. These measurements were made and recorded using digitizing oscilloscopes. The data was plotted and is shown in Figs. 3–9.

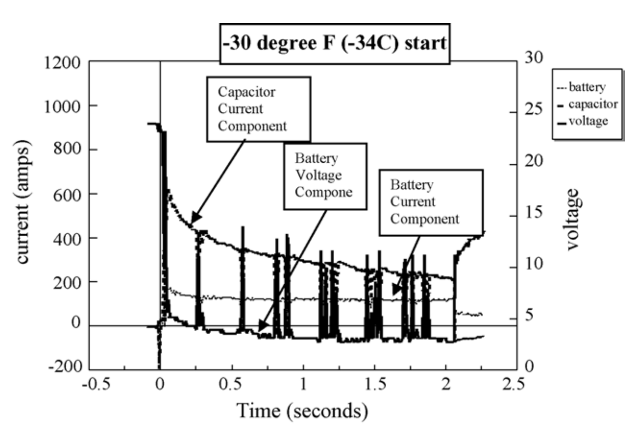

Fig. 3. Environmental test at −30 °F (−34 C).

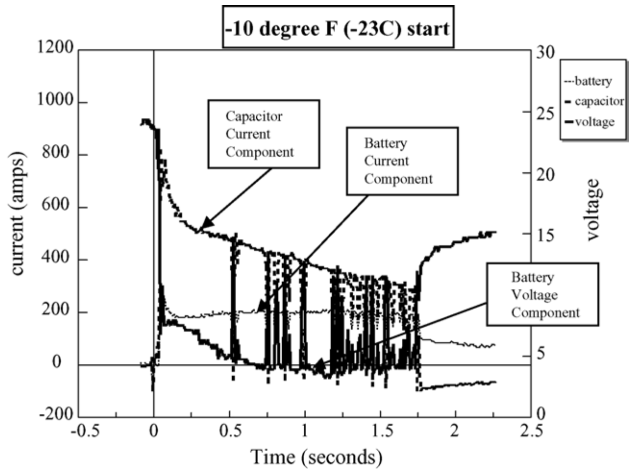

Fig. 4. Environmental test at −10 °F (−23 C).

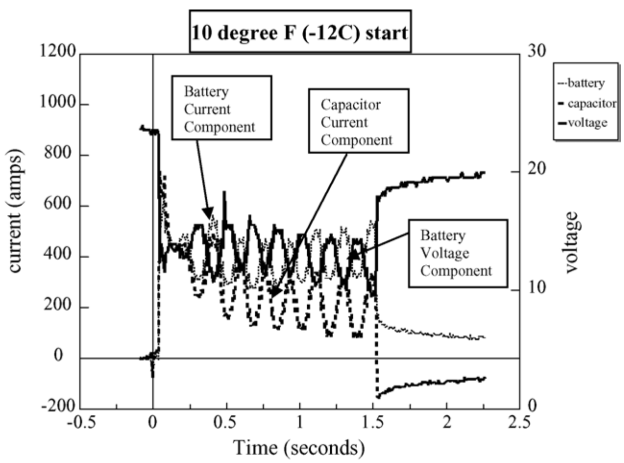

Fig. 5. Environmental test at 10 °F (−12 C).

Briefly, the data taken at −30 and −10 °F (−34 and −23 °C) show a situation where the starting motor could not crank the engine. The reason for this was that the engine was not "winterized" for operation at these temperatures. Subsequent tests on an engine having a lower viscosity oil in the crankcase allowed it to spin freely. However, the data shown in the figures allowed the locked rotor resistance of the starting motor to be estimated for use with the mathematical model. The current contributions at the lower temperatures clearly show that the capacitor is the major contributor toward providing the torque necessary to crank the engine. The data at the higher temperatures show that the battery is the predominant contributor. The figures at the higher temperatures show

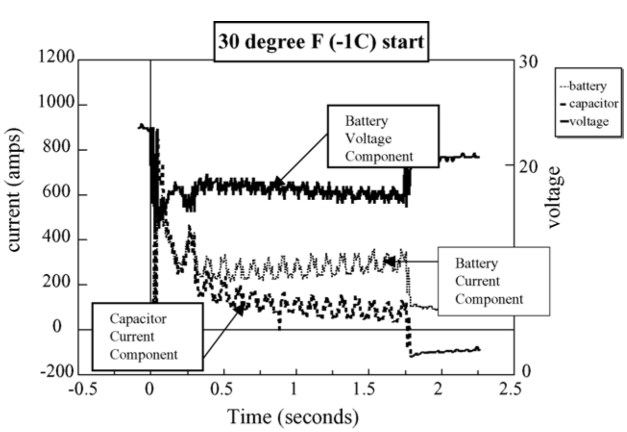

Fig. 6. Environmental test at 30 °F (−1 C).

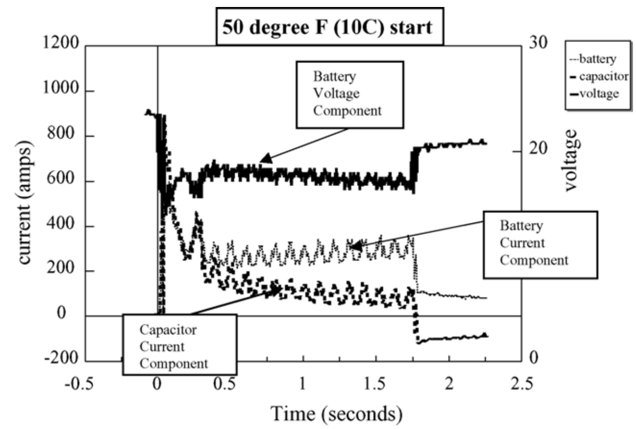

Fig. 7. Environmental test at 50 °F (10 C).

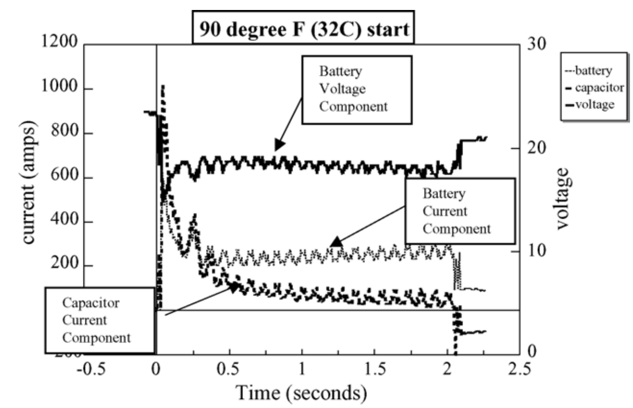

Fig. 8. Environmental test at 90 °F (32 C).

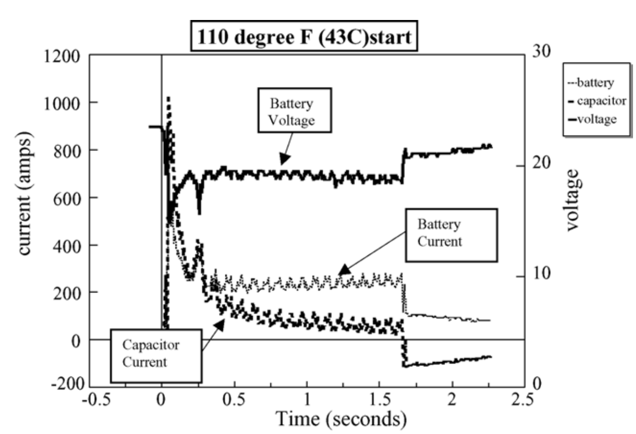

Fig. 9. Environmental test at 110 °F (43 C).

the individual battery current and capacitor current components for a freely rotating engine. The oscillations in the currents and voltages represent the compression strokes of the engine. The data taken at 70 °F (21 °C) was omitted as a figure as it does not reveal anything significantly different from the trend established by the in the preceding and subsequent figures.

4. Examination of the model

Using the 70 °F (21 °C) data together with the characterization data taken from the battery and the capacitor, the current–time profile was simulated and compared to that measured. This is the current passing through the starter motor. The model does not consider the effect of individual cylinder compression strokes. These oscillations were modeled but they provided no further clarification. As a result, the average value was preferred in order to simplify the model. The comparison is shown in Figs. 10 and 11. It is to be noted that the model also provided the time-dependent current responses of the individual components of the hybrid system.

Extending the modeling exercise, 3D plots of the starting current, time, and battery polarization resistance where generated to show the effect of the capacitor assist. Figs. 12 and 13 show that as the battery internal resistance

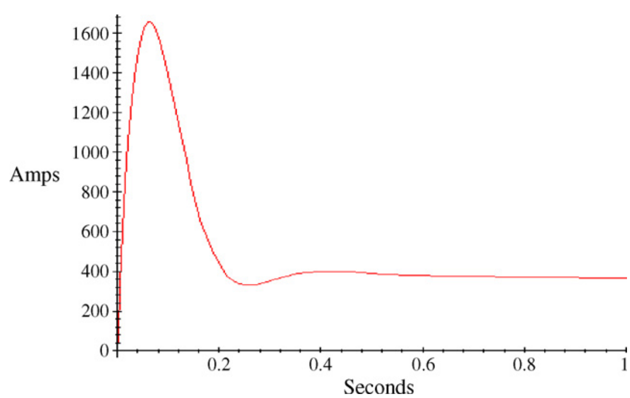

Fig. 10. Modeled total current response in A vs. time in s at 70 °F (21 C).

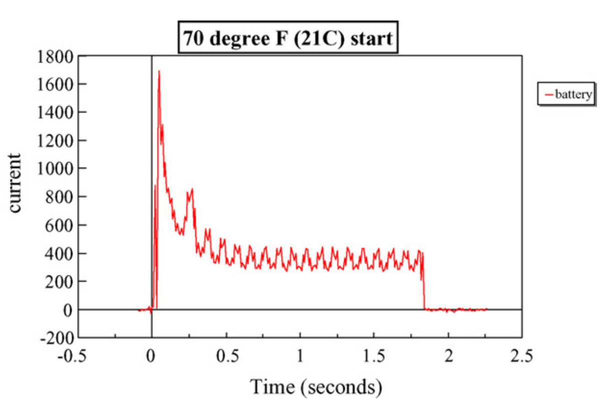

Fig. 11. Measured total current in A vs. time in s at 70 °F (21 C).

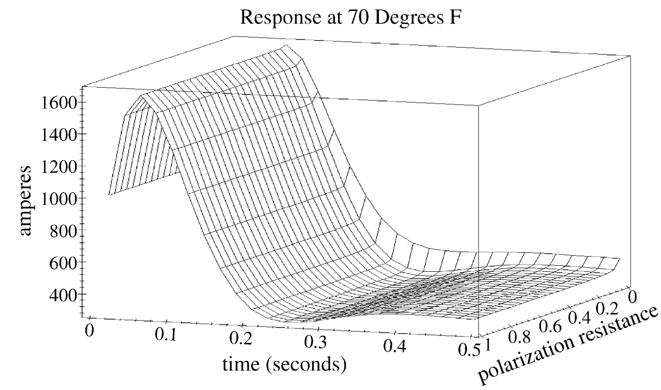

Fig. 12. Simulated response surface with a capacitor assist.

increases, the capacitor provides the necessary current to initiate the start.

As an interpretative issue, the equivalent series resistance of the battery is affected by state of charge, temperature and the extent of battery degradation. The logical inference is that the use of an electrochemical capacitor as a battery assist for engine starting can extend the life of a battery and extend the operational temperature range in which the battery can operate. Although not shown in this study, the high temperature response can in some cases show improvement. The reason for this is that the rate of self discharge at high temperatures can reduce the state of charge of charge of a battery after a long stand period. Low state of charge condition can reveal itself as an increase in battery resistance. In such cases, the capacitor becomes the primary contributor of the starting current. This improved surge current response was demonstrated in subsequent experiments.

Since the data provided a measure of the equivalent series resistance of the battery and the capacitor, a simulation was generated of the effect of temperature on the current–time profile. This is shown in Figs. 14 and 15. The figures show the influence of the presence and absence of the capacitor as a function of ambient temperature.

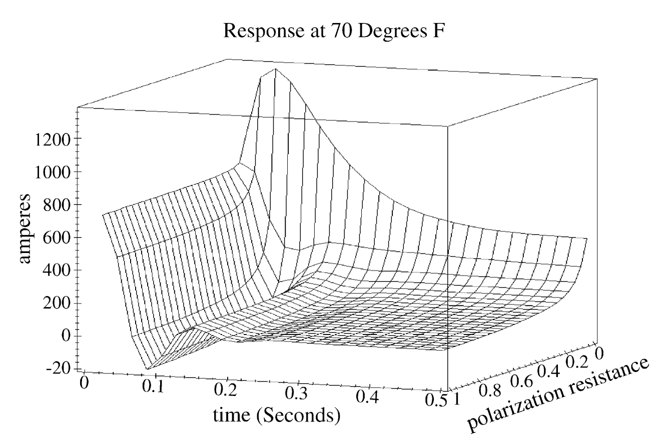

Fig. 13. Simulated response surface without a capacitor assist.

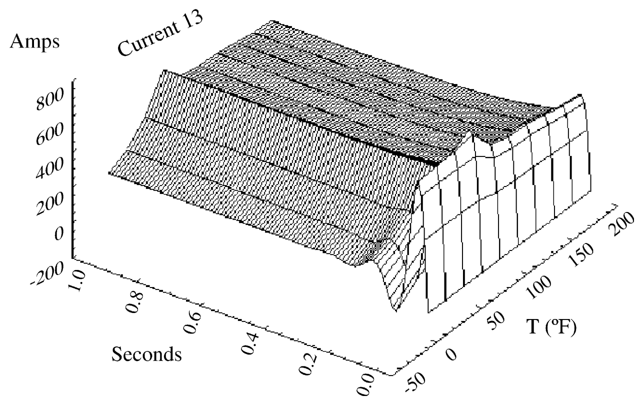

Fig. 14. Modeled current (A) vs. time (s) vs. temperature (°F) without a capacitor assist.

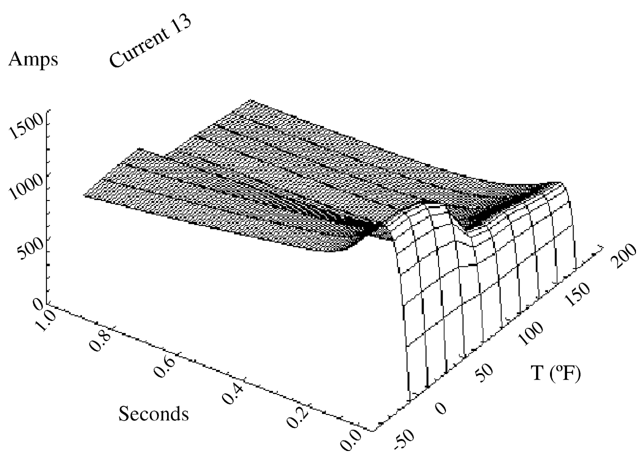

Fig. 15. Modeled current (A) vs. time (s) vs. temperature (°F) with a capacitor assist.

5. Conclusion

The feasibility of using an electrochemical capacitor as a power assist device was demonstrated using a numerical simulation. In addition, the capacitor's effectiveness was confirmed experimentally using the engine taken from a 5-tonne military truck. The modeling exercise provided a basis for inferring that use of a capacitor in association with a battery can extend the life of the battery and the operating temperature range of battery operation.

The capacitor-assisted battery application described here is an example of a hybrid power supply. The modeling approach is somewhat general in that it designates the power supply in terms of a Thevenin equivalent circuit. This means that any power source can be simulated in this model. Also, the equivalent circuit representation of the load can be modified to model other applications. Doing this allows the current in each of the branches to be computed in the time domain. That is, the interaction between the components becomes evident and quantifiable. This provides a means for optimization of the components. Or alternatively, the hybridized concept can be examined and the responses of the designed components analytically predicted.

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