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Ultra-Capacitors as Energy Regenerators in Fuel Cell and Hybrid Vehicle Powertrains

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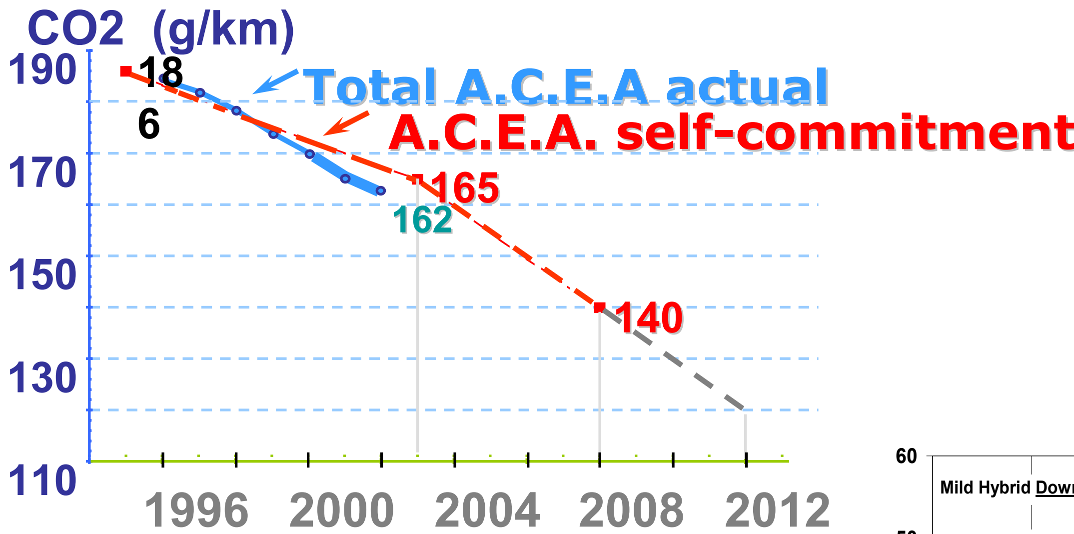
Outline

- Global CO2 and the push for reduced emissions
  - 2008 emissions target and hybridization ON-cost
- Illustrations of Vehicle Energy Recuperation
  - Toyota ES^3 Concept Vehicle
  - Paul Scherrer Institute & ETHZ prototype FCHV
  - Early systems with Flywheels and FW + Battery Combinations
- Are Ultra-capacitors a viable technology as a vehicle energy regenerator?
- Capacitors in lieu of magnetics: A new thrust in the high voltage→ 42 V → 14 V power conversion area
  - Zero sequence power conversion
  - Switched Capacitor Converter
- Conclusions

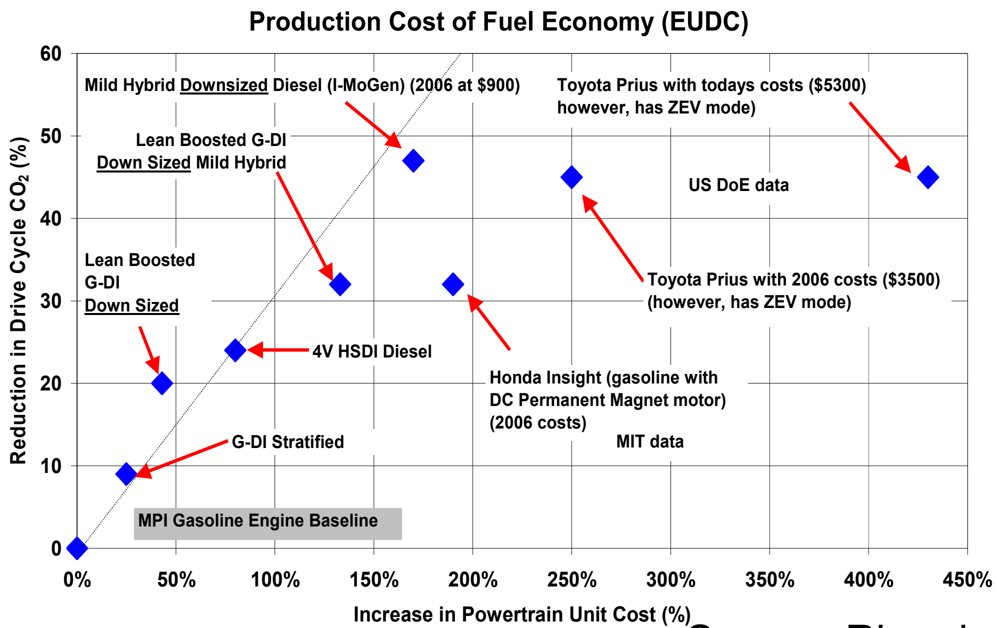
Global CO2 and the push for reduced emissions



Source: Renault

European OEM's have a self Imposed target of <140 gCO2 By 2008

The OEM value equation is Saturating out as hybrid Electric fraction exceeds ~40%



Source: Ricardo

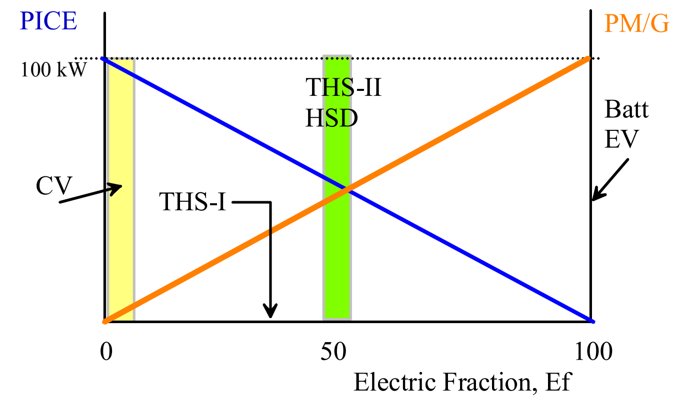
Hybrid Propulsion System Evolution

- Performance today is finally becoming on par with customer expectations from their vehicles as seen from the following comparison.
- The benchmark on conventional vehicle performance is ~10 kW/125 kg

Vehicle	Curb mass	Engine Power	M/G Power	Electric Fraction	Peak specific power
	(kg)	(kW)	(kW)	(%)	(kW/125 kg)
Civic	1242	63	10	14	7.35
Prius	1254	53	33/10	38	8.6
Escape	2053	80	65/28	45	8.8
HSD	1295	57	50/10	47	10.3

Illustrations of Vehicle Energy Recuperation

- When EF→ 50% a condition of Synergy is achieved between ICE & M/G



- Now lets look at some energy regeneration

  Concept vehicles of recent vintage

- Toyota ES^3 Concept Vehicle

4 cyl, 1.4 liter, TDI

Lock-up torque converter & CVT

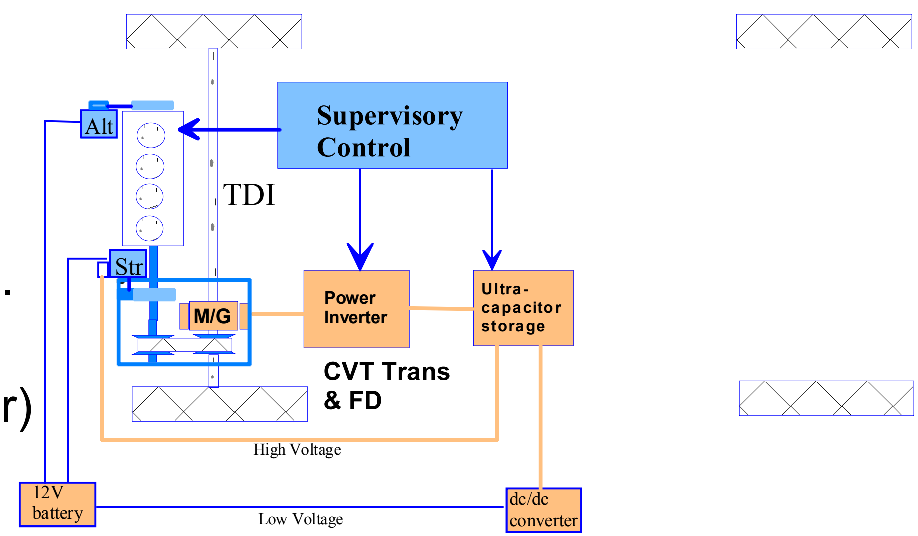
Idle-stop strategy

Brake energy regeneration

Ultra-capacitor energy storage sys.

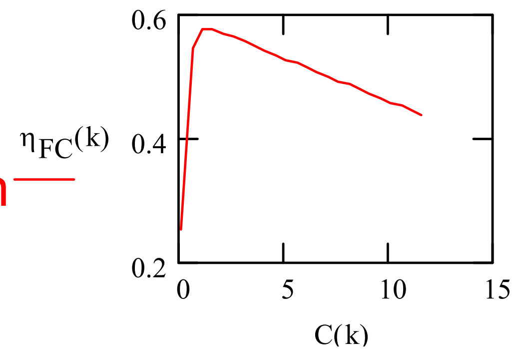
<2.7 liter/100 km (EC mode)

Meets Euro Step IV (with low sulfur)

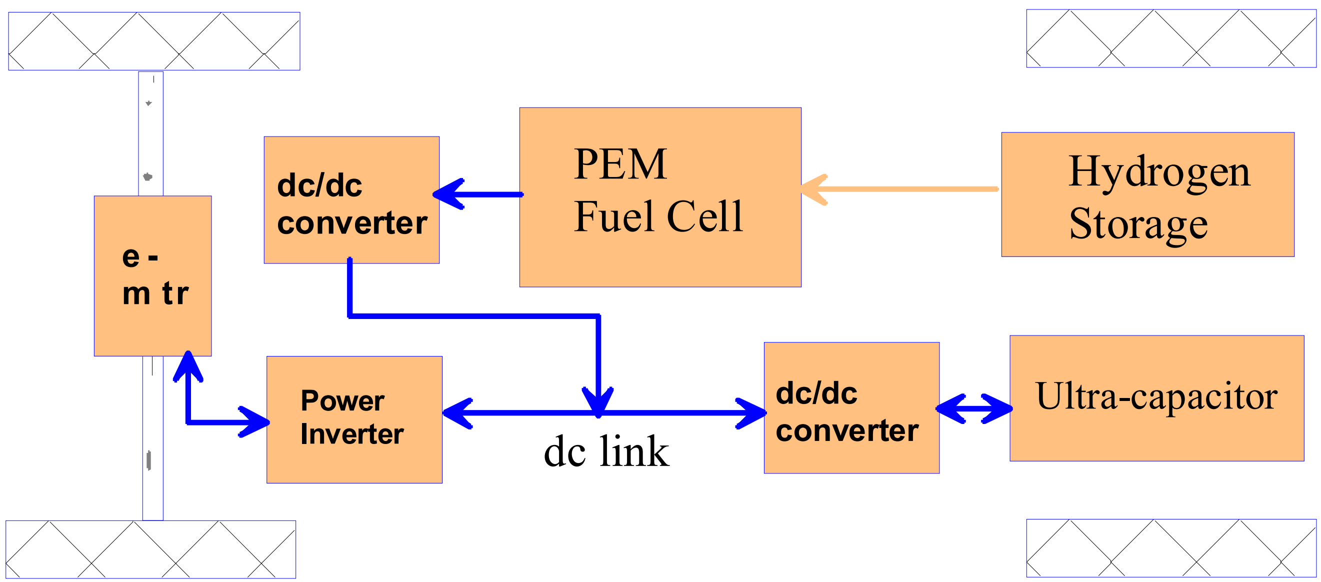


Illustrations of Vehicle Energy Recuperation

- Paul Scherrer Institute & ETHZ FCHV
- 48 kW FC + 360 Wh UC bank
- UC delivers 50 kW peak power for 15 s launch
- FC 10%→90% ramp time still ~ 10s
- 75 kW traction motor (360 V dc link)

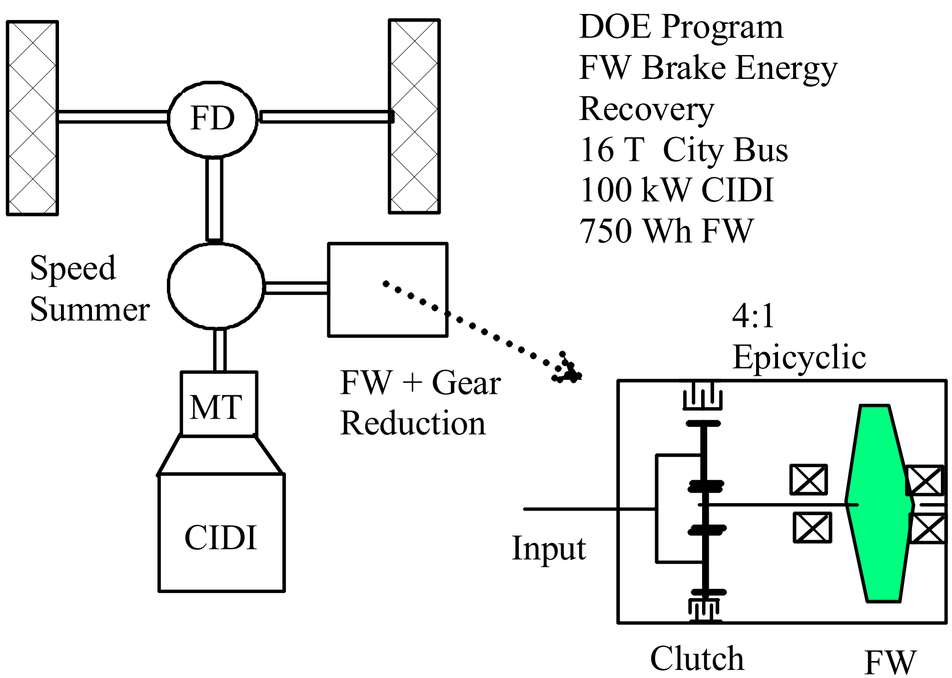


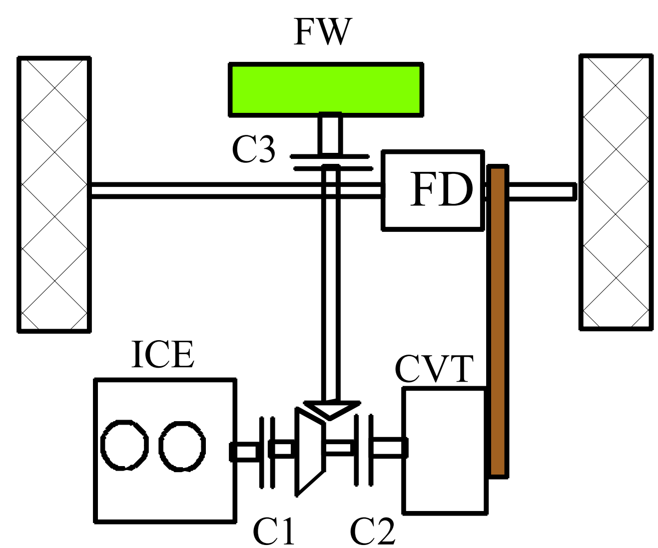
Fuel Cell Eff.
Highest at part
Load and drops
With incr. current
Water condenses
And chokes
Reaction sites



Illustrations of Vehicle Energy Recuperation

- Early systems using Flywheels and Battery + Flywheel Combinations
- In late 1970's DOE funded the build of city bus prototype vehicles that used brake energy recuperation to reduce fuel consumption
- Most of these propulsion architectures relied on hydrostatic transmissions (power split) with flywheel energy recuperation and launch assist.

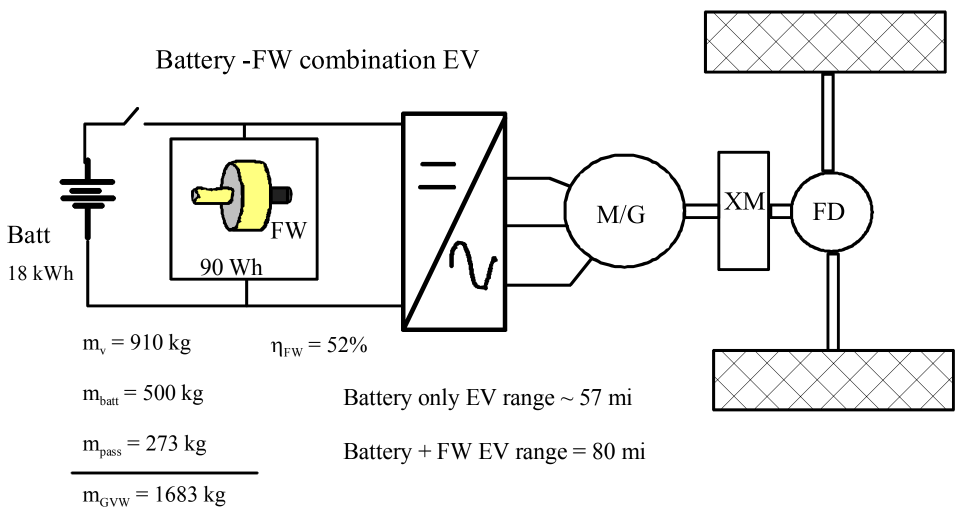


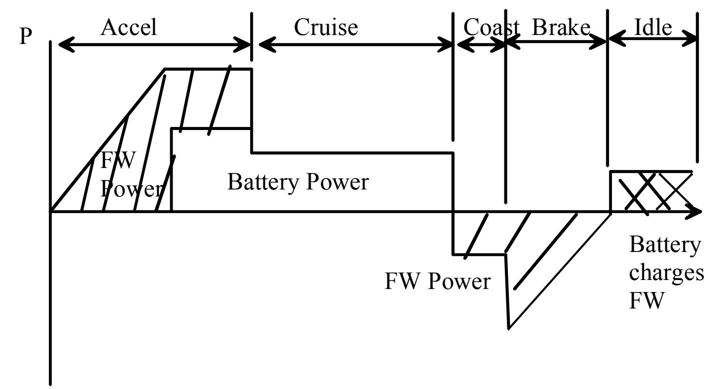


Reference: Flywheel Technology Symposium, Scottsdale, AZ, Oct. 1980
S.V. Kulkarni paper & N.H.Beachley
A.A. Frank paper.

Illustrations of Vehicle Energy Recuperation

- Vintage 1970's automotive system developed around Battery & Flywheel energy Storage system (Ref. Flywheel Technology Symposium, Oct 1980. paper by N.H. Beachley, A.A. Frank, "Control Considerations for a Flywheel Hybrid Automobile With a mechanical CVT")





Note:
Steel rotor FW's 3-5 Wh/kg
Composite FW's 10-15 Wh/kg

Are Ultra-capacitors a viable technology as a vehicle energy regenerator?

- Ultra-capacitors today still have an ESR double the threshold value necessary for ultra-capacitors to meet automotive ESS efficiency targets.
- The energy storage system in a power assist hybrid is sized to deliver acceleration performance, generally for the t_{z85} target (see [2] in paper).
- Consider the case of an energy storage system, ESS, for an SUV power assist hybrid that is required to meet a 90% ESS efficiency:

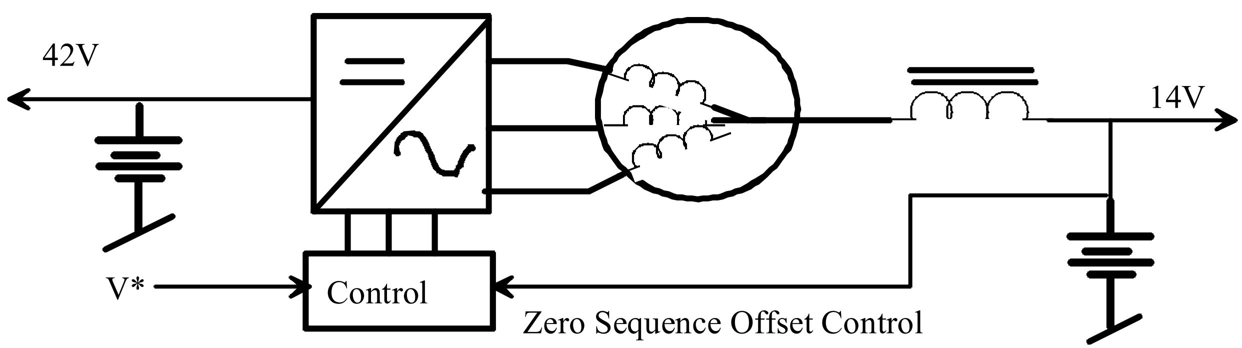
403 Wh energy and 94 kW of peak power for 21s(t_{z85})

	Capacity, Wh	Available Energy, Wh	# cells	Cell rating	Total mass, kg	Total Volume, liter	Pack eff, %	R_{cell}, mΩ	R_{cell} for η=90%	Reduction factor
Li-Ion	2596	1560	144	4.33 Ah, 4.15V	41	9.62	77.8	2.8	1.408	0.502
Ultra-cap	597.6	403.4	226	2700 F, 2.7V	135.6	90.4	79	0.6	0.286	0.477

Compared to an ultra-capacitor a Li-Ion pack is lighter, but efficiencies virtually track. Also, the necessity to decrease ESR by a half is evident in both cases.

Capacitors in lieu of magnetics: A new thrust in the high voltage→ 42 V → 14 V power conversion area

- Firstly, we can assume that ultra-capacitor materials and process improvements will meet the challenge of cutting ESR by half or better.
- With improved ultra-capacitor performance a new frontier of "magnetics-less" components opens up that shows promise of reducing ON-cost and package size and of improving efficiency.
- Secondly, it is apparent that new techniques are being developed that realize dual and even triple functionality out of existing hybrid components:
  - Consider the Toyota Crown THS-M next generation concept M/G with integrated 42V/14V converter

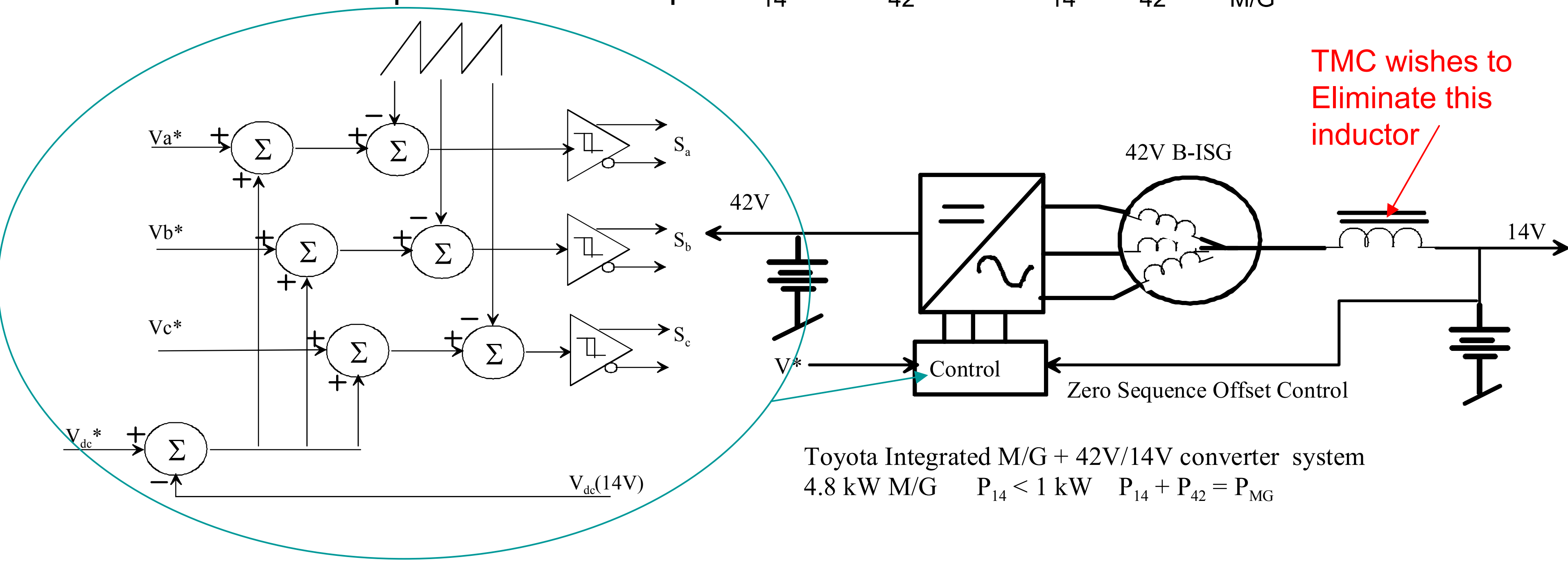


Toyota Integrated M/G + 42V/14V converter system
4.8 kW M/G $P_{14} < 1$ kW $P_{14} + P_{42} = P_{MG}$

Reference: MIT/Industry Consortium Program Rev Meeting, 5-6 March, 2003 Paper by Kimitoshi Tsuji Toyota Motor Co.

Present Trends to Increase Hybrid Component Functionality: Toyota Crown THS-M Concept

- Concept 42V/14V converter using zero sequence offset control in existing 42V, 4.8 kW, Motor/Generator in Belt-ISG configuration
- Full capability of the M/G is realized:
  - 42V power to crank the engine
  - Generates power as dual output: P_{14} and P_{42} where $P_{14} + P_{42} = P_{M/G}$



Toyota Integrated M/G + 42V/14V converter system
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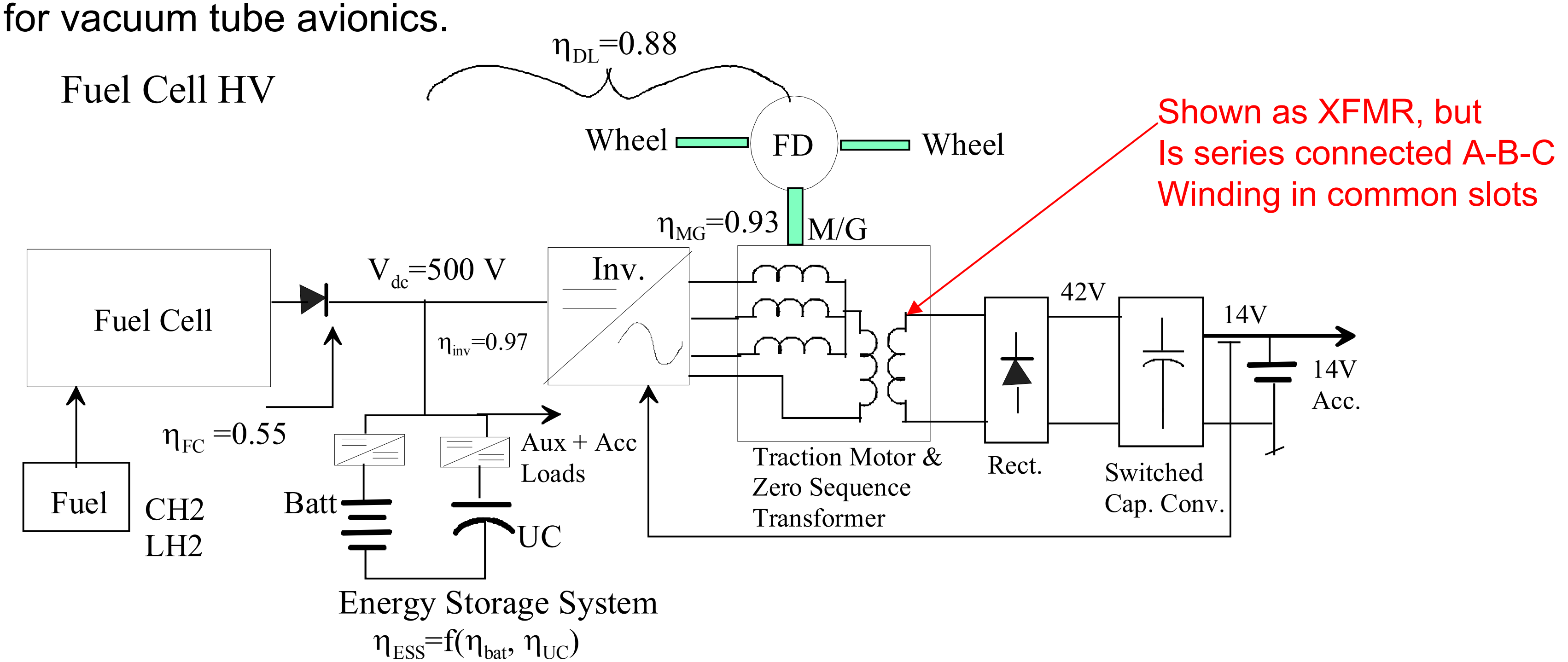
Integrated Regenerative Energy Processing Vehicle Propulsion Architecture

- Propulsion system proposal that further develops the concept of increased functionality of existing magnetics components
- Traction motor is now both a propulsion component and an energy conversion component without adding mass or increasing package volume.
- Concept of dual windings in common slots is not new. Electro-Craft Corp in the 1960's used this in their Mototronic M/G and military used in 28V →300V converters for vacuum tube avionics.

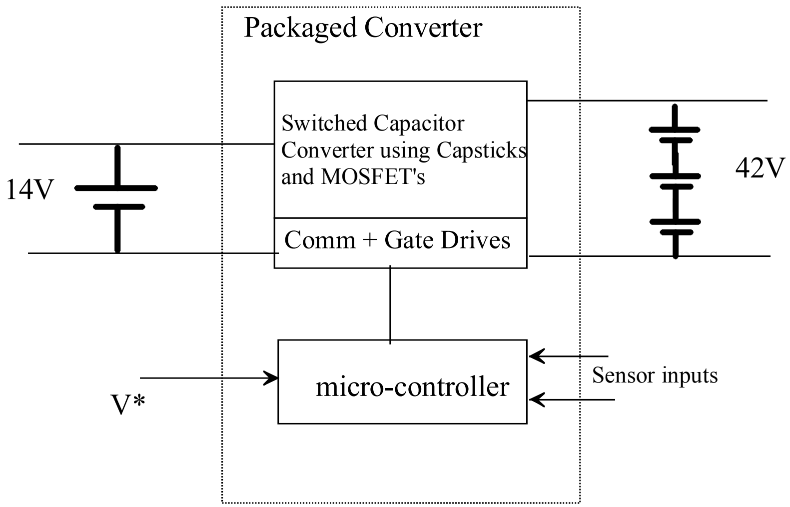


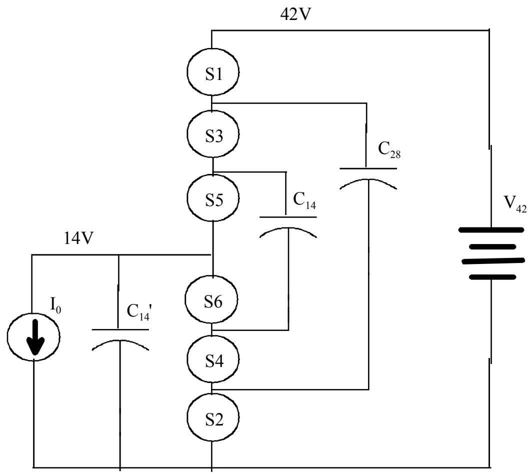
Integrated Regenerative Energy Processing Vehicle Propulsion Architecture

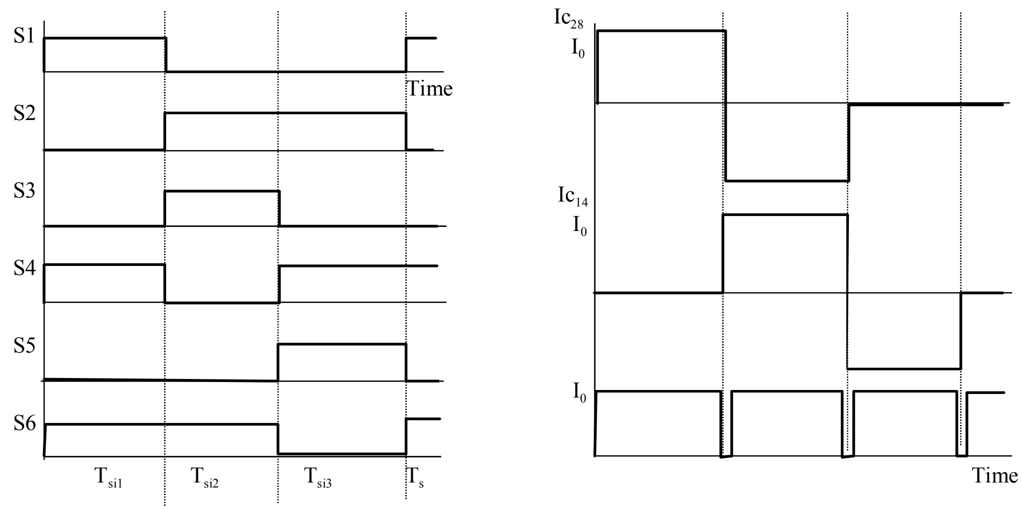
- In this system the vehicle traction system high voltage (200V → 500V) is converted to 42V power for vehicle ancillaries (chassis and HV supporting subsystems)
  - Zero sequence winding is a series connection of a second winding across the three phases.
  - With the appropriate turns ratio the output of this zero sequence winding provides an output at 42 V when full wave rectified.
- The integrated regenerative energy processing architecture uses a battery + ultra-capacitor ESS in much the same manner as the 1970's DOE system employed a battery + flywheel.
- Since OEM's still require 14 V for all legacy systems it is now necessary to add a further power conversion stage, a 42V/14V converter.
- The concept of a switched capacitor converter will realize the no new magnetics and provide dc transformer action.

Switched Capacitor Converter for 42V/14V

- Capacitor only converter. Active switches are used to transfer packets of charge between a set of three capacitors, each charged to 1/3 the high side potential.

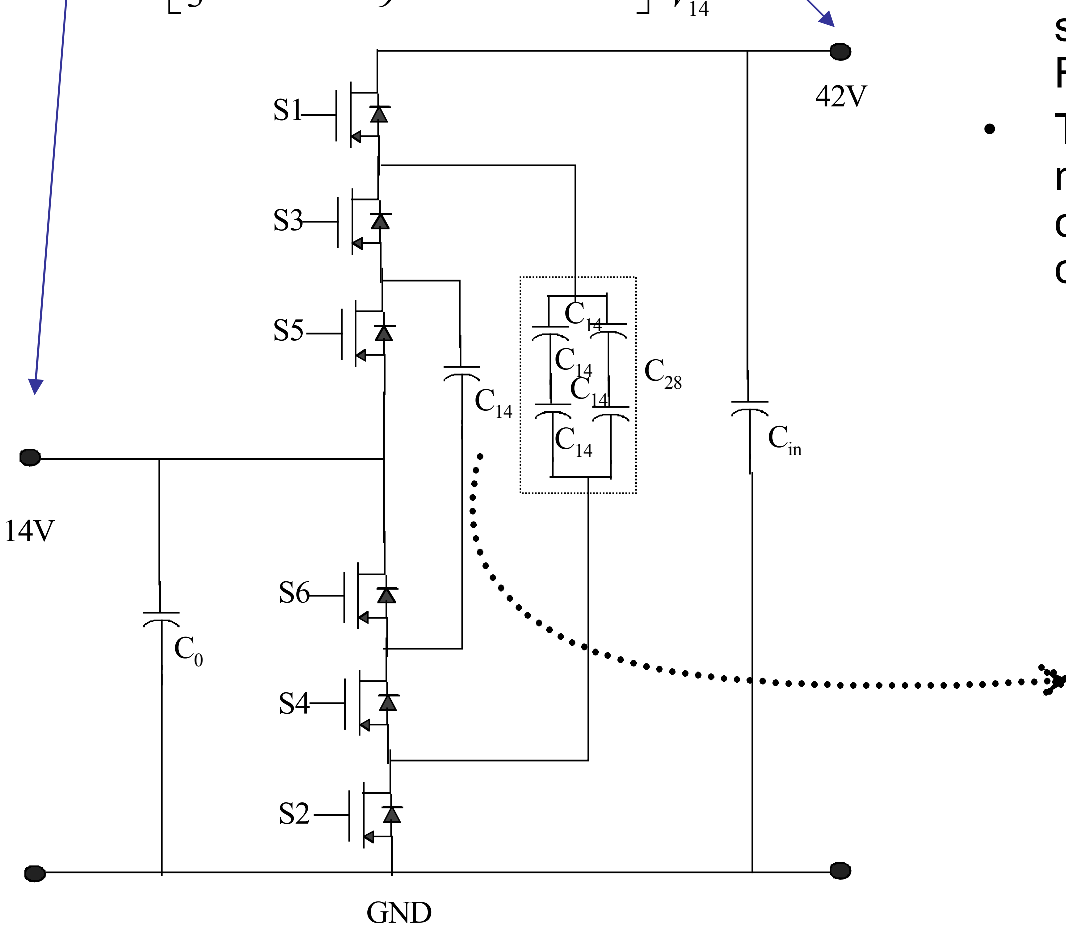




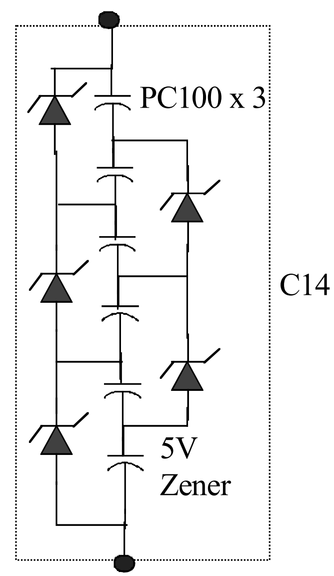


Switched Capacitor Converter for 42V/14V

$$\eta = \frac{1}{1 + \left[\frac{2}{3}R_{ds}(ON) + \frac{4}{9}\left(ESR_{14} + ESR_{28}\right)\right]\frac{I_{o(14)}}{V_{14}}}$$



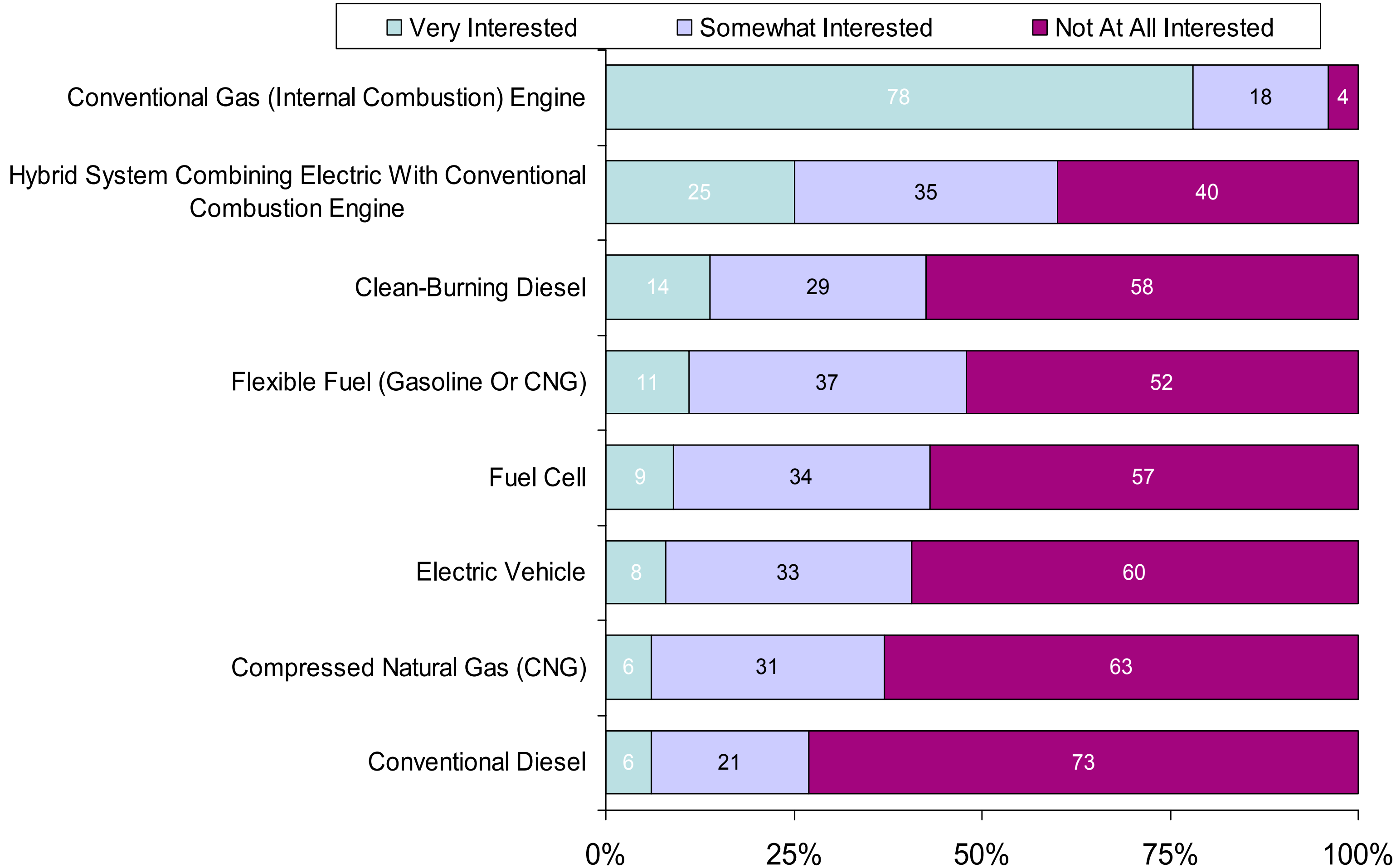
- Low voltage MOSFET's are used, such as IR Direct FET's, having $R_{ds}(ON) < 5\ m\Omega$
- The energy transfer capacitors again must have low ESR since two capacitors in series contribute to continuous losses.



Conclusions

- Several trends are evident in the arena of hybrid power and propulsion systems:
  - Large penetration hybridization is centered in Asia-Pacific region with a focus on diesel in Europe and refined ICE's in NA.
  - 42V as the next generation automotive electrical system is floundering in NA, followed by Europe, but is alive in Asia-Pacific (THS-M and successors)
- Each propulsion technology has its merits, but also strong cost obstacles
  - Diesel must meet particulate matter emissions levels. ES^3 diesel does, but only when using an ultra-capacitor energy regenerator and idle-stop strategy
  - ICE's in NA may trend to hydrogen fuel to meet 2008+ emissions targets, but H2 reduces ICE output by 30% to 50% → hybridization is needed as augmentation
- Strong ON-cost pressures and demand for package reduction are resulting in the use of higher bus voltages (THS-II is at 500V)
  - THS-II Hybrid Synergy Drive uses a boost converter (200V → 500V)
- Demand is strong for magnetics-less power conversion
- For ultra-capacitors to mesh with these new trends its ESR must be halved

Drivers for hybridization: Customer pull



Source: Delphi