Ultra-capacitor Augmentation of the Vehicle Electrical System to Reset its Power Budget

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Abstract—**Average electrical burden in passenger vehicles, cars and light trucks, has escalated in recent years from 500 W to 700 W and higher. Year over year growth in electrical loads is now between 100W to 150W with no end in sight. OEM's maintain that a 14V electrical system can sustain such growth and moreover, that 14V electrified ancillaries are containable as well. With alternator technology now exceeding 3000W and currents above 200A it is incumbent upon the industry to evaluate means to reset the vehicle power budget. This paper argues that such power budget resetting may be realized economically using existing 14V alternator and battery technology but augmenting the vehicle charging system with a 28V ultra-capacitor module. The series connected battery and ultra-capacitor module provide regulated 42V for high power electrical loads leaving the base 14V system unchanged.**

Keywords- ultra-capacitors, distributed modules, vehicle power and propulsion technologies

I. INTRODUCTION

There have been notable attempts by researchers in recent years to augment the vehicle electrical distribution system, EDS, with local energy storage to facilitate distribution bus regulation and stability [1,2,3,4]. In addition, there are after market products available that include carbon ultra-capacitors to stiffen the bus locally at high power features such as audio amplifiers. Other after market suppliers are beginning to offer e-boosters that replace the conventional 14 V alternator with a switched reluctance machine belt driven starter alternator that is autonomous to the vehicle EDS and uses a dedicated 48 V battery plus ultra capacitor electric energy storage system [5]. Toyota Motor Corporation at the JSAE 42 V International Symposium [6] noted that many electric features on the horizon are beyond the capability of 14 V power supply. Such systems as higher power engine cooling fans, electric power steering for heavy weight vehicles, electric A/C, power assist mild hybrid, active suspension and electric 4 wheel drive are all beyond the capability of 14 V power supply. As these and other new features are added to the vehicle electrical system burden the result will be diminished performance unless the electrical energy storage system, ESS, capacity is proportionally increased.

In an earlier work [1] it was noted that Toyota Motor Co. has now introduced ultra-capacitor distributed modules into its Prius-II hybrid electric vehicle as redundant power for its electronically controlled brake system. The ECB back-up module consists of 4 strings of 7-cells each for a combined 58F at 16.1V maximum. The ECB distributed module in this implementation is therefore capable of storing 0.93Wh of standby energy for the brakes. In effect, the market is already seeing the application of ultra-capacitors as distributed electrical power caches for critical loads in automotive systems.

There are also ongoing efforts aimed at improving our understanding of the benefits of ultra-capacitor modules in automotive systems [7,8] and the development of appropriate models and simulations [9,10]. Other investigators have explored how ultra-capacitor modules benefit the vehicle EDS as local energy caches at critical locations and even their use in fuel cell power trains. In [11] the author discusses the synergy between fuel cells and ultra-capacitors where the ultra-capacitor acts as a dynamic power buffer, captures regenerative energy and provides boost to the fuel cell for peak efficiency. Moreover, according to Hydrogenics, the ultra-capacitor and fuel cell combination extend MEA life and helps reduce the FC stack size. To further illustrate the propulsion implementations of ultra-capacitors consider the Honda Motor Company FCX. Honda employs an ultra-capacitor only ESS in their FCX fuel cell vehicles now being leased to U.S. cities in California. In that application the ultra-capacitor bank is sized in much the same manner as the VRLA battery in the Crown mild hybrid, that is, nominal SOC at approximately 78% with +/- deviations of 24% depending on drive cycle. This latter point is worth emphasizing, because the rating of the ESS is highly dependent on the customer usage as reflected in standardized drive cycles. Therefore, the ESS must be sized based on exposure to multiple drive cycles.

The fact that vehicle power loads continue to escalate has led OEM's to also investigate higher powered electrical generating plants. International Rectifier developed its active integrated rectifier regulator, AIRR, for the Daimler-Chrysler Maybach luxury car. The AIRR was designed to output 350A at 6000 rpm and 200A at idle [12]. Switched mode rectifiers have also been employed on conventional Lundel alternators fpr the purpose of enhancing their output [13]. In a novel

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http://www.intertechusa.com/studies/PowerManagement/PM_Study.htm; may be consulted regarding the claim of electrical load content increase.

implementation of power electronics Toyota Motor Co. investigated the merger of active rectification and zero sequence current control to effect dual output from a Lundel alternator [14].

These on-going developments in high capacity vehicle alternators and the first signs of ultra-capacitor distributed modules indicate that the 14V electrical distribution system is fast approaching its saturation point. Work has been going on for years now that support the introduction of 42V as the next generation automotive voltage level. However, the introduction of 42V PowerNet has been postponed until perhaps 2008 or later. Why? Because, automakers have opted instead for better 14 V components and systems to fill in the lag in timing of 42 V PowerNet. Take exterior lighting for example. In a highline vehicle the lighting load may amount to 60 A on a 14 V system. So automakers are replacing the power hungry incandescent filament bulbs with more efficient light emitting diode arrays. Red LED's for tail and brake lamps, White LED's for headlamps and interior lighting. Furthermore, many attempts at 42 V integrated starter alternator, or ISA, have been sidelined in favor of idle-stop functionality at 14 V instead. This is because the cost of introducing idle stop plus up-rating the vehicle electrical distribution system was prohibitively expensive. Automakers began implementing 14V, 3.5 kW alternators that could also be driven as motors to re-start a warm engine [15,16].

This paper will explore another possibility to fill the lag in introducing 42V PowerNet and that is to develop an interim 42V bus supported by an ultra-capacitor energy cache along with the standard 14V alternator and battery rather than a full 42V charging system.

II. THE PSEUDO 42V ARCHITECTURE

A. Supporting 42V Ancillaries from 14V Power

Figure 1 illustrates the pseudo 42V PowerNet. In this architecture the 14V charging system performs as usual, but with one notable exception: 42V high power loads are supported in part by the 12V VRLA battery and the remainder by the 28V ultra-capacitor module. This means that vehicle charging system pulse loads are reduced to a third of that had these same power loads been confined to 14V power only. For illustration only electric assist power steering, braking and LED lighting are shown as higher power and recently introduced electrical loads. But, the main point of this study is to focus on electric assist power steering, EPS and electronically controlled braking, ECB, and in the future electro-mechanical brake, EMB, systems.

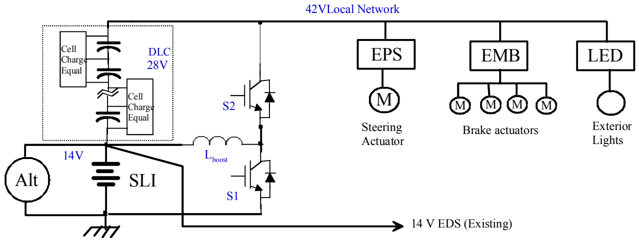

Fig. 1 Pseudo 42V PowerNet

At the present stage of automotive evolution the electrical loads having the most direct impact on the EDS, as well as, generation and storage systems are electric assist power steering, EPS, and electromechanical brakes, EMB as these begin to find application. EPS is here now on vehicles with lower steering loads so that a 14 V power supply is adequate. However, as steering loads increase through, for example, front end vehicle weight increases coupled with trends to lower ratio steering and exacerbated further by suspension geometry changes it is not possible for 14 V systems to handle the demands. Randy Frank [17] illustrates the situation in a table excerpted from an SAE Future Transportation Technology Conference paper by S. Murthy and T. Sebastian that compares the EPS actuator size, harness current and motor output power when the EPS rack load is increased from 5 kN to 10 kN. In this illustration the actuator size in a 14 V power supply vehicle goes from 1 pu to 3.25 pu. The corresponding EDS current increases from 55 A to 114 A and the motor shaft power increases from 222 W to 475 W. A real world comparison is to note that the steering load for a pick-up truck can approach 14 kN compared to only 8 kN for the Chevrolet Corvette that comes standard with EPS. As a rule, EPS currents greater than 85 A dictate that EDS voltage should be increased. In a conventional 14 V system, delivering 14 kN of steering effort will require upwards of 130 A at the power steering electric motor. That is far more than a production alternator can deliver at idle.

Because EPS maximum loads occur during slow maneuvering speeds such as in parking lots and parallel parking on streets when the engine is near idle speed, consequently the alternator output is limited leading to insufficient EDS voltage regulation. Hence, a battery contribution is necessary to supplement the alternator output. This means that in a high rack load vehicle that unless the EPS actuator is designed to deliver rated force at low battery conditions the steering performance, gain and responsiveness, will become functions of EDS voltage and the customer will notice it. More detail on the EDS regulation issue may be found in [1].

B. Sizing the Ultra-capacitor Module

This study will introduce the Maxwell Technologies D-cell Module rated 14V, 58F, 18mΩ as an energy module and 10.8mΩ as a power module. Figure 2 illustrates the D-cell configuration on a PWB having a series string of 6 cells rated for continuous 2.5V/cell operation. It is recommended that cell potential be restricted to 2.5V or lower for applications that require 10 years of service life. Elevated temperatures and excessive cell potentials lead to life reduction via leakage current increase and electrolyte dissociation. In Fig. 1 a series connected pair of D-cell modules comprise the upper energy buffer in the 42V Pseudo PowerNet. The combined module has a net capacity of 29.2F at 30V nominal.

The Maxwell module contains a cell balancing network on the reverse side of the PWB. Non-dissipative, self powered, cell balancing is implemented using a rail-to-rail analog comparator to drive a complimentary pair of BJT transistors that divert current between pairs of cells. Rated for up to 300 mA of current bypassing, the module will stabilize D-cells sufficiently for automotive use.

Fig. 2 D-cell module (6 cells, 350F, 2.5V each)

III. MODELING THE PSEUDO 42V POWERNET

The pseudo 42V PowerNet is modeled as an inductor input half bridge dc/dc converter where the D-cell module is the charge transfer accumulator. In this arrangement, the alternator and its regulator function remain unchanged, but the half-bridge converter has a voltage setpoint control loop closed around the series combination of battery and ultra-capacitor module as shown in Fig. 3. The control loop is designed to maintain the 42V bus regulation while current is transferred from the alternator-battery charging system into the ultra-capacitor via the boost inductor, L_{boost}. A PWM modulator controls the main switching transistor, MOS2, according to the error between the 42V setpoint and the monitored bus voltage. This analog mixed signal model consists of the main network in SPICE compatible format (conservative nodes) and the signal processing blocks (non-conservative nodes). Interface into the controller is via the feedback voltage sensor monitoring terminal. Main switch PWM modulation input is via its control signal input definition as noted. The controller performs fixed frequency triangle comparison PWM.

The major functional groups in this simulation are discussed in the following subsections starting with the charge transfer controller, the D-cell module, and 42V loads. Network voltage probe points are illustrated with numerical call-outs at the left in this figure.

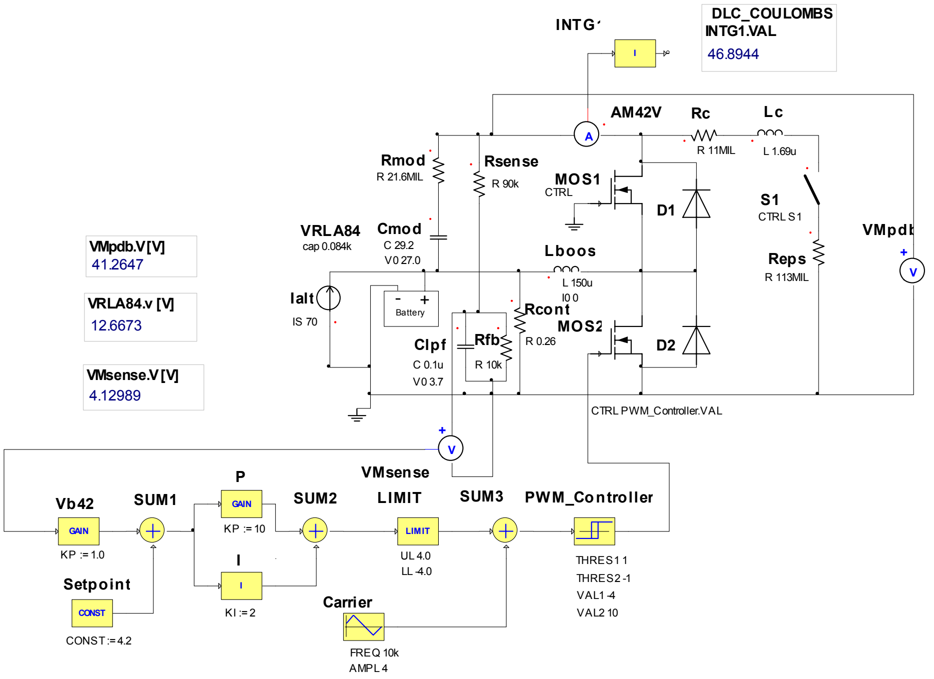

Fig. 3 Circuit model for the 42V regulator (Ansoft Simplorer model)

A. *Charge TransferController*

The start up transient is modeled as shown using a simple current source for the alternator output. To limit simulation time, the D-cell ultra-capacitor module initial voltage is set to: V_{co}= 27.0V. With this choice of initial condition the charge transfer monitor, DLC_Coulombs, shown as a digital integrator in the upper right in Fig. 3 shows that 46.8944 C of charge were transferred. This agrees well with the circuit variables: V_{DLC} = VMpdb.v – VRLA84.v = 41.273 – 12.667 = 28.606 V. The D-cell ultra-capacitor voltage was therefore charged by: $V_c = V_{DLC} - V_{co} = 28.606 - 27.0 = 1.606$ V. The net charge transfer is therefore, $Q=CV_c$ = 1.606V * 29.2F = 46.895 C.

Figure 4 illustrates the boost inductor current when the PWM frequency is set to 10k Hz and the inductor is rated at 150 μH.

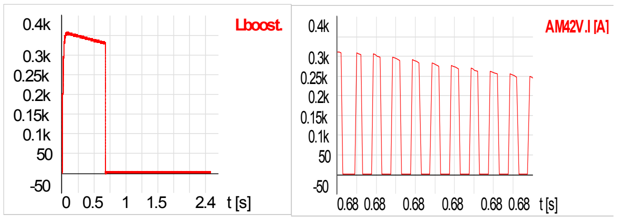

Fig. 4 Start-up current transient

In Fig. 4 the PWM regulator is designed for 400A of input current from the 12V VRLA battery. The battery used is an empirical model that is part of the Simplorer tool Automotive Library. Boost regulator current delivered to the D-cell ultra-capacitor is shown in Fig. 4 RHS. The ultra-capacitor input current in Fig. 4 is an expanded view using a 1.0 ms sliding window.

A state machine controller is added to the simulation in Fig. 4 to control the switching of an EPS load model. The initial conditions on D-cell ultra-capacitor charge are held and the EPS load is then scheduled to occur at 0.75s for a duration of 2s. During this load switching event the simplified charging system consisting of current source and VRLA battery model (84 Ah) is retained. The charging system is set to deliver 70A into the 12V system with approximately a 60A hotel load. Vehicle hotel loads are modeled with a 0.26Ω resistance, R_{cont}. The result is shown in Fig. 5 for EPS load current (Left) and boost inductor current (Right).

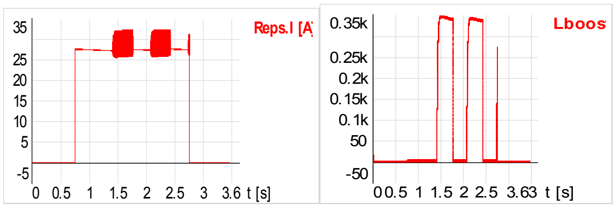

Fig. 5 PowerNet response to EPS load change

At 0.75s into the EPS load the boost converter charge pump responds to the droop in 42V bus voltage and injects charging pulses with amplitude of 360A. The presence of such large switching transients disturbs the EDS voltage leading to perturbations on the EPS load current as shown. The character of this EDS disturbance caused by such excessive current transfer is shown in the voltage trace in Fig. 6 measured at the voltmeter location in Fig. 4 for VMpdb.

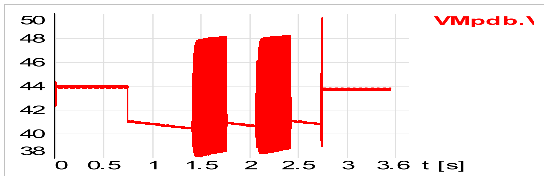

Fig. 6 PowerNet distribution voltage during EPS engagement

At 750ms in Fig. 6 the EDS voltage step reflects the load current of 28A through the VRLA battery plus DLC internal resistance of 21.6 mΩ, or an 0.8V step on the 42V system. Because the charging system is unable to fully support the 14V network during this load application the VRLA battery terminal potential drops by 2.3V from its charging system potential of 15V to 12.6V for a total drop of 3.1V as depicted in Fig. 6.

This magnitude of EDS voltage disturbance would not be acceptable in the production automobile. Therefore, a closer look at the charging system requires that the simple current source model of the alternator be replaced with an empirical model of the Lundel alternator and this exercise then repeated. But first, we take a look at the battery plus ultra-capacitor in bootstrap configuration and its efficiency.

B. *Battery plus Ultra-capacitor Bootstrap*

The D-cell module plus a VRLA 12V battery combination is capable of supporting an EPS load of 1.2kW for approximately 10s. During this interval the EDS voltage remains at or above 30V. This means a strategy to charge pump the boost capacitor can be relaxed to some lower average current and thereby minimize the cost of the boost converter. To illustrate this, the energy storage system is modeled with a constant power load of 1.2kW and the system variables monitored. Figure 7 shows the ESS model (Top) plus VRLA battery current and voltage (Center) and the DLC voltage (Bottom).

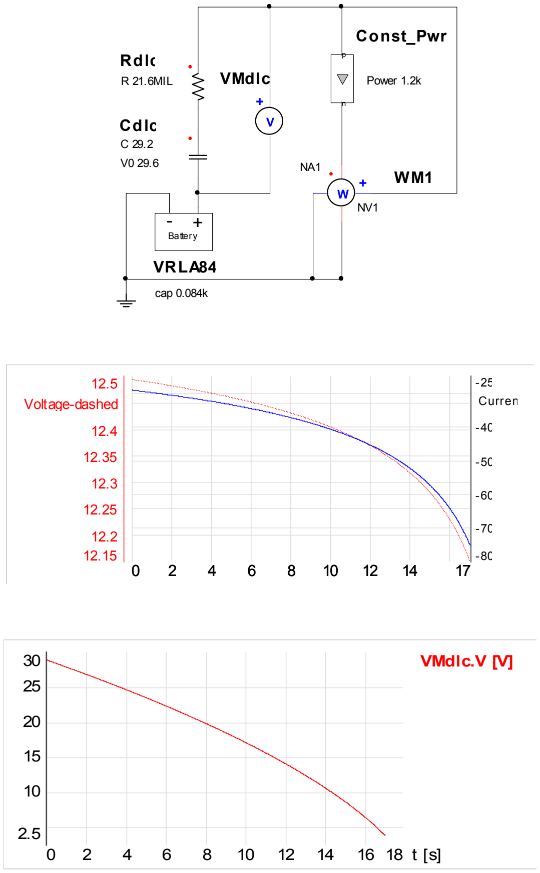

Fig. 7 Energy storage system with constant power load

The ESS system voltage at 9.7s has dropped to 30V, 12.4V on VRLA plus 17.6V on DLC as shown in Fig. 8.

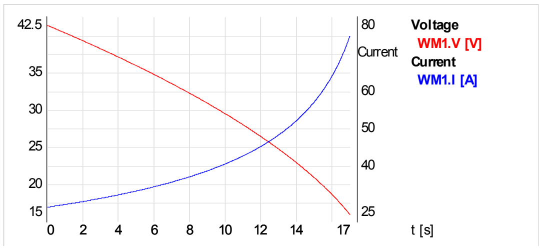

Fig. 8 Energy storage system current and voltage to load

During the constant power discharge of the ultra-capacitor in the bootstrap configuration its discharge efficiency is not constant. Under constant power discharge the ultra-capacitor efficiency can be calculated to be:

$$\eta_d = (1 - ESR\frac{I_{dlc}}{V_{dlc}}) \tag{1}$$

A plot of (1) is shown in Fig. 9 for the case of an EPS power level of 1.2kW and for the D-cell power module having an ESR of 21.6mΩ. For this particular set of data the efficiency has a mean value of 0.926, a median value of 0.962 and a minimum value of 0.582 (at 17s into discharge).

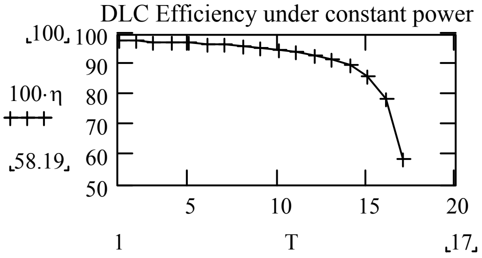

Fig. 9 DLC efficiency at constant power discharge

The discharge efficiency at this power level relative to its matched load efficiency was shown to be (2) in a previous work [1].

$$\eta_0 = \frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{P_0}{P_{ML}}} \qquad P_{ML} = \frac{V_{c0}^2}{4ESR} \tag{2}$$

Nominal discharge efficiency according to (2) is 0.969 (P_{ML} = 10kW) which is very nearly the median value of the constant power discharge efficiency. From these observations it is clear that combining an ultra-capacitor with a VRLA battery in a totem pole configuration leads to a more efficient manner of delivering peak power to electrified ancillaries than direct connection via the 14V EDS.

C. *Impact on the Charging System Power Budget*

To assess the impact of the bootstrap connected ultra-capacitor on the charging system power budget it is instructive to first approximate its discharge current under constant power conditions. The current trace in Fig. 8 can be roughly approximated using an exponential function as:

$$I_{dlc}(t) = I_0 e^{\frac{t^2}{a}} \qquad I_0 \sim \frac{\eta_0 P_0}{(V_{c0} + V_{b0})} \tag{3}$$

Where a=325 and I_0~28 A provide a fair approximation to the discharge current shown in Fig. 10 where Idlc and Vdlc are the monitored ultra-capacitor variables under constant power conditions. Note that at 17s the D-cell module is nearly completely discharged, its voltage has dropped to V_f= 3.87V. This is a discharge factor, $\sigma=V_f/V_{c0}$ = 0.13 so the energy extracted, $W_{useful} = (1-\sigma^2)W_{avail}$ = 0.982.

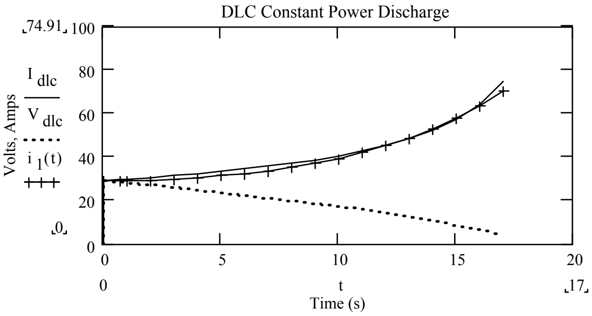

Fig. 10 Functional approximation of DLC current

Using (3) the power budget can be computed and from this the ESS energy budget and its relative apportioning between the VRLA and DLC. In this analysis the DLC ESR=R_{ic} and VRLA ESR=R_{ib}. Consider the DLC energy available at its terminals:

$$W_{dlc} = T\left\{V_{c0} - R_{ic} I_0 e^{\frac{T^2}{a}} - \frac{I_0}{C}\int_0^T e^{\frac{\tau^2}{a}} d\tau\right\} I_0 e^{\frac{T^2}{a}} \tag{4}$$

Taking again T=9.7s as the time at which the EDS bus voltage droops to 30V and using initial conditions on DLC and VRLA as V_{c0}=29.6V and V_{b0}=12.6V leads to a DLC energy output of W_{dlc} = 6.801 kJ. Likewise for the battery, in which case it's delivered energy is:

$$W_{bat} = T\left\{V_{b0} - R_{ib} I_0 e^{\frac{T^2}{a}}\right\} I_0 e^{\frac{T^2}{a}} \tag{5}$$

Which yields W_{bat} = 4.7 kJ. The load, under constant power conditions for T-seconds, consumes an amount of energy: $W_{load} = P_0 T$ = 11.64 kJ. The total energy delivered by the bootstrap ESS is therefore W_{dlc} + W_{bat} = 11.5 kJ where the error is due to the approximation used for current. The result is summarized in Table 1. Note that when compared to providing the same load support as the conventional 14V EDS the proposed pseudo 42V PowerNet EDS unburdens the VRLA energy storage by 60%. This leads to improved VRLA warranty owing to reduced energy cycling provided the energy used to replenish the DLC is provided by the alternator not the battery itself. This implies that a net charge system is used.

TABLE I. ENERGY STORAGE SYSTEM BUDGET

	Energy Storage System		
	Units	VRLA (14V only)	VRLA + DLC (14/42V EDS)
W_{dlc}	kJ	0	6.8
W_{bat}	kJ	11.6	4.7
W_{load}	kJ	11.6	11.6
W_{bat}/W_{load}	#	1.0	0.40

IV. SYSTEM USING LUNDEL ALTERNATOR MODEL

Simplorer simulation automotive libraries contain useful models of the major electromechanical components and these are applied next to help further refine the model of Fig. 3. Charge pumping using the wide hysteresis band controller of Fig. 3 leads to short duration, high current magnitude bursts both at key-ON and during prolonged high power load application. The system of Fig. 3 can be modeled more simply as a controlled current source feeding the bootstrap connected ultra-capacitor from the alternator output as shown in Fig. 11. The link between the engine model and alternator represents the mechanical shafts and pulley ratio. The alternator is a current source model based on speed input from the engine. Electrical loads consist of fixed power electronic loads and switched power loads to represent scheduled loads.

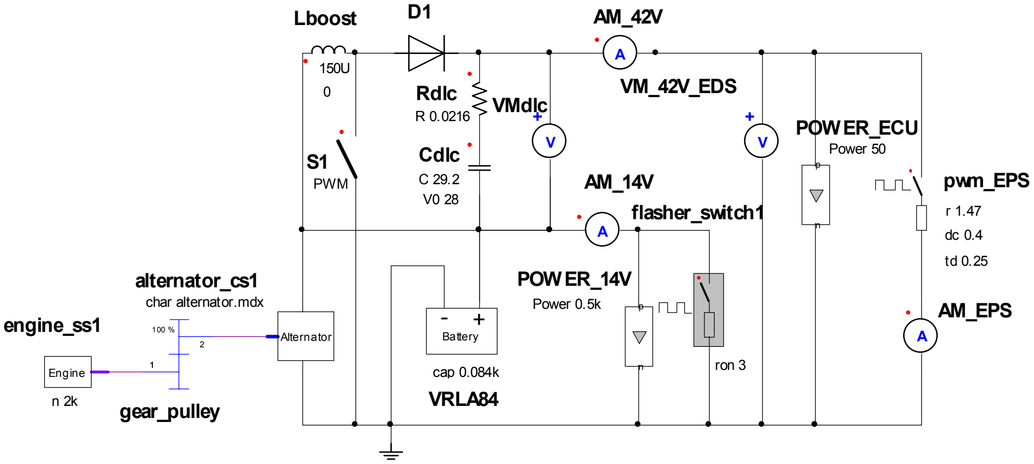

Fig. 11 Refined system model of the battery and ultra-capacitor

A. System Response Without Source Power

In the system of Fig. 11 a small boost converter maintains charge on the D-cell ultra-capacitor module (R_{dlc} and C_{dlc}). The power of Simplorer is utilized in this arrangement to develop the PWM control input to the boost switch is from the ultra-capacitor voltage measurement, VMdlc, compared to a setpoint and this error is used as feedback. Simplorer therefore completes closed loop control of the boost regulator using only three basic equations. With the alternator and boost omitted from the simulation the battery and ultr-capacitor respond to the connected loads as depicted in Fig. 12. Note the EDS system capacity to support the 42V bus for a significant time interval.

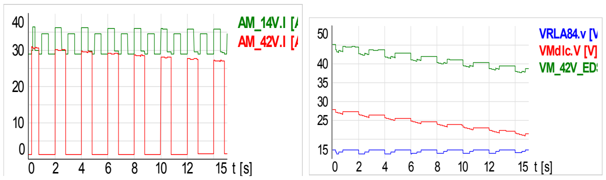

Fig. 12 EDS load currents and voltages without source input

B. System Response With Source Power

When the alternator and boost converter are engaged and the same loads applied to both the 14V and 42V bus the regulation on the 42V PowerNet is adequate to sustain the EPS load. During these conditions (engine speed, n_{eng} = 1.8k rpm and alternator speed, n_{alt} = 4.5k rpm) the alternator current is approximately 84A. Figures 13 through 15 give the VRLA battery voltage and current, the 14V and 42V EDS bus voltages and currents for this condition. In Fig. 13 positive battery current represents charging conditions. The remainder of the alternator output is sourcing the 14V EDS loads (38A) plus the dc/dc boost converter current to the ultra-capacitor.

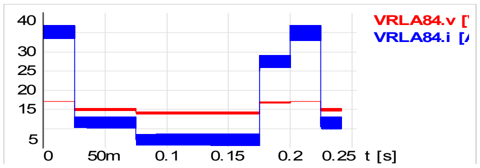

Fig. 13 VRLA battery current and voltage with source input to 14V & 42V busses to maintain regulation (at reduced time scale).

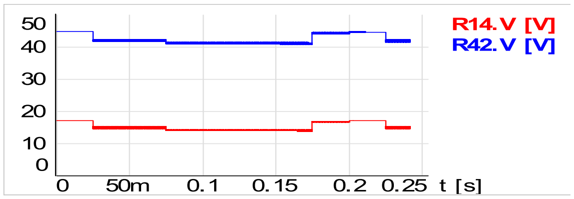

Fig. 14 EDS bus voltage during scheduled load changes for 14V and 42V bus.

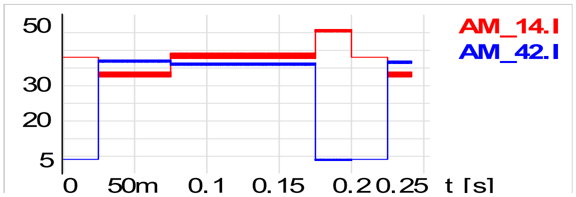

Fig. 15 EDS network bus currents ($I_{14}V$ = 38A, I_{42V} = 5A, 36.6A)

It is important to note in the above example that even with a modest boost converter wattage that the D-cell bootstrap ESS can support significant electrified loads and its bus regulation.

The power of Simplorer is further illustrated by the ease with which the average input current of the boost inductor in Fig. 11 can be obtained. With the addition of a few simple signal conditioning blocks the dc average of the current can be computed. Figure 16 illustrates the addition to Fig. 11 needed to achieve this.

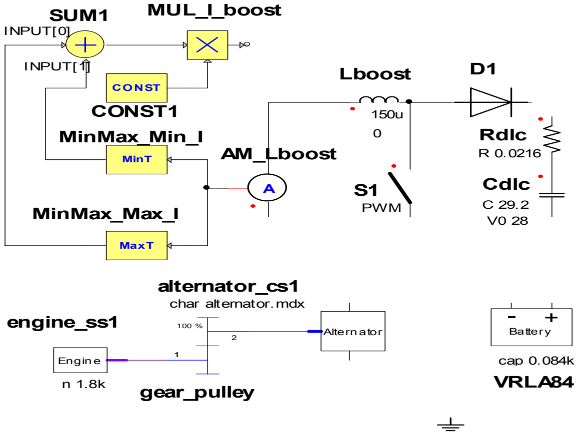

Fig. 16 Derivation of boost inductor average current during transients

With the addition of signal conditioning the boost inductor (150mH) average current can be obtained as shown in Fig. 17.

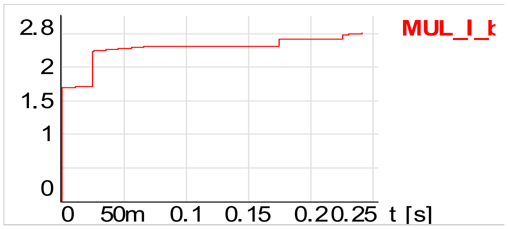

Fig. 17 Boost inductor current with signal conditioning

C. *Benefits of the Bootstrap Ultra-capacitor and VRLA*

The real benefit of a totem pole connection of a VRLA battery and the D-Cell ultra-capacitor ESS is the ready availability of a 42V PowerNet bus as an overlay harness. This means that existing 14V legacy EDS harness and components remain unchanged and that future electrified ancillaries can be accommodated during the interim years without the OEM incurring excessive ON cost. With the proposed system the OEM wins and the customer wins. The OEM wins because the price of introduction is minimal and the customer wins because of improved functionality and improved fuel economy.

V. CONCLUSION

This paper has shown that the power budget of existing automotive products can be effectively reset with the addition of newly introduced D-Cell ultra-capacitor boost modules. Connected in a bootstrap, or totem pole, configuration with ultra-capacitor on top of the existing VRLA lead-acid battery, the combination electric energy storage system is capable of supporting future electrified power ancillaries while remaining backwards compatible with the existing 12V electrical component base. With this system, OEM's need not completely revise the automobile parts inventory, but simply add new 42V components as needed. The vehicle electrical charging system remains as is with the addition of a small boost converter needed to sustain charge on the D-Cell module.

The major benefit of the ultra-capacitor bootstrap electric energy storage system as the charging system source for electrified ancillaries is that existing VRLA battery cycling is reduced by 60%. This means improved life of the VRLA battery and better regulation of both the existing 14V EDS bus and the overlay 42V pseudo-PowerNet.

It was further shown that with a D-Cell electric energy storage system that electrified ancillaries can be sourced with power at much higher efficiency than if a second battery were installed. Under constant power discharge conditions the D-Cell exhibits better than 96% efficiency as opposed to the much lower efficiency of a lead acid battery. This in itself is reason for OEM's to give serious consideration to ultra-capacitor technology. In a previous paper it was shown that ultra-capacitor technology is expected to reach cost levels of $0.025/F, a level at which the system proposed here begins to fall within the cost targets of automotive systems.

ACKNOWLEDGMENT AND NOTE

J.M.M. thanks Mr Richard Smith of Maxwell Technologies, Inc., for his many helpful discussions on ultra-capacitor technology in distributed modules and the Ansoft Corporation for use of Simplorer simulation tools.

A successor paper will explore in more depth the ability of the D-Cell boostCAP module cell balancing networks during transient scheduled load changes to maintain cell voltage. This is critically important to the automotive industry in this particular implementation because the D-Cell module eliminates the need to install a second battery in the vehicle. Therefore, long term reliability is essential to the success of this proposed EDS architectural change.

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