Ultra-capacitor Assisted Battery Storage for Remote Area Power Supplies: A Case Study

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Abstract: **Remote areas power supplies (RAPS), with their crucial requirement for good inverter input voltage regulation, differ markedly from other applications such as uninterruptible power supplies (UPS), electric vehicles (EVs) and hybrid electric vehicles (HEVs). Also, the overall cost of remote area power supplies is significantly affected by the life expectancy and the cost of associated battery storage. Ultra-capacitors can be used to smooth battery current demand. A smoother current demand results in a steadier inverter input voltage. There are also claims that a smoother current demand profile improves the life expectancy of lead acid batteries. This case study aims to quantify the potential benefit of ultra-capacitor assisted battery storage. It is shown that significant benefits are possible if ultra-capacitors are used together with lead-acid or nickel iron batteries.**

I. INTRODUCTION

Reviewing available and emerging technologies for remote area power supplies, it is found that all such power sources suffer from some form of degradation and/or energy loss that need to be minimised, or at least optimally alleviated to achieve competitive life cycle costs. These energy source problems can be categorised as:

Type (i) Accumulated degradation: Examples are: inherent corrosion, interface material changes or repetitive start-up and shut down that seriously reduce long term life of the system or its components.

Type (ii) Base load requirements: Here energy sources require a significant continuous base load to allow longevity to be achieved in critical components.

Type (iii) Efficiency with load demand: Some energy sources or energy converters have to be near full load to achieve optimal efficiency.

Type (iv) Output voltage stability: The natural voltage stiffness of some energy sources may not meet the requirements of applications such as RAPS. Voltage ‘stiffness’ and stability is of prime importance to operate off the shelf domestic or commercial appliances.

Type (v) Mismatch between energy availability and load demand profiles: The availability of energy from renewable sources does not normally match the daily or seasonal energy demand cycles.

The following energy sources were investigated in terms of the above categories with the aim of identifying storage systems that would help alleviate their inherent limitations.

- Photovoltaic (PV) solar cells (Si, CdS/Te, CIGS, Dye), with efficiencies of 8 – 18%, provide energy from a sustainable source, but availability of supply is subject to variability of isolation level. Life expectancy is of the order of 20 – 30 years. Photovoltaic energy sources have characteristic limitations categorised as types (iv) and (v) above.
- Wind generators, with 25 – 35% efficiency, are supplied from a sustainable source, but energy availability is limited by variability in wind speed profiles. Life expectancy is about 20 years. Wind energy sources have characteristic limitations categorised as types (iv) and (v) above.
- Diesel internal combustion engines using LPG, CNG, biogas, bio-diesel or mixed fuels including hydrogen operate at typical peak load efficiencies of 20% to 40%. Life expectancy is around 25 years, but offline overhaul maintenance is needed every 5 – 8 years. Highest efficiencies for medium speed to high speed stationary engines occur at 70% to 80% full load. Diesel internal combustion engines have characteristic limitations categorised as types (ii) and (iii) above.
- Solid Oxide Fuel Cells (SOFC), using fuels such as hydrogen, LPG, CNG, and biogas and operating in co-generation mode to produce domestic hot water have claimed 35 – 45% efficiencies. Life expectancy is up to 5000 hours. Operational temperatures range from 750°C to 950 °C. SOFCs require a mandatory base load. Frequent start-up and shutdown can seriously degrade SOFC operation and reduce life expectancy by an order of magnitude. SOFC have characteristic limitations categorised as types (i) and (ii) above.
- PEM fuel cells can use hydrogen, methane, methanol, or ethanol as fuel. Due to fuel purity requirements of greater than 99.9999%, PEM cells are likely to require major overhaul every 3 to 5 years. Also early degradation of the PEM film can occur as a result of sudden load changes. These cause hotspots as a result of uneven formation and coalescent of the water droplets when ancillary equipment systems do not handle the increased water vapor formation at high load change rates. PEM fuel cells also have poor output voltage stability. Typically, doubling the current demand will halve the voltage output. To date, this has limited the application of PEM fuel cells to experimental EVs or HEVs. PEM fuel cells have characteristic limitations associated with types (i), (iii) and (iv).

Many of the above listed limitations, which affect RAPS applications in particular, are overcome by the use of battery storage. For remote sites, the choice of battery type critically affects overall life cycle costs. In general the more geographically remote the RAPS application is, the more cost effective a low maintenance long life system becomes.

II. SURVEY OF BATTERY TYPES FOR RAPS

Table I in the Appendix presents a summary of characteristics of the following major battery types [1]: Lead acid (all types), Edison (Ni-Fe), NiCad (Ni-Cd), Nickel Metal Hydride, Vanadium Redox and Zinc Bromine flow batteries, Zinc-Air and Iron-Air and the CSIRO Furukawa Battery's Ultra-battery. On the basis of the listed battery characteristics in Table I, and using the criteria of interest for RAPS, such as life expectancy, robustness and resistance to negligent maintenance practices, life costs for remote community application, and commercial availability – the lead acid sealed gel battery and the Edison Ni-Fe battery were short-listed as the most suitable candidates for this study. The lead acid gel sealed battery, which is virtually maintenance free besides periodic equalisation charge requirements for large strings, is the most cost effective by far. The NiFe battery, on the other hand, was chosen because of its exceptionally long life of over 30 years, its robustness, and its ability to handle total discharge. Also, provided watering is adequate, it is not damaged by overcharging. Ultra-batteries and flow batteries were not considered further because they are not commercially available. Referring to Table 1 in the appendix, it can be seen that the major concerns regarding the two chosen batteries are:

- Battery life in the case of the lead acid battery is limited, and the manufacturer's recommended depth of discharge (DOD) must be kept below an average maximum of 20% for RAPS application. DOD and charge regime are parameters that severely limit the life of this battery. During this lifetime of deep discharge cycling, in order of importance, the principal reasons for failure are: accumulation of effects of sulfation, grid interface damage, grid corrosion and loss of active material capacity, leading to the need for battery replacement every 3 to 5 years [2-6]. EV and HEV standardised testing for high step loads and high start currents surges, have in some extreme cases resulted in the reduction of life from 900 to 50 cycles.
- NiFe (or Edison) batteries on the other hand, have excellent robustness, and the ability to be almost totally discharged without any risk of damage. However, when used with an inverter, short duration high demand current surges may, due to their higher internal resistance, reduce the battery rail voltage below that of the allowable inverter input limit, resulting in shutdown of the inverter. The NiFe battery also has a lower Wh efficiency of 60 % compared to 75% in the lead acid battery, highlighting their higher internal resistance.

III. ULTRA-CAPACITORS

Commercially available ultra-capacitors have a life expectancy of 50,000 to 100,000 cycles. Compared to batteries, they can deliver very high discharge rates. Their energy efficiency is of the order of 80%. However, the following comparison highlights the fact that the major weakness of the ultra-capacitor is its cost per unit of recoverable stored energy.

- $0.50 to $1.10 per Whr for lead acid, total discharge. Multiply by 5 for a DOD of 20%.
- $1.50- $2.20 per Whr for Ni-Fe, total discharge
- $780K per Whr for a 2.7 Volt, 3000 Farad ultra-capacitor, 25% energy discharge.

Despite the high capacitance, the currently available ultra-capacitors have a low voltage rating making series connection essential to achieve useful voltages. The abovementioned two characteristic limitations point to restricted roles for ultra-capacitors. Potentially, they can cost effectively assist batteries by relieving them from having to supply short duration high current surges or they can be used to buffer the batteries from sharp step changes in current demand. This is detailed further in Section VI.

IV. CASE STUDY – RAPS LEAD ACID AND NICKEL-IRON BATTERIES LIFE COSTS

For a remote community or family, a photovoltaic array or IC engine power source would be a typical option. Here the PV system is sized to the recognised standards [7] [8] to provide sufficient power for daytime use, plus charge the batteries during the normal lowest seasonal solar insolation level. Similarly, for the IC engine to be most efficient, the engine would be run during the day to satisfy normal demand as well as for battery charging to prepare the battery for the 12 hour evening to morning period when there would be less tolerance to noise. For this case study, only the daily storage cycle is considered. For a domestic family in a remote area, assuming all loads are electrical, with the exception of cooking and water heating, a typical battery current demand curve is shown in Fig. 1 for a 12V battery storage.

This load profile in Fig. 1 is for the running of lights, water pump, entertainment, ventilation fans, kitchen appliances (including microwave), refrigeration, washing and parasitic load of the inverter itself. There is an example of a rapidly changing current in the very early stage of the load demand that would correspond to a conventional microwave cooking at

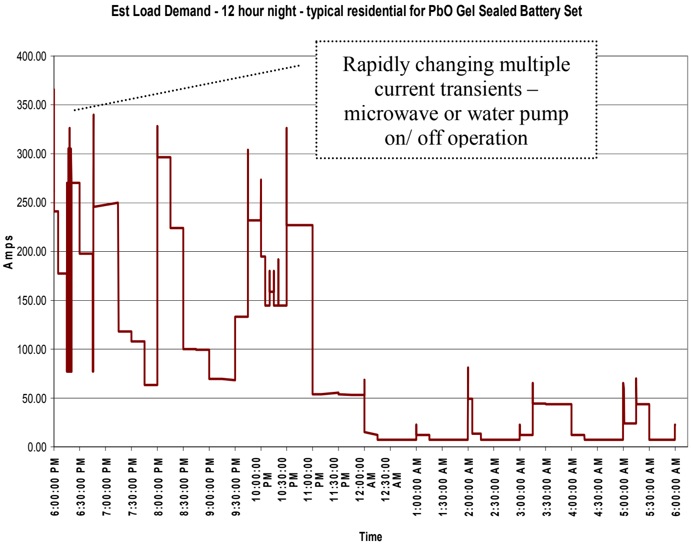

Figure 1: Typical 12 Hour Night Period Domestic Load Demand

less than 100% power or to a water pressure pump with low flow rates stopping and starting. Assuming an 85% average conversion efficiency for the inverter, the daily demand is worked out to be 1000Ahr. The current demand includes several load steps of up to 300A. There is a daily total of eleven short duration surge current demand, or 4015 current surge events per annum that are above 225 Amps. The latter half of the night reflects much lower usage. Fifty per-cent of the energy demand occurs before 9 pm, with a further 40% occurring prior to midnight. It is during this latter demand period from 10pm to midnight that the inverter is likely to drop out because of low input DC voltage, particularly in the case of the Ni-Fe battery. Increasing the capacity of the Ni-Fe battery will solve this problem, but this increases the capital outlay. For the lead acid batteries, there is a different set of limiting parameters. On top of handling the repeated daily eleven (11) transient peak currents that adds to degradation and consequent premature aging through accumulated loss of lead grid to active plate material, it is necessary to keep the total DOD to below 30% of battery capacity. Typical domestic RAP current demand makes it unlikely for these batteries to reach their design life of 3.5 years. A life expectancy of 2.5 to 3 years is more realistic unless the installed battery capacity is over and above what is for daily storage.

V. INITIAL OPTIMAL BATTERY SIZING

For remote area power supplies, long and robust system life, with minimal capital and replacement costs are of primary concern. The more geographically remote the RAPS application is, the longer is the life expectancy that will be sought. A 10, 20 or 30 year life is normal considerations depending on just how remote the RAPS application is. The same domestic load demand curve of Fig. 1 is the basis for the following comparative analysis between lead acid and Ni-Fe batteries. It is notable, that generally different energy storage systems are required to best match different energy sources or energy converters. As an example solar cells have a life expectancy of 30 years or more, whereas fuel cells may require PEM membrane replacement every few years. For this study, PV or IC engine generation ,or combinations thereof, are considered the likely scenarios for a typical remote Australian inland domestic dwelling, or emerging nation remote community centre that have no power grid connection available.

A. Lead Acid Battery Life Costs

These can be costed by using the battery manufacturer's data. Published data on cycle life versus DOD was used to find the life expectancy for a deep cycle valve regulated gel lead acid battery set. Using the domestic demand curve example already described, it is found that 1000Ahr per daily cycle is required from 12V supply is required. This can be used to calculate the expected life expectancy in years for different depths of discharge of ranging from 10% to 60% and for different RAPS system design lives of 10, 20 and 30 years.

In this example, pairs of two series connected standard 6RA225 [6V, 225 Ahr C(8)] sealed gel lead acid battery blocks are used to achieve the 12V supply requirement. As shown in table II, the total number of blocks depends on the allowable depth of discharge. The calculation method is based on a 'best case' scenario, as most lead acid batteries with surge and step loadings succumb due to internal lead grid interface problems before the design life is reached. Therefore all battery blocks required and number of battery set replacements per period are rounded up to a whole number. Option three, with 30% DOD, is the optimum cost option. However, taking into account many deep cycle battery manufacturers' warranty condition of 20% maximum DOD, option 2 may have to be adopted instead.

TABLE II. LEAD ACID BATTERY CYCLE LIFE COSTS VS. DOD

From RA6-225 Manufacturers Data Sheet for this 6V 225 Amp hour C(8) rate battery					**Number of Sets required per period (Yrs)**		
PbO Option	Est Battery PbO size Ahr capacity		Expected life based on 1 cycle per day	Number of battery blocks	10	20	30
1	@10% DOD =	9999.00	6.00	46	2	4	5
2	@20% DOD =	4999.5	3.84	22	3	6	8
3	@30% DOD =	3333.0	3.42	16	3	6	9
4	@40% DOD=	2499.8	2.47	12	5	9	13
5	@50% DOD =	1999.8	1.42	10	8	15	22
6	@60% DOD =	1666.5	1.10	8	10	19	28

Direct Costing Cycles Battery Infra-structure for each option					Corresponding discharge
PbO Option	10 Year Planned Life	20 Year Planned Life	30 Year Planned Life	Comment	C(8)
1	$ 45,724.00	$ 91,448.00	$ 114,310.00		621
2	$ 32,802.00	$ 65,604.00	$ 87,472.00		297
3	$ 23,856.00	$ 47,712.00	$ 71,568.00	Optimal	216
4	$ 29,820.00	$ 53,676.00	$ 77,532.00		162
5	$ 47,712.00	$ 89,460.00	$ 131,208.00		135
6	$ 39,760.00	$ 75,544.00	$ 111,328.00		108

Future Value Method of Costing PbO Battery Infra-structure for each option applying the average rate of discount of 3.9% (from ABS figures since 1994 to present)					
PbO Option	10 Year Planned Life	20 Year Planned Life	30 Year Planned Life	Comment	C(20)
1	$ 35,480.56	$ 61,579.39	$ 59,376.00		269.1
2	$ 26,353.54	$ 34,983.21	$ 50,614.23		128.7
3	$ 18,879.80	$ 31,849.48	$ 40,816.57	Optimal	93.6
4	$ 25,043.71	$ 37,698.68	$ 40,236.18		70.2
5	$ 41,825.67	$ 69,923.76	$ 88,799.79		58.5
6	$ 36,160.81	$ 66,118.16	$ 86,243.22		46.8

If a discount rate is applied to future spending, as expected, higher % DOD are favoured. With a 3.9% discount rate, which is the average value from the Australian Bureau of Statistics (ABS) from 1994 to the present, optimum cost remains within option 3 for the 10 year and 20 year planned life but shifts to 40% DOD for the 30 year planned life. Again warranty conditions may still dictate the choice to be option 2.

To further check the suitability of Option 3, the C(20) discharge rate is 90.6 Amps. The IEEE Std 1013-2007 [7], Section 8 (c), recommends that momentary load values, particularly those near the end of discharge cycle should correspond to the C(20) rate. However, for this domestic load 50% of load demand is prior to 9.30 pm, and between 9.30 and 10.30pm where another 30% of the load demand is taken up, there are 3 momentary load spikes corresponding to a range between 250 A and 350 A.

Calculating the internal battery impedance, from the individual 6V cells of 4.0 m-Ohm, into 8 parallel strings of 2 in series batteries, Option 3 lead acid battery set will yield an internal resistance at 25°C of 1.0 m-Ohm. There is also an estimated 0.3V drop for lead connections.

For a momentary current load spike of the order of 340A between 9.30 pm to midnight, this will correspond to a 0.34V internal battery voltage drop at room temperature. So allowing about a 0.3V loss for lead connections, the battery must remain above 11.14V at all times during this period, to prevent a low voltage inverter disconnect. With a 30% DOD of discharge, the terminal voltage should remain above this when the battery is fully charged with its full new capacity rating. However as the battery ages and looses capacity, the problem of transient LV inverter alarm disconnection will begin to occur.

B. Ni-Fe Battery Life Costs

Table III provides details of the 10 x 1.2 V cells that are required to produce a suitable 12 V supply.

As can be seen by this, the cost of the Ni-Fe battery for the long cycle life are significantly below those of the lead acid, based on the ability of the Ni-Fe not being limited by DOD requirements. However, reviewing the general discharge characteristic of the 1220Ahr Ni-Fe (Alternative 1) for a C(4) to C(8) discharge rates in Fig. 2, where 90% of load demand occurs - reveals that the battery will have a terminal voltage of 0.9 to 1V per single cell after a 6 hour discharge period, corresponding to 9V to 10V for the entire series set. This makes the use of alternative impractical with an inverter, where a low voltage drop out at 10.5V will occur in spite of the DOD not being a problem.

TABLE III. NI-FE BATTERY COST FOR CYCLE LIFE > 30 YEARS

Ni-Fe Alternative 1:
1220 amp hour, 12 Volt string of cells of European origin with a life expectancy over 30 years
Total Supply Cost = $ 16,524.59

Ni-Fe Alternative 2:
Australina Asian Origin Ni-FE batteries with a life expectancy of 40 years
2 x 800 Amp-hour 12 Volt Strings to give a 1600A-hr battery
Total Supply Cost = $ 19,901.64

Ni-Fe Alternative 3:
2 off 1220 amp hour, 12 Volt strings of cells of European origin with a life expectancy over 30 years 2440 Ahr capacity
Total Supply Cost = $ 33,049.18

This can be offset, for example by increasing the Ahr battery capacity, but checking the battery internal resistance for the other two alternatives provides for a 340A momentary spike occurring between 9.30pm – 11.30pm in the load demand curve:

- Ni-Fe Alternative 2: 1600A-hr battery internal resistance of 2.5m-Ohm giving 0.85V internal voltage drop.
- Ni-Fe Alternative 3: 2440A-hr battery internal resistance of 0.82mOhm giving 0.27V internal voltage drop.

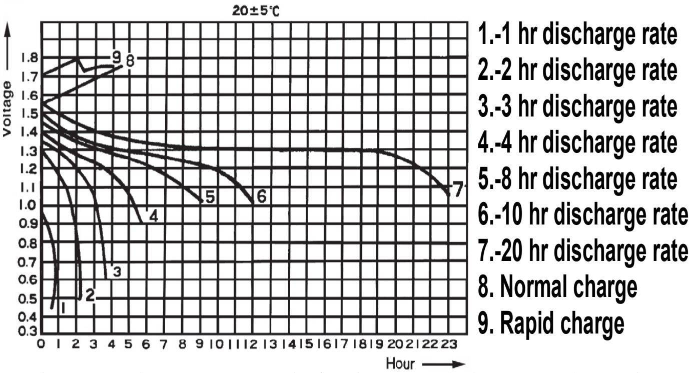

Figure 2: Ni-Fe Battery Terminal Voltage vs. Discharge Rate (1.2 Volt Nom. Cell)

So increasing the capacity of the battery allows for the voltage spikes to be better tolerated, and inclusion of the lead and connection voltage drop of 0.3V requires alternative 2 to provide a minimum terminal voltage of 11.65V and alternative 3 to provide 11.07 V. This would prevent the inverter to drop out on low voltage. Alternative 2 is still marginal preventing inverter low voltage drop out during the period of 9.30 pm to midnight.

VI. ASSISTING BATTERY DISCHARGE WITH ULTRA-CAPACITORS

Now, could ultra-capacitors, even with their high cost per kW-hr, economically assist these batteries in dealing with their internal voltage drops during high transient peak currents? One recent prominent development example in the use of ultra-capacitors has led to the first battery hybridisation in the CSIRO Furukawa Battery's Ultra-battery [5]. This hybrid technology alleviates damage caused by high demand transients on battery supplies [6]. High transient current demands cause damage to the Pb grid collector to active material interface, as well as potential loss of active plate material which results in severe reduction in life expectancy of the battery. This is a useful battery for HEVs, where battery stiff line voltage and continuous deep discharge are not part the requirements. For use in RAPS, as an example, the voltage of a nominally 12V battery must stay between 10 to 17V for high quality inverters, and 10.5 to 15.5V for standard inverters which are meant for 240V domestic or remote community use. The Ultra-battery is not particularly suitable to RAPS applications because:

1) Energy is returned to the inbuilt ultra-capacitor only when the battery is recharged. In the RAPS application being considered, battery recharging does not happen for at least 12 hours during which multiple current surges have to be supplied. Capacitor charging needs to intersperse those current surges.

2) The inbuilt ultra-capacitor can only discharge down to 10.5V which is the inverter low voltage limit. The ability of the ultra-capacitor to satisfy current surges diminishes as the battery discharges reaching zero at the inverter voltage limit.

Placing an ultra-capacitor outside the battery in parallel with the inverter input, with a charge / discharge circuit appears to be the answer for RAPS that are used in domestic and community applications. The control system could allow the battery to provide the general load current demand, while the ultra-capacitor could supply the momentary transients and help smooth step load changes thus maintaining the battery voltage above the LV drop out of the inverter. This would effectively extend the batteries' usable depth of discharge for RAPS applications.

The capacitance value needed can, for example, be calculated from the load cycle shown in Fig. 2. It is noted [9] that for domestic appliances with reactive loads profiles, disturbance durations due to direct on line starts last a maximum of 30 - 40 cycles of the 50Hz or 60Hz supply frequency. This equates to most disturbances being less than 1 second. The capacitance C required to satisfy a current demand of magnitude I and duration t is given by

$$C = (I \times t) / V \qquad (1)$$

Where V is the change in voltage.

For a 350A surge lasting 1 second, the capacitance needed, assuming discharge from 12V to 6V, is 29.2 F. To allow an ultra-capacitor to safely work within the input voltage range of an inverter, there would be a requirement for six (6) series connected 2.7 Volt 600 F ultra-capacitors. This arrangement would be capable of supplying 2 to 3 of the 350A, 1 second surges without having to be recharged. The capacitor charge circuit would also have to be able to restore sufficient charge for a series of multiple bursts over, say, a 10 second interval. The configuration in Fig. 3 is specifically chosen with the different placement of the ultra-capacitor compared to the CSIRO Furakawa Ultra-battery with the express purpose that it becomes part of the inverter input stage.

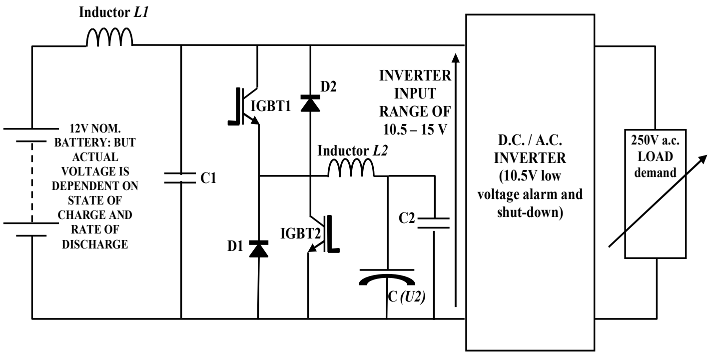

Figure 3: Ultra-capacitor assisted RAPS battery storage

Note: Capacitor C2 is added as a low ESR capacitor in parallel to act as a shunt for any higher frequency ripple to prevent damaging the ultra-capacitor due to high frequency ripple heating within. Without this, the ultra-capacitor has the potential to reach end of life up to 40% before its design life [10]. IGBT1, diode D1, inductor L2 and the ultra-capacitor C form a step down DC to DC converter which can charge the ultra-capacitor to a maximum voltage just under that of the battery. IGBT2, diode D2, and inductor L2 form a step up DC to DC converter that allows energy to be extracted from the ultra-capacitor regardless of its state of charge. While the power electronic circuit presented in Fig. 3 is essentially the one proposed Huták and Vorel [11] for EV or HEV applications, control requirements for RAPS applications are quite different. Of particular importance to RAPs application is the maintenance of input voltage of the inverter within a relatively tight tolerance. DC bus voltage regulation is not an important requirement for EV or HEV applications. The control strategy that will be adopted is essentially the hysteretic control of the battery current a set maximum allowable discharge rate using the on/off switching of the IGBT2. However, the novel outworking of this strategy is that this IGBT2 is switched to the off state to increase current; and to the on conduction state to decrease current supply from the ultra-capacitor to the inverter d.c. input bus. This is the inverse of normal current control.

VII. POTENTIAL ADVANTAGES WITH ULTRA-CAPACITY HYBRID RAPS BATTERY SYSTEMS

A. *Lead Acid Battery:*

As per the worked example of the lead acid battery, the 15 - 20% cost losses of cycle life due to high transient load or load steps would be recovered by using ultra-capacitor energy to assist the lead acid battery. The costs for such an input ultra-capacitor circuit are nominally $500 worth of ultra-capacitors and an estimated $2,000 for additional power electronics as an input module for the inverter. Taking into account end of life (EOF) considerations for the ultra-capacitor, and noting that there are nominally 4,000 cycles per annum of momentary currents, then the estimated life according to Maxwell for their capacitors [12] would be of the order of 16 - 20 years where the capacitance value would have reduced to 80% or less of rating, and the ESR would likely have more than doubled. So for the lead acid battery case, where RAPS systems life is 15 years or less, this would not be an issue, whereas if the RAPS system were a PV energy based system with and expected life of more than 30 years, then the ultra-capacitors would require replacement at the half-life. So based on this understanding, the overall investment cost saving would be 9 - 12.5% on average.

B. *Ni-Fe Battery:*

In this case, the cost saving in utilising Ni-Fe alternative 2 instead of Ni-Fe alternative 3 is $13,000 net for $3,500 investment in ultra-capacitors and power electronics and control. This would result in a 27% saving to give a total 30 year life cost for the Ni-Fe battery system of $23,500, noting again and accounting for the need for the ultra-capacitors to be replaced at the system half-life of 16 – 20 years

VIII. CONCLUSION

Preliminary findings from this case study point to significant potential benefits that could be realised with the use of ultra-capacitor to assist batteries forming part of RAPS systems. Cost savings ranging from10-12.5% for lead acid sealed gel battery applications, to 29% for Ni-Fe battery applications are potentially achievable. In the Ni-FE case, a step-up DC to DC converter operating as a voltage regulator between the battery and the inverter may result in additional savings. The Ni-Fe battery, assisted with ultra-capacitors, shows promise for an optimum economic solution where life expectancy of above 20 years is sought. For infra-structure life cycles of less than 20 years, the lead acid battery assisted by ultra-capacitors is the most likely optimum economic solution. Prototype systems are being put together to provide practical confirmation of the preliminary findings of this study.

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APPENDIX: TABLE 1: SUMMARY OF BATTERIES OF INTEREST CHARACTERISTICS FOR RAPS ENERGY STORAGE

RAPS application Deep Discharge Battery type	Life (yrs) / cycle	Anode	Cathode	Reaction mechanism	Self Discharge per week[2]	Recommended % DOD	Practical battery			Rec. C(A) Charge Rate	Overcharge ability	Efficiency	
							Nom. V	Specific energy Wh/kg	Energy density Wh/L			Ah %	W-hr %
PbO Sealed Gel	3 – 8 yr / 50-1500	Pb	PbO_2	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$	1%	<30	2.0	35	70	0.07	limited	90	75
Edison (Ni-Fe)	> 30 yr / > 4000	Fe	Ni oxide	$Fe + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)_2 + Fe(OH)_2$	7.5%	90	1.2	30	55	0.20	excellent	80	60
Nickel-cadmium	8 -15 yr / 500 - 2000	Cd	Ni oxide	$Cd + 2NiOOH + 2H_2O \rightarrow 2Ni(OH)2 + Cd(OH)_2$	5%	90	1.2	35	100	0.20	excellent	70	60
Nickel-metal hydride	2-5 yr / 300 – 600	MH	Ni oxide	$MH + NiOOH \rightarrow M + Ni(OH)_2$	7.5%	90	1.2	75	240	0.1	Limited	65-70	55 - 65
Zinc / bromine Redox Flow Battery	20 yr / >2000 cycles	Zn	Br_2	$Zn + Br_2 \rightarrow ZnBr_2$	N/A	95	1.6	70	60	Varies acc'd to design of active elec-trodes	N/A – once Zn is fully deposit-ed on carbon electrode charging ceases.	70	64.5
CSIRO Ultra-Battery	~3000 HEV cycles	Pb U-Cap	PbO_2	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$ & Carbon fibre matt with Anode	1%	30 – 70%	?	?	?	?	?	?	?