Ultra-capacitor Augmentation of the 14 V Vehicle Electrical System to Support Auxiliary 42 V Subsystems

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Abstract: The average electrical burden in passenger vehicles, cars and light trucks, has escalated in recent years from 500 W to 700 W and higher. Growth in electrical loads is now 100 W on average per year. During this time the vehicle electrical energy storage system, in the form of an SLI battery, has increased in energy rating proportionally in order to minimize the battery contribution to average electrical loads. The trend to higher battery contribution has added an additional weight burden to the vehicle, reduced the electrical distribution system voltage regulation, and increased battery wear out mechanisms. In this paper it is shown that judicious placement of the recently introduced D-cell ultra-capacitor distributed energy module in the vehicle electrical generating and storage system will provide a local dual voltage electrical distribution system, EDS. The 42 V dedicated branch of the EDS is available to support new electrified auxiliaries such as electric assist power steering, future electromechanical brakes and introductions of red and white LED exterior lighting operating at voltages higher than 14V.

I. Introduction

There have been notable attempts 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 [5]. 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 [6]. Toyota Motor Corporation at the JSAE 42 V International Symposium in 2003 [7] 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 capacity is proportionally increased. This paper explores the advantages of offsetting further battery system up-rating with ultra-capacitors in series with the battery as the source of 42 V power. The overlay 42V bus, or pseudo-42V PowerNet, is readily installed and backwardly compatible with the existing component base.

II. Vehicle Electrical Distribution System, EDS, With Ultra-capacitors

It is well known that the EDS complexity, cost and weight have increased dramatically since the introduction of electronic engine controls in the early 1980’s [8,9]. According to a recent study on vehicle power management by Intertech [10] which shows that electrical loads in high end products are growing at 150 W per year and that the average vehicle may see electrical load increases of 100 W per year as existing functions are electrified and new electrically actuated features and amenities are added.

This rise in average load places increased demands on the engine driven alternator, particularly at idle where the alternators ability to generate is limited and where its shaft torque is maximum. High torque at the alternator pulley translates to the need for wider serpentine belts, a larger belt wrap angle around the drive pulley and larger bearings in the engine to withstand the attendant higher belt tensions (reflected to the bearings as side loading).

One suggested means to mitigate the peak power loading of the vehicle EDS has been to introduce distributed energy modules at the actuator layer in the vehicle electrical architecture hierarchy as shown in Fig. 1. At the present stage of automotive evolution the electrical loads having the most direct impact on the EDS and its generation and storage systems are electric assist power steering, EPS, and electromechanical brakes, EMB as these begin to find application. EPS is here now and on vehicles with lower steering loads, a 14V power supply is adequate. However, as steering loads increase through for example front end vehicle weight increases, trends to lower ratio steering and suspension geometry changes, it is not possible for 14V systems to handle the demands. Randy Frank [11] 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 (ref. Table 1 below). In this illustration the actuator size in a 14V power supply vehicle goes from 1 pu to 3.25 pu if the EDS voltage remains at 14V. The corresponding EDS current increases from 55A to 114A and the motor output 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, for EPS currents greater than 85A dictate the EDS voltage should be increased to 42V. In a conventional 14 V system, delivering 14 kN of steering effort will require upwards of 130A at the power steering electric motor. That is far more than a production alternator can deliver at idle.

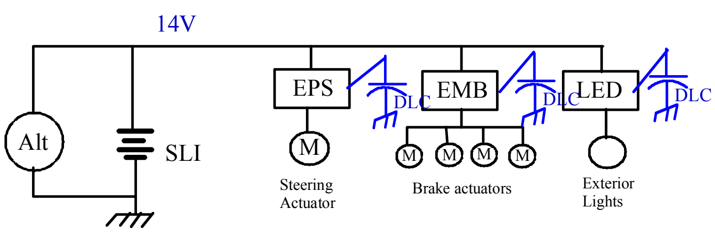


Fig. 1 Ultra-capacitor distributed module concept

Table 1. Electric Power Assist Steering [from 11])

Rack Load=	5 kN		10 kN	
EDS Voltage	14V	42V	14V	42V
EPS Current	55A	18A	114A	25A
Harness loss	15W	1.3W	91W	7.6W
Motor Power	222W		475W	
Relative Size	1.0	0.95	3.25	2.4

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, the alternator output is current limited, the EDS voltage regulation becomes impaired. Hence, battery contribution is necessary to supplement the alternator output. This means, for example in high rack load vehicles, 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. Figure 1 illustrates the case of ultra-capacitor distributed modules being used at only critical loads that have very high peak to average power demand.

III. Ultra-capacitor Augmented EDS for dual 14V/42V

The market is already seeing the application of ultra-capacitors as electrical power caches for critical loads in automotive systems. The new Prius for example uses an ultra-capacitor power cache in the electronically controlled brake system, ECB, as redundant back up power. Other examples are emerging in European automobiles and this trend is expected to continue and to expand rapidly as both the benefits of ultra-capacitor distributed modules are recognized and as the cost of such modules continues to decrease.

There are ongoing efforts aimed at improving our understanding of the benefits of ultra-capacitor modules in automotive systems [12,13] and the development of appropriate models and simulations. 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 [14,15,16]. For example, Honda Motor Company employs an ultra-capacitor only ESS in their FCX fuel cell vehicles now being leased to U.S. cities in California [17]. 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 its exposure to multiple drive cycles.

III. 1 Pseudo-42V PowerNet

Figure 2 illustrates the architecture of the D-Cell ultra-capacitor enabled overlay 42V EDS. In this concept a pair of D-Cell modules rated 14V and 58F are stacked in series and connected to the vehicle battery A-line. The combination provides a voltage rating of 28V nominal and 29.1F for energy storage. Ultra-capacitor module charge is maintained by a half-bridge buck/boost converter, shown as a unidirectional boost in this Fig. 2.

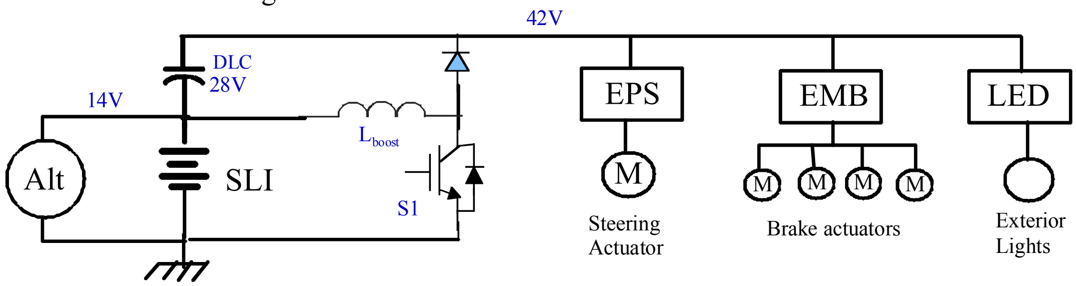
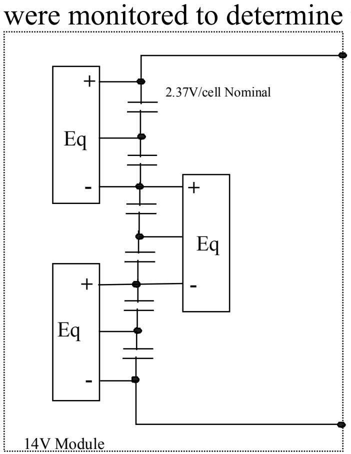


Fig. 2 The Pseudo 42V PowerNet Architecture and Electrified Loads

III.2 Experimental Results

One concern in such an arrangement shown in Fig.2 is the charge equalization between the individual cells in the 28V ultra-capacitor module (pair of D-Cell BoostCAP Modules). A D-Cell module depicted in Fig. 3 and coming equipped with built in non-dissipative electronic cell balancing was charged on the bench and allowed to stand for 10 days. During this extended stand time the module and cell potentials were monitored to determine the degree of balance realized.



Attribute	Value	Units	Comments
Capacity	350	F	Nameplate +30/-10%
Mass	54	g	Including case
Volume	51	cc	Including case
Rated Voltage	2.5	V	Nominal
Cell ESR	3.2	mΩ	For energy cell
Specific pulse power	9.0	kW/kg	At matched load
Specific energy	5.66	Wh/kg	Nameplate rating

D-Cell parameters (Energy Cell)
For the 14V Module:
C_{mod} = 58.3F, R_{mod} = 19.2mΩ Energy, 10.8mΩ Power
V_{cmax}<= 16.1V, P_{ML} = 2.6 kW Energy and 4.67 kW Power

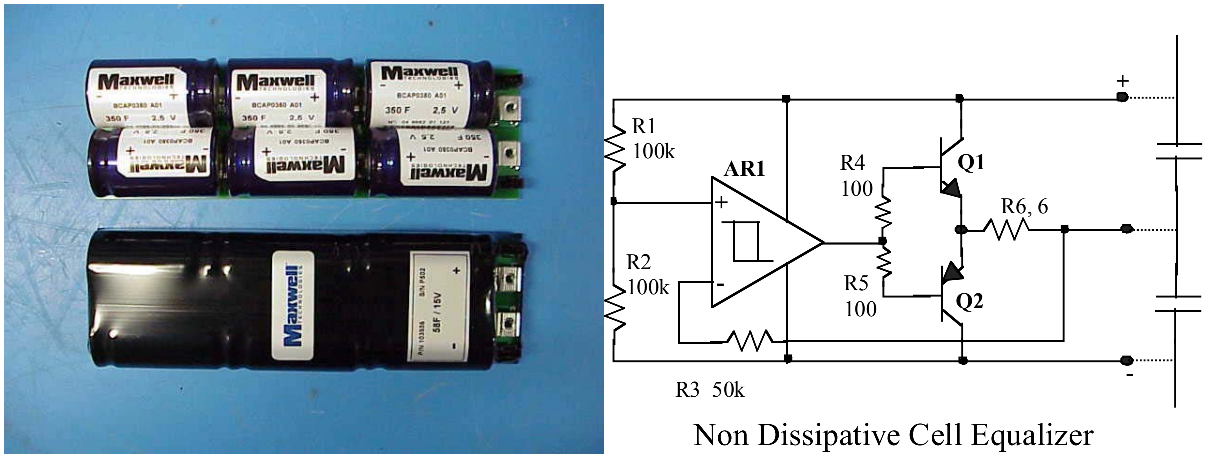


Fig. 3 D-Cell Module Rated 14V and 58.3F (Top Left: Equalizer Scheme, Top Right: Cell & Module Parameters, Lower Left: D-Cell pack, Lower Right: Schematic of the Cell Equalizer – patent pending by Maxwell Technologies, Inc)

Figure 4 captures the individual cell average potential deviation from nominal for the D-Cell module during 238 hours of stand time. Cell #1 is at the lower right (neg post) in Fig.3 and so on to cell #6. The average cell potential, V_{c0} = 2.096V at time =0 decreasing to 1.610 V at time = 238 h shown in the Left Hand plot of Fig. 4. After the extended stand time the cell balance remains within +/- 6mV of nominal as shown in the Right Hand side of Fig. 4. Initially, cell balance data was taken every 4 hours, then every 24 hours at the same time of day except for the interval from 20h to 140h during which time the module was not monitored. It is expected that the cell equalization exhibits balancing activity over the entire time span.

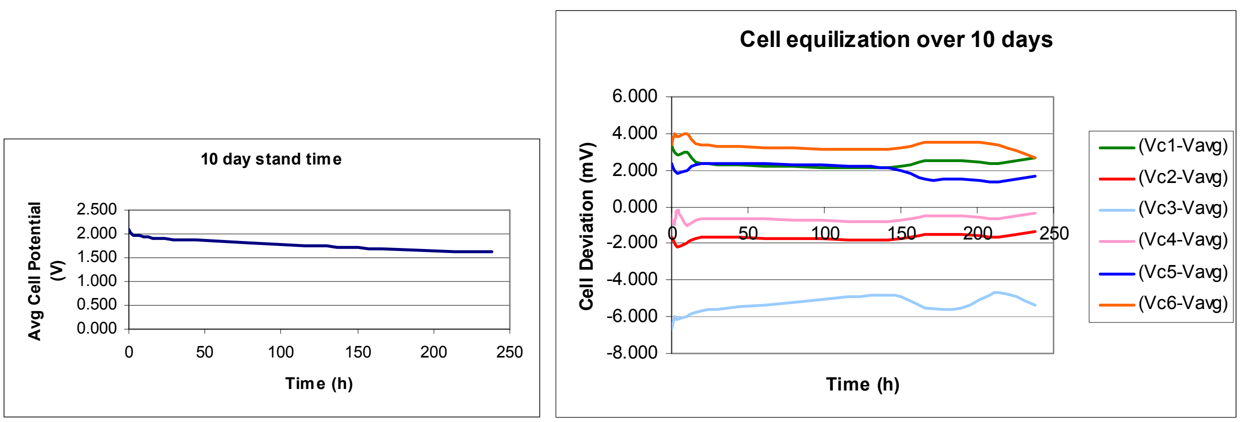


Fig. 4 Average cell potential and cell equalization during extended stand time.

The next step in this characterization phase is to determine if the D-Cell module used in the pseudo 42V PowerNet EDS will maintain cell balance after pulse discharging at EPS levels (1.2 kW at 42V). This assessment was done in two steps, first the module was fully charged to battery potential of 12.6V and then completely discharged to 0 current into a fixed resistance $R_L=1.6\Omega$ to reset the capacitors. At the end of this discharge the module potential recovered to about 200mV. Secondly, a smaller fixed resistance of 0.344Ω was switched across the charged module for 10.5s to represent a long event EPS power demand of 34.5A. Fig. 5 illustrates a simulated discharge event of the D-Cell module: Left: complete discharge to 0A in 140s (τ = 21.2s), Left: a 10.5s partial discharge. The charts in Fig. 5 are plotted using Simplorer v.6 with a simple model for the ultra-capacitor.

For this condition:

$$i(t) = \frac{V_{c0}}{(ESR + R_L)}\left(1 - e^{-\frac{t}{\tau}}\right) \qquad (1)$$
$$v_c(t) = -\frac{1}{C}\int_0^T i(\xi)d\xi$$

The charge removed from the D-Cell module during this pulse is Q_{10s} = 284.5C which means the ultra-capacitor potential decreases from V_{c0} = 12.58V to $V_c(T) = V_{c0} - Q_{10s}/C$ = 12.58 – 4.88 = 7.7V. The measured final voltage was 7.82V which means the figure used for capacitance in (1) is actually somewhat larger than the nominal value of C_0 = 58.3F.

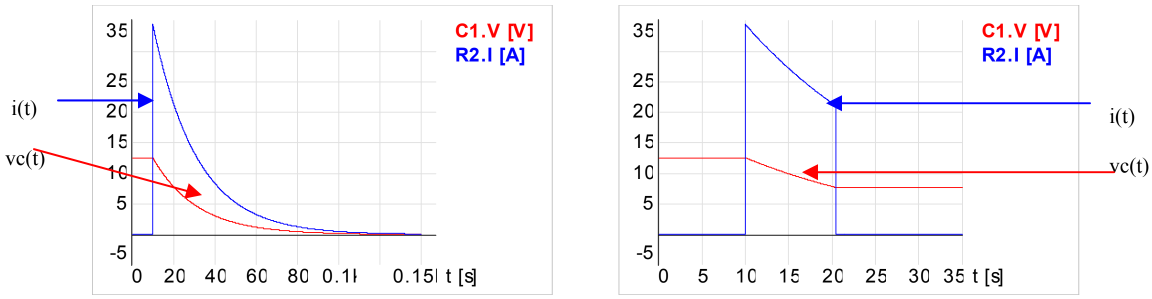
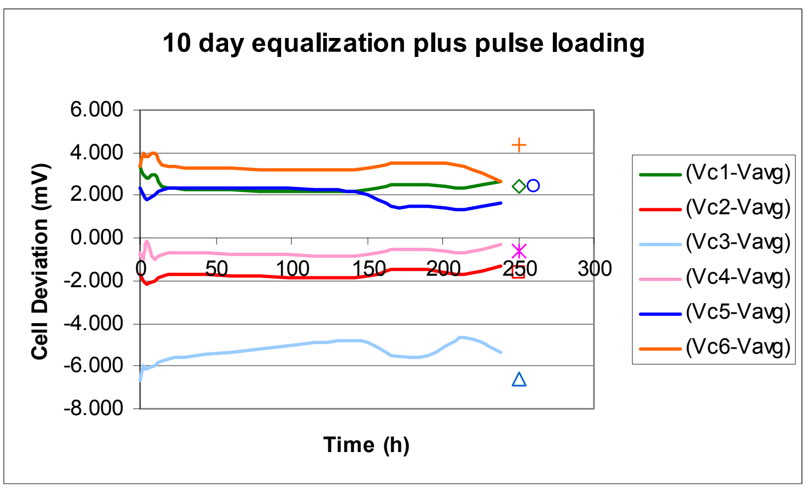


Fig. 5 Pulse test of the D-Cell module(Left: full discharge, Right: 10.5s pulse)



Cell balance deviation from nominal (mV)

	@238h	@260h
Vc1	2.67	2.4
Vc2	-1.33	-1.6
Vc3	-5.33	-6.6
Vc4	-0.33	-0.6
Vc5	1.67	2.4
Vc6	2.67	4.4

At 238h Vc0 = 9.66V
****Recharge *****
At 260h Vc0 = 12.35V

Fig. 6 D-Cell module cell balance at pulse test time + 22h (marked with symbols at 260h)

From these static and dynamic tests of the D-Cell module it is apparent that the cell equalization will be sufficient to maintain cell balance over prolonged periods of stand time followed by high current pulse loading. This is the customer usage profile for an EPS system in the automobile.

Although not mentioned in the preceding treatment of cell equalization, the Maxwell D-Cell modules also contain an internal provision for module-to-module equalization (module balance circuit) that links the D-Cell packs in a series string together and provides voltage balance across them. This circuit is integral to the pack and must be employed to insure that a series string of D-Cell modules will meet the overall cell balance requirements and if series strings of cells are placed in parallel to increase storage rating.

III.3 Ultra-capacitor Up ESS with Charge Pump

The BoostCAP module shown in Fig.2 is more correctly represented as a series string of D-Cell units with the interlaced non-dissipative charge balancing networks as noted in Fig. 7. The 28V module has its charge replenished from the vehicle charging system (alternator and 12V battery) via a small boost converter. The rating of this converter is dependent on the connected loads and on the types of customer usage (drive cycles with steering cycle modification). More on this topic in section V.

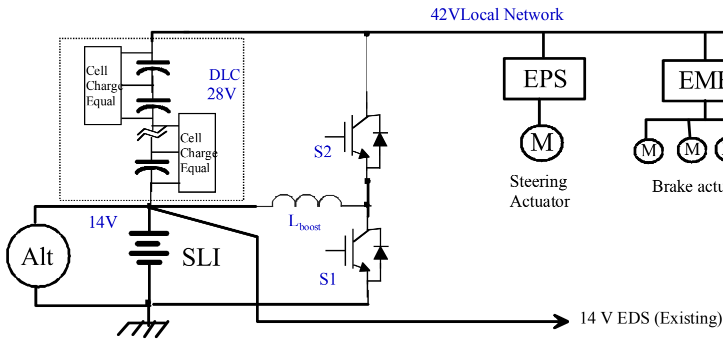


Fig. 7 Ultra-capacitor UP 42V PowerNet

IV. Benefits of the Pseudo 42V PowerNet

It is fact that electrochemical cells exhibit wear out due to Faradic action (mass transfer) so that the gross operating cost of a VRLA battery for example can be shown to be \$0.015/Wh-cycle of throughput energy [2]. This accounting makes use of the cycle life versus DOD of the VRLA with assumptions of \$2/kg for stored energy and \$4/kg as the cost of weight in the automobile. The ultra-capacitor on the other hand is not subject to the same wear out mechanisms and is capable of full charge cycling for perhaps 500,000 cycles or more. The D-Cell module is capable of storing on the order of 1Wh of energy, which if exercised to 75% DOD and assuming \$2/Wh (\$0.0025/F projection for 2010), yields a cost of throughput energy of \$0.0000143/Wh-cycle. This is far superior to the VRLA and the reason this architecture is being promoted.

However, the Ultra-capacitor Up architecture in Fig. 7 does not completely eliminate battery cycling when higher powered electrical loads are energized. But the fact that now only 1/3 of the load current is passed through the battery versus 100% in the case of a 14V system supporting EPS, means that battery cycling is indeed much reduced. How much was shown by the authors in [1] for the same case of an EPS load of 1.2 kW. If we assume that the vehicle charging system is designed for net charge then the energy to recharge the ultra-capacitor is derived from the alternator not from the battery. This energy management strategy then leads to the energy storage system burdens shown in Table 2.

Table 2 Energy Storage System Budget

	Energy Storage System		
	Units	VRLA (14V only)	VRLA+DLC(14/42V)
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

Table 2 reveals that the ratio of 12V battery energy relative to EPS load energy is reduced from unity in the case of a 14V only system (today's architecture) to 40% when the pseudo 42V PowerNet architecture is employed. This is a very significant benefit of the concept and it would lead to not only higher pulse power delivery to high powered electrified loads but to improved energy storage system warranty as well.

Again, the caveat is that the vehicle charging system cannot have a deficit charge energy management strategy.

V. EDS Simulation Results

To identify the appropriate charge pump rating so that the 28V rated ultra-capacitor module may be sustained in the presence of both drive cycle fluctuations on charging system output capability and accounting for electrified load customer usage we use Simplorer automotive library models for the EDS to construct a simplified EDS model of the 14V/42V architecture having a fixed 14V load of 750W and an assumed customer usage file scheduled load for the EPS.

V.1 Simulation Under Deficit-charge Conditions

To model deficit charging the powertrain to alternator coupling is modeled without a pulley ratio so that alternator drive speed will drop to engine idle rpm during significant portions of the drive cycle. During such intervals the alternator output is zero and the battery must contribute to network loading. Figure 8 illustrates the dual voltage network as simulated under deficit-charge and Fig.'s 9 through 11 reveal the modeled behavior. The dc/dc converter is modeled as an ideal dc-transformer: $i_{14}v_{14} = i_{28}v_{28}$.

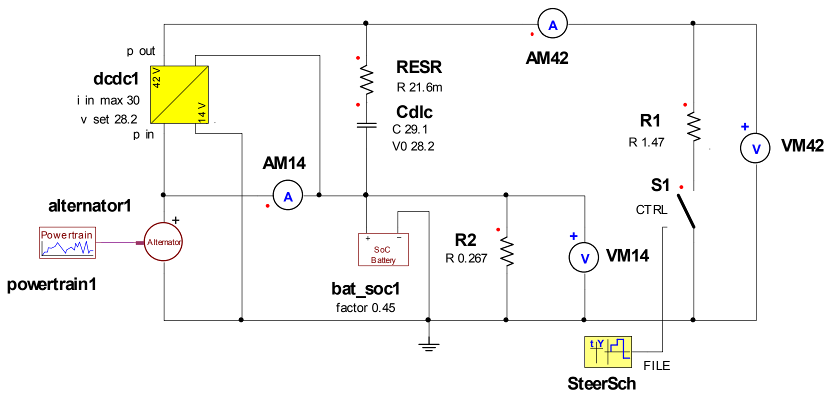


Fig. 8 Dual Voltage PowerNet Under Drive Cycle Input Without Pulley Ratio and Scheduled EPS Load

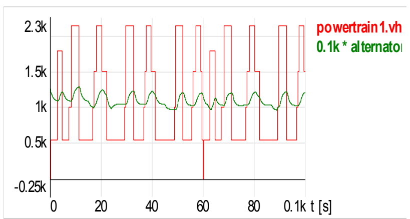


Fig. 9 Alternator Speed Profile and Voltage

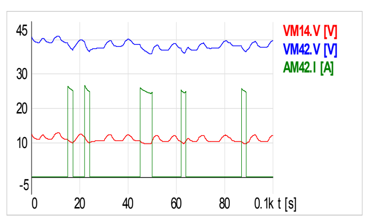


Fig. 10 Network Voltages and EPS Schedule

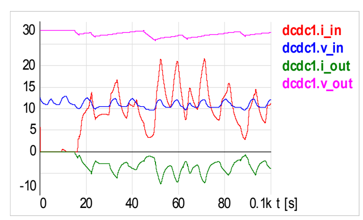


Fig. 11 Dc/dc Converter I/O

The drive schedule illustrated in Fig. 9 is representative of a city cycle. Figure 10 shows that with random levels of alternator input power to the vehicle electrical networks and for the EPS loading schedule that both the 14V and 42V networks are maintained even when the dc/dc converter is rated at only 420W (input limited to 30A). Finally, as Fig. 11 illustrates, the converter responds to ultra-capacitor D-Cell module discharge by charge pumping from the alternator supply. In this example, the alternator input was intentionally driven at speeds below its cut-in (no pulley ratio between the powertrain1 drive cycle rpm and the alternator model). However, under this deficit charging condition the battery is committed to supporting the D-Cell charge transfer leading to further cycling as seen in Fig. 12 below.

V.2 Simulation Under Net-charge Conditions.

To illustrate a net-charge condition the pulley ratio between powertrain and alternator is re-inserted and the model is simulated. In this case the net alternator output will be higher because it will contribute output at engine idle rpm. Figure 13 is compared with Fig. 12 to show the difference in battery contribution between the two classes of charging system behavior.

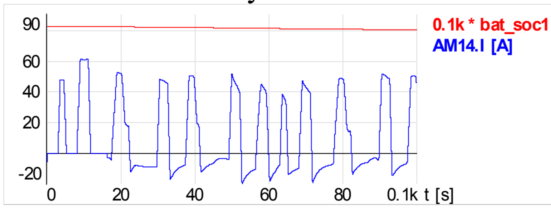


Fig. 12 Battery Contribution Under Deficit-Charge

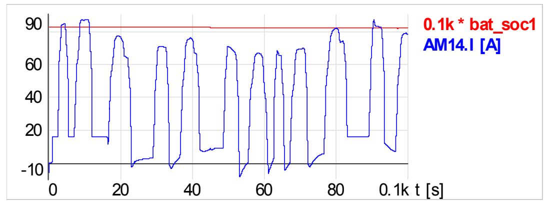


Fig. 13 Battery Contribution Under Net-Charge

Note the decrease in battery SOC in Fig. 12 versus the same conditions in Fig. 13. Figure 14 is the same as Fig. 8 with the exception of the modeled pulley ratio: n2/n1 = 2.3.

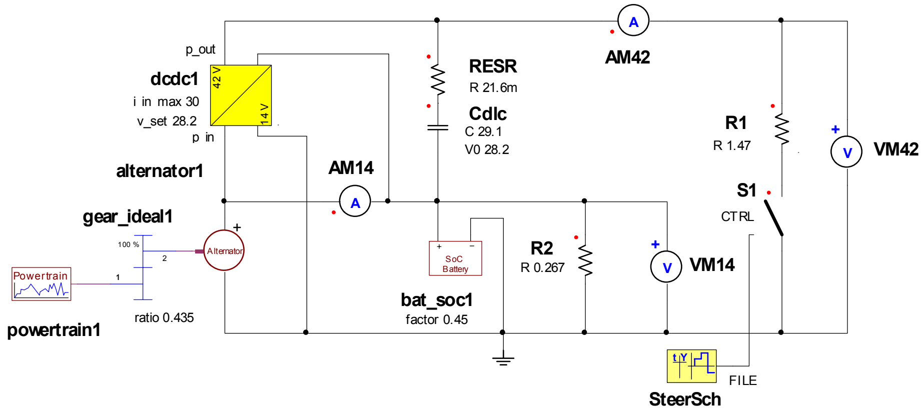


Fig. 13 Dual Voltage PowerNet Under Drive Cycle Input with Pulley Ratio and Scheduled EPS Load

Figure 13 has no other changes in the system shown in Fig. 8 other than the gearing. The addition of a gear ratio increases alternator output thereby delivering higher charge to the battery and to the dc/dc converter. Battery SOC is maintained without undue cycling and the network voltage levels are maintained with improved regulation. These behaviors can be observed in Fig.'s 14 through 16 and are the counterparts to Fig.'s 9 through 11 for the deficit-charge case.

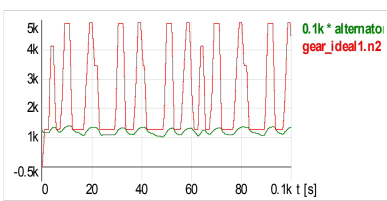


Fig. 14 Alternator Speed Profile and Voltage

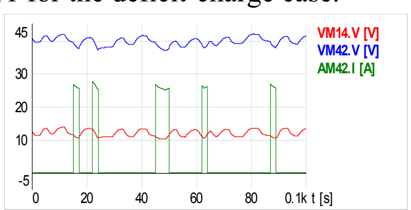


Fig. 15 Network Voltages and EPS Schedule

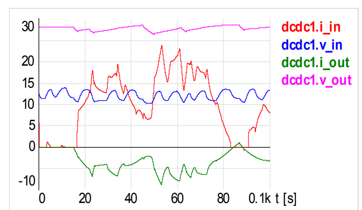


Fig. 16 Dc/dc Converter I/O

Under net-charge conditions the 42V network is better regulated as shown in Fig. 15 and dc/dc converter input current exhibits higher local peaks but overall becomes more discontinuous as shown in Fig. 16. From this we surmise that additional power loads at the 42V level can be supported with the same 420W dc/dc converter because it has yet to reach its input current limit. For even higher power loads at the 42V bus, or for more continuous duty of existing loads, it may be necessary to up-rate the converter.

V.3 Battery Cycling

The claim that net-charging and the ultra-capacitor boosted 42V pseudo PowerNet architecture promote a reduced battery cycling condition can be examined by referring to Fig.'s 17 and 18 which compare battery current under both net and deficit-charge. In the case of deficit-charge there is significant net discharge hence loss of SOC whereas in the second case under net-charge there is more nearly a zero average battery current. The architecture demands that whatever current flows through the high powered 42V load also flows through the battery so peak to peak current pulses are unchanged (charts have the same scale. Note however, that had the EPS load been supported at 14V the peak to peak current pulses would be three times higher.

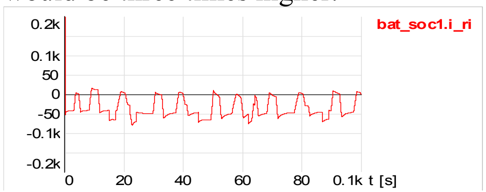


Fig. 17 Battery Current in Deficit-Charge Condition

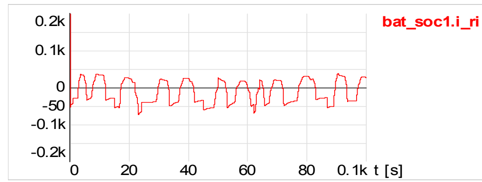


Fig. 18 Battery Current in Net-Charge Condition

VI. Conclusions

This paper has shown that judicious use of ultra-capacitor modules for critical loads in the automobile can offset the need for up-rating the SLI battery while maintaining EDS regulation and system performance. The pseudo-42V PowerNet as an interim measure reduces peak battery currents by a third relative to the same loads at 14V only. Moreover, with present cost trends in ultra-capacitors the energy cycling necessary to support higher powered functions at 42V can be met without need for a second battery or a full conversion of the vehicle electrical distribution system to 42V. The ultra-capacitor boosted 42V PowerNet using the D-Cell module is more compact and lighter than a dedicated 36V second battery. Measurements show that D-Cell module charge balance is sustained quite well both over time and in the presence of dynamic charge/discharge events.

Augmentation of the vehicle electrical system with D-Cell modules provides a bridging action to future 42V only PowerNet and at the same time provides an interim charging system measure that is more reliable in the presence of energy cycling and furthermore it reduces the 12V battery cycling by 60% when compared to providing the same function at 14V alone. An ultra-capacitor enabled 42V second voltage can be less expensive, more reliable, lighter and more efficient than alternative implementations at 14V alone.

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