Second Life Battery Energy Storage Systems: Converter Topology and Redundancy Selection

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Abstract

Battery energy storage systems have traditionally been manufactured using new batteries with a good reliability. The high cost of such a system has led to investigations of using second life transportation batteries to provide an alternative energy storage capability. However, the reliability and performance of these batteries is unclear and multi-modular power electronics with redundancy have been suggested as a means of helping with this issue. This paper reviews work already undertaken on battery failure rate to suggest suitable figures for use in reliability calculations. The paper then uses reliability analysis to investigate six different multi-modular topologies and suggests how the number of series battery strings and power electronic module redundancy should be determined for the lowest hardware cost using a numerical example. The results reveal that the cascaded dc-side modular with single inverter is the lowest cost solution among the topologies.

1 Introduction

This paper looks at six different multi-modular converter topologies from a reliability, cost and voltage perspective and uses numerical analysis to determine the most appropriate topology for use with second life batteries connected to an electricity grid system at low voltage. In order to assess the different technologies it is necessary to deal with redundancy issues and comparative cost calculations between the six topologies. There is no easy closed form expression to do this, so numerical analysis has been used. This method of choosing a topology and its associated redundancy should be used as a guide because of the difficulty in getting comparative failure rate information.

The paper starts by looking at published failure rates of batteries and compares these to the failure rate of the power electronics. Typical values are then used within reliability and comparative cost calculations to determine the best way of connecting the batteries and what level of redundancy to use to meet a minimum power and reliability at lowest cost factor. Generally the failure of any battery bank and its impact on overall system reliability has not been considered to be significant compared to the power electronics. This is shown in publications where conventionally single-stage, two-stage and/or three-stage high frequency converter based topologies have been considered to be sufficient for energy storage applications [1] – [3] and where large numbers of series batteries (or series-parallel combination) form a battery bank before a line side converter interfaces with grid. This paper is different from previous work in this area because a representative failure rate of the second life battery is considered as being worse than the failure rates of the power electronics and associated components, therefore the battery needs to be included in, and in fact, dominates the analysis. The Authors looked into this issue [4] previously and determined for grid support applications a multi-modular converter could be the lowest cost option of meeting a fixed reliability compared to more conventional designs. This paper looks in more detail at multi-modular designs and uses reliability analysis to help decide the type of multi-modular converter, the module size and the level of redundancy.

2 Failure Rates

System reliability estimates can be found from component failure rate. The MIL-HDBK217F handbook [5] lists the approximate basic failure rate λ of electronic components along with factors to take into account operating conditions such as temperature or losses. The reliability can be found from the failure rate using (1)

$$R(t) = e^{-\lambda t} \tag{1}$$

The reliability of any system comprising different numbers of power stages can be expressed as in (2) where n is the total number of power stages and the term R_i corresponds to the individual reliability of the power stages.

$$R_m = \prod_{i=1}^{n} R_i \tag{2}$$

The reliability of a system with redundancy ($R(k,n)$) of 'k-out-of-n' form) can be calculated using equation (3)

$$R(k,n) = \sum_{i=k}^{n} \binom{n}{i} {R_m}^{i} (1 - R_m)^{n-i} \;\; \forall\, n \geq k, \tag{3}$$

2.1 Battery failure rate

The remaining quality and life span of a battery after its first life can be dependent on a number of factors including, but not limited to; the battery chemistry, the number of cycles, the discharge current, the State of charge (SOC) or Depth of discharge (DOD) swing, and the cell temperature. There exists many publications looking at some or all of these variables for a range of chemistries under a variety of lab based conditions. Typically the temperature is held to be constant (either ambient or around 45°C-50°C) with either a constant charge-discharge regime to a set SOC or DOD or a constant drive cycle. Battery chemistry and even the same chemistry from different manufacturers due to different manufacturing processes show differences in life cycle, failure modes and capacity fade. In addition to the other factors listed above, the failure rate of second life transportation batteries are also dependent on failure mechanisms related to how hard the batteries were driven inside the vehicle. At present most published data is based on VRLA, Li Ion or NiMH chemistries.

Previously published papers on battery lifecycle testing are largely split into a number of subsets;

1. Small scale testing (small numbers of cells) under fixed conditions including typical drive cycles.
2. Theoretical failure rates adjusted from experimental data, like that above, to take into account factors such as temperature and even proposed maintenance strategy which may be compared to either lab or field tests.
3. Field testing experience.
4. EV experience on a drive cycle.

A large proportion of the tests (especially for VRLA batteries) are also undertaken on behalf of the telecommunications industry and their use in backup supplies which traditionally float until needed and which is less relevant to the application presented in this paper. It is difficult to get a fixed expression for battery failure rate, especially those that have completed a first life and are in a second life application. The remaining number of cycles was suggested to be one method to predict the battery life. However, this is dependent on how batteries would be used in their second life application and the proposed DOD on each cycle. A sample of previously published data is shown in Table 1. A "?" marks where the data is not known and "(T)" and "(V)" indicate telecoms and vehicle applications respectively. The estimated lifespan for the purposes of this paper, is based on the capacities (start and end of test) column. The failure rate is based on the estimated life span extrapolated linearly to 0% capacity. Where lifespan is given in cycles as opposed to years, a nominal 200 cycles per year (from a typical EV application) is used to estimate failure rate.The range of failure rate values go from 0.2 to 40×10^{-6}. Within this paper, this range is used to investigate the effect of the variation of failure rate on power electronic topology choice.

2.2 Converter components failure rate

Recent research related to the reliability of power electronic systems has concentrated on the reliability of the power electronic converters/components (switches and capacitors etc.), where the reduction of switches/capacitors, the stresses and component optimisation were the key to improve reliability. The source failure rate has generally been assumed to be negligible and is ignored completely, for example, in references [21] – [22]. The electrolytic capacitor and the power electronic switches were identified as the weakest links in the power circuit. A reasonable way to predict the failure rate of the capacitor is to use manufacturer lifetime datasheets such as Cornell Dubilier, Revox Rifa along with the Arrhenius equation [22]. The projected range of lifespan or failure rate of the electrolytic capacitors and other components are shown in Table 2. Power Converter reliability is based on the reliability of the components. A range of possible failure rate is given in Table 2, assuming a range of practical operating and junction temperatures (e.g 80 – 120^{o}C for MOSFETs and 80 – 100^{o}C for IGBTs).

Subset	Reference	Temperature	Battery	%DoD	Capacity at start –end of test	Estimated Lifespan	Estimated Failure rate/hr
1	[7]	(20^{o} C)	VRLA	Varied (T)	Varied - 50%	2-9 years	$1x10^{-5}$ to $6x10^{-5}$
1	[6]	?	VRLA	?	New- 50%	7 years to 50%	$8x10^{-6}$
1	[8]	20oC /40o C	VRLA	Varied	New- 80%	30 to 100 years	$2x10^{-7}$ to $7x10^{-7}$
2	[9]	25^{o}C to 40^{o}C	VRLA	80% (V)	New- 80%	200 cycles	$2x10^{-5}$
3	[10]	20^{o}C	VRLA	Varied (T)	New - 50%	(11 years)	$1x10^{-5}$ to 50% fade
4	[11]	?	VRLA	? (T)	?	4-6 years	2-$3x10^{-5}$
4	[12]	?	VRLA	Varied (V)	New- 80%	40,000 cycles	$1x10^{-7}$
4	[8]	20oC /40o C	VRLA	Varied	New- 80%	4 to 36 years	$1x10^{-6}$ to $1x10^{-5}$
2	[14]	25^{o}C - 40^{o}C	LiIon	25% from 90% initial SOC	New to 90%	Aprox. 100000 cycles	$2x10^{-7}$
2	[15]	50^{o}C and other	LiIon	(V)	New to 82%	5250 cycles	$8x10^{-7}$
2	[16]	43^{o}C	LiIon	50%	New to EOL	1300 cycles	$2x10^{-5}$
2	[17]	25^{o}C	LiIon	50% – 80%	New to EOL	3000 /500 cycles	$4x10^{-5}$ to $7x10^{-6}$
2	[18]	20^{o}C	LiIon	30% - 80% (T)	New	3000- 30,000 cycles	$7x10^{-7}$ to $7x10^{-6}$
2	[19]	25^{o}C	LiIon	40% (V)	New to 80%	10,000 cycles	$2x10^{-6}$
2	[20]	45 – 55oC	LiIon	100%	New to 64%	800 cycles	$2x10^{-5}$
5	[13]	?	LiIon	20%- 60%	New to 80%	1 year	$2x10^{-5}$

Table 1: Range of inferred failure rates of batteries

Component	*Range of Failure Rate λ x $1\text{-}10^{-6}$ hrs*	Range of projected lifespan/MTTF (1/λ)	Failure rate *x $1\text{-}10^{-6}$ hrs* (used in calculation)
Switch (λ_{sw1}) – MOSFET	1.8 – 3.14	30 – 60 years	2.47
Switch (λ_{sw2}) – IGBT	0.9 – 1.22	90 – 100 years	1.06
DC-link Electrolytic capacitor (λ_{cap})	2.8 – 5.5	20 – 40 years	4.15
Filter Inductance (λ_L)	0.0004 – 0.0006	> 100 years	0.0005
dc-dc converter ($\lambda_{DC\text{-}DC}$) → ($2\lambda_{sw} + \lambda_{cap} + \lambda_L$)	6.4 – 11.5 (MOSFET based) 4.6 – 7.94 (IGBT based)	10 – 18 years	9
dc-ac converter ($\lambda_{DC\text{-}AC}$) → ($4\lambda_{sw} + \lambda_{cap} + \lambda_L$)	10 – 17.5 (MOSFET based) 6.4 – 10.38 (IGBT based)	7-12 years	14 (MOSFET) and 8.4 (IGBT)

Table 2: Range of failure of power electronic components

Previous work on reliability of power converters that includes the power source, is mostly based on wind power and PV applications, where wind speed and inhomogeneous radiation (partial shading) affect the failure rates of the power converter operation as described in references [23]. Work that is more closely related to this application includes previous optimisation work on a parallel converter configuration [24] using converter failure, a fixed reliability target and optimising the overall system cost. However, this method is complicated to use in this current context because of the interdependencies between a) the number of modules b) number of series batteries/module, c) module power rating and d) desired range of reliability. For example, the number of series batteries/module directly affects module reliability. A high number of series batteries/module reduces module reliability which in turn demands very high number of redundant modules to meet desired reliability target. On the other hand – a low number of series batteries/modules increases the module reliability but it reduces module power rating which then demands very high number of modules to meet overall power rating. Therefore, a careful selection of series batteries strings and converter redundancy is necessary to meet desired power and reliability at the same time. Future research will be to include this dependency within a formal optimisation routine. However, at this stage numerical analysis can help with topology selection.

3 Topology Reliability Comparison

It should be noted that the reliability of sensors, drivers or cooling system has not been taken into account in this analysis and is assumed to be the same for each topology From table 2, a second life battery cell ($\lambda_{batt} \approx 0.2 – 40 \text{ x}10^{-6}$ hrs) can be less reliable than switches ($\lambda \approx 2 – 3 \text{ x } 10^{-6}$hrs) and capacitors ($\lambda \approx 3 – 5 \text{ x}10^{-6}$hrs). At the very extreme end of reliability of the second life battery – this becomes the most dominant feature of the reliability of the system and results will be looked at both including and excluding the power electronics for comparison.

Different multi-modular topologies for use with a second life battery system are shown in Fig 1. These topologies can be broadly divided into two categories: cascaded form and parallel form. (All the topologies can be designed to have redundancy against battery failure). Fig 1(a) shows a conventional cascaded multilevel converter where battery banks are directly connected to the main dc-link of each dc-ac module. Fig 1(b) shows a parallel structure where dc-ac modules are connected in parallel. Fig 1(c) shows the cascaded multilevel converter with integrated dc-dc converter while Fig 1(d) shows the parallel form of Fig 1(c) where dc-ac modules are connected in parallel on the grid side. Figure 1(e) and 1(f) show varying forms of (c) and (d) where only a single dc-ac converter is used. Topology (e) requires additional switches to be able to bypass faulty modules (not shown but included in the analysis). A general means of creating redundancy is to use a '*k*-out-of-*n*' system, where any *"k"* modules must be operating to ensure the system power output is assured. '*n*' number of modules is required to meet the desired reliability and "R_m" is module redundancy which in turn is dependent on "*x*" the number of series connected batteries.The failure rate of different battery cells could be different for different cells but for simplicity all the batteries are assumed to have the same failure rate. The challenge is to select the best topology and its values of *n*, *k* and *x* to ensure an acceptable reliability target (R), at a minimum power level (*P*) keeping cost to a minimum value. A minimum voltage is also set such that 240V ac can be achieved (without a grid connected transformer single phase).

The system cost has been determined as a function of switch kVA rating ($f_1(kVA)$) , inductor and capacitor rating ($f_3(J)$ and $f_4(J)$), driver cost (as a function of switch rating, ($f_2(kVA)$) and sensor cost (f_5) by plotting costs against size from large scale component suppliers and deriving the line of best fit. Fig 2, for example, shows the costs of different manufacturer's switch components as a function of rating. The equation represents the line of best fit and consequently function $f_1(kVA)$.

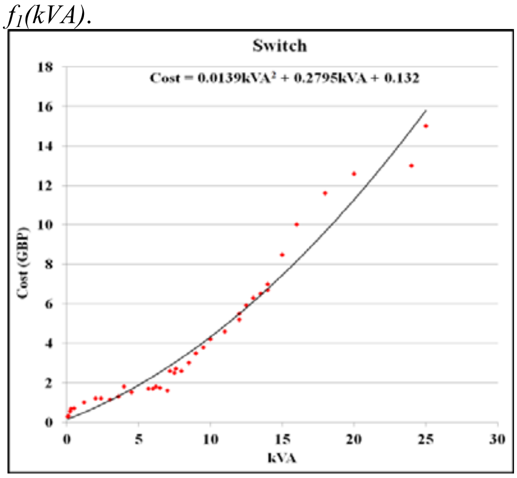

Fig 2 : Cost of components against rating

Batteries are considered only as series strings with any parallel configurations being implemented through the power electronics.

4 Calculation of *k*, *n* and *x*

The equations associated with each topology for each of the constraints are shown in Table 3 to 5, (where the subscript refers to the topology in fig 1), V_{cell} is the cell voltage, I_{batt} is the cell current, b is the boost ratio of the dc-dc converter.

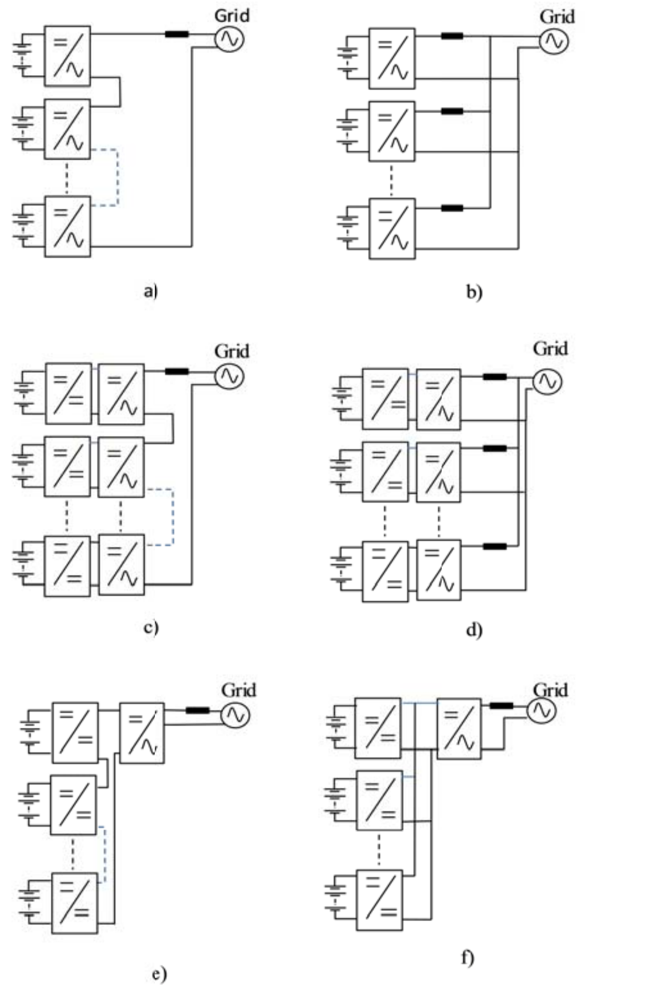

Fig. 1: Different multi-modular topologies:

Top.	Min Power Output	Minimum x to ensure sufficient dc voltage
a	$P = k_a x_a V_{cell} I_{batt}$	$x_{min,a} > 340/k_a V_{cell}$
b	$P = k_b x_b V_{cell} I_{batt}$	$x_{min,b} > 340/V_{cell}$
c	$P = k_c x_c V_{cell} I_{batt}$	$x_{min,c} > 340/b_c k_c V_{cell}$
d	$P = k_d x_d V_{cell} I_{batt}$	$x_{min,d} > 340/b_d V_{cell}$
e	$P = k_e x_e V_{cell} I_{batt}$	$x_{min,e} > 340/b_e k_e V_{cell}$
f	$P = k_f x_f V_{cell} I_{batt}$	$x_{min,f} > 340/b_f V_{cell}$

Table 3: Topology equations for power and voltage

	Reliability:	Where
a	$\sum_{i=k_a}^{n_a} \binom{n_a}{i} R_{m,a}{}^{i} (1 - R_{m,a})^{n_a - i}$	$R_{m,a} = e^{-(x_a \lambda_{batt} + \lambda_{DC-AC})t}$
b	$\sum_{i=k_b}^{n_b} \binom{n_b}{i} R_{m,b}{}^{i} (1 - R_{m,b})^{n_b - i}$	$R_{m,b} = e^{-(x_a \lambda_{batt} + \lambda_{DC-AC})t}$
c	$\sum_{i=k_c}^{n_c} \binom{n_c}{i} R_{m,c}{}^{i} (1 - R_{m,c})^{n_c - i}$	$R_{m,c} = e^{-(x_c \lambda_{batt} + \lambda_{DC-DC} + \lambda_{DC-AC})t}$
d	$\sum_{i=k_d}^{n_d} \binom{n_d}{i} R_{m,d}{}^{i} (1 - R_{m,d})^{n_d - i}$	$R_{m,d} = e^{-(x_d \lambda_{batt} + \lambda_{DC-DC} + \lambda_{DC-AC})t}$
e	$\sum_{i=k_e}^{n_e} \binom{n_e}{i} R_{m,e}{}^{i} (1 - R_{m,e})^{n_e - i} + e^{-\lambda_{DC-AC} t}$	$R_{m,e}$ $e^{-(x_e \lambda_{batt} + \lambda_{DC-DC} + 2\lambda_{sw1})t}$
f	$\sum_{i=k_f}^{n_f} \binom{n_f}{i} R_{m,f}{}^{i} (1 - R_{m,f})^{n_f - i} + e^{-\lambda_{DC-AC} t}$	$R_{m,f} = e^{-(x_f \lambda_{batt} + \lambda_{DC-DC})t}$

Table 4: Topology equations for reliability

	Approximate cost indicator (switch+ inductor/capacitor + drivers)
a	$4n_a f_1(x_a I_{batt} V_{cell}) + 4n_a f_2(x_a I_{batt} V_{cell}) + \frac{n_a}{2} f_3(C(x_a V_{cell})^2) + 2n_a f_5$
b	$4n_b f_1(x_b I_{batt} V_{cell}) + 4n_b f_2(x_b I_{batt} V_{cell}) + \frac{n_b}{2} f_3(C(x_b V_{cell})^2) + 3n_b f_5$
c	$2n_c f_1(x_c I_{batt} b_c V_{cell}) + 6n_c f_2(x_c I_{batt} V_{cell}) + 4n_c f_1\left(x_c \frac{I_{batt}}{b_c} b_c V_{cell}\right) + \frac{n_c}{2} f_4(L_{boost} I_{batt}{}^2) + \frac{n_c}{2} f_3(C(b_c x_c V_{cell})^2) + 3n_c f_5$
d	$2n_d f_1(x_d I_{batt} b_d V_{cell}) + 4n_d f_1\left(x_d \frac{I_{batt}}{b_d} b_d V_{cell}\right) + 6n_d f_2(x_d I_{batt} b_d V_{cell}) + \frac{n_d}{2} f_4(L_{boost} I_{batt}{}^2) + \frac{n_d}{2} f_3(C(b_d x_d V_{cell})^2) + 4n_d f_5$
e	$2n_e f_1(x_e I_{batt} b_e V_{cell}) + 2n_e f_1\left(x_e \frac{I_{batt}}{b_e} b_e V_{cell}\right) + f_1\left(4k_e x_e \frac{I_{batt}}{b_e} b_e V_{cell}\right) + (4n+4) n_e f_2(x_e I_{batt} V_{cell}) + \frac{n_e}{2} f_4(L_{boost} I_{batt}{}^2) + \frac{n_e}{2} f_3(C(x_e b_e V_{cell})^2) + 3n_e f_5$
f	$2n_f f_1(x_f I_{batt} b_f V_{cell}) + 2n_f f_1\left(x_f \frac{I_{batt}}{b_f} b_f V_{cell}\right) + f_1\left(4k_f x_f \frac{I_{batt}}{b_f} b_f V_{cell}\right) + (4n+4) n_f f_2(x_f I_{batt} V_{cell}) + \frac{n_f}{2} f_3(L_{boost} I_{batt}{}^2) + \frac{n_e}{2} f_3\left(C(x_f b_f V_{cell})^2\right) + 3n_f f_5$

Table 5: Topology equations for cost

5 Numerical results

The results generated below assume a fixed battery type, a fixed cell voltage, fixed battery reliability and a constant boost ratio. Obviously with respect to second life battery systems – none of this is necessarily the case, but acts as an indication for valid topology choice. Losses and efficiency of each converter type are not explicitly calculated but may be included in future analysis.

The following values are used in this example; V_{cell} = 3.3V, I_{batt} = 20Ahr, minimum time period = 5 years, minimum system reliability = 70%, minimum power = 1kW, boost ratio of all dc/dc converters is set to 5, battery failure rates - 0.2×10^{-6}, 7.7×10^{-6} and 40×10^{-6}.

Top.	Lowest cost solution					
	Including power electronics in reliability calculation			Excluding power electronics in reliability calculation		
	x	n/k	Cost/K_1	x	n/k	Cost/K_1
a	1	2	1825	1	1.05	1004
c	1	3	1240	1	1.04	433
e	1	2	1045	1	1.04	390
b	104	4	2571	104	3	1876
d	21	2	1373	21	2	915
f	21	7	1431	21	3	412

Table 6: Results for (λ_{batt}= 0.2x10^{-6})

Top.	Lowest cost solution					
	Including power electronics in reliability calculation			Excluding power electronics in reliability calculation		
	x	n/k	Cost/K_1	x	n/k	Cost/K_1
a	1	3	2546	1	1.43	1360
c	1	4	1733	1	1.47	611
e	1	3	1537	1	1.47	554
b	No practical solution			No practical solution		
d	No practical solution			No practical solution		
f	No practical solution			No practical solution		

Table 7: Results for (λ_{batt}= 7.7x10^{-6})

Top.	Lowest cost solution					
	Including power electronics in reliability calculation			Excluding power electronics in reliability calculation		
	x	n/k	Cost/K_1	x	n/k	Cost/K_1
a	No practical solution			1	7	380 x10^3
c	No practical solution			1	6.3	383 x10^3
e	No practical solution			1	6.3	286 x10^3
b	No practical solution			No practical solution		
d	No practical solution			No practical solution		
f	No practical solution			No practical solution		

Table 8: Results for (λ_{batt}= 40x10^{-6})

Tables 6-8 show the lowest cost solution for each of the topologies with and without the power electronics in the reliability calculation. The results show the following;

- If the battery reliability is low (e.g. λ_{batt}= 40x10^{-6}) then it is impractical to use second life batteries within any application because of the cost needed to overcome the low system reliability.
- A cascaded connected converter is a better option than a parallel connected converter because of the high series number of batteries needed to attain the voltage level in the parallel configuration and the impact of this on reliability.
- Configurations with a boost converter present offer a better option than without for the same reason (ie reducing the number of series batteries to attain the voltage levels).
- Topology e) offers the best cost value as it combines the cascaded configuration with a boost converter. This is even with the extra switches present because of the comparatively high reliability of the large dc/ac converter.
- If the power electronics is removed from the reliability calculation then the *n/k* ratio result for (e) is equal to (c) but the cost is lower because the VA rating of the large dc/ac converter is equal to *k* multiplied by the module VA rating as compared to n multiplied by the module VA for topology (c) in Table 5.
- The choice of topology is independent of the battery failure rate and also the power electronics reliability within the fixed bounds of this example.
- Not visible by the results table – but also understandable- is that having set *x* to the lowest possible value; *k* is also a minimum value in order to meet the voltage at minimum cost.

The result of the numerical analysis has been plotted in 3D plane showing the variation of cost against *n/k* against *x*. The ratio *n/k* is chosen because it's difficult to visualise the system results in 4D. Fig 3 presents a set of numerical solutions for all those solutions for the cascaded dc-side modular topology e) (at λ_{batt} = 0.2x10^{-6}) which meet a minimum reliability, power and overall dc bus voltage with and without power converter reliability. It can be seen from Fig 3 that the solutions appear primarily as a series of lines of constant *x* starting at *x* = 1. The cost of the solutions gradually moves upwards when the *x* increases as greater redundancy is needed to meet reliability which impacts cost. The set of solutions reduces at higher battery failure rate (solutions become less dense on 3D plane). A similar type of variation is found for parallel topologies in Fig 4 (topology f)) but it can be seen that the optimum solution starts at higher *x* (*x* = 21) to meet the voltage constraint.

6 Conclusion and Future work

This paper uses a numerical approach to look at the best choice of topology and associated values for x, k and n at a lowest cost factor for a minimum dc bus voltage and reliability. It concludes that minimizing x and k as far as possible is the best method to reduce overall cost and that a series configuration cascaded converter is better for this than a parallel configuration. The method is at best an approximation and misses out key parameters which need to be considered in future work such losses and/or converter efficiency (better for cascaded configurations due to low on state resistance of lower voltage devices), size, effect of a hybrid system with different battery chemistries and effect of operation of topology on battery life possibly using a more general optimization function.

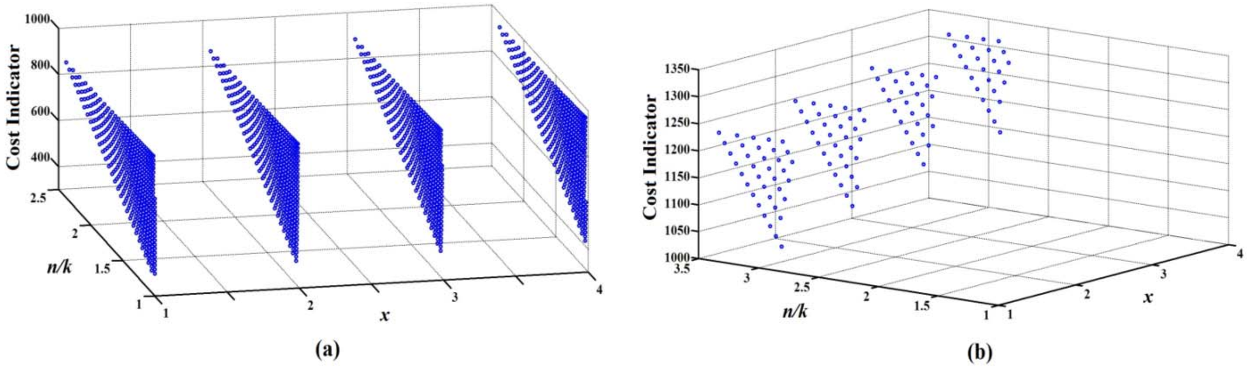

Fig 3 Cascaded dc-dc topology at $\lambda_{batt}= 0.2x10^{-6}$: a) Cost against n/k against x without PE reliability b) Cost against n/k against x with PE reliability

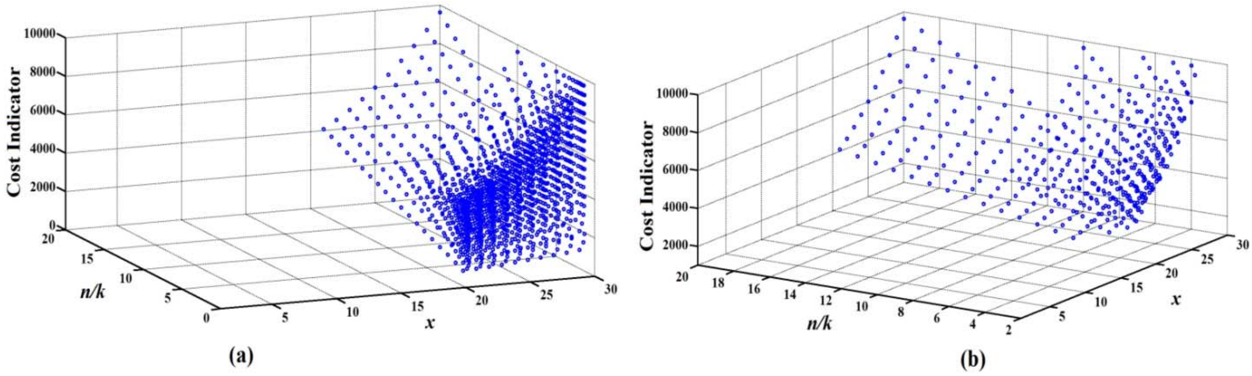

Fig 4 Parallel dc-dc topology at $\lambda_{batt}= 0.2x10^{-6}$: a) Cost against n/k against x without PE reliability b) Cost against n/k against x with PE reliability

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9 References

[1] Serban, I.; Marinescu, C.; "A look at the role and main topologies of battery energy storage systems for integration in autonomous microgrids," OPTIM, 2010., pp.1186-1191

[2] Ponnaluri, S.; Linhofer, G.O.; Steinke, J.K.; Steimer, P.K.; "Comparison of single and two stage topologies for interface of BESS or fuel cell system using the ABB standard power electronics building blocks," Power Electronics and Applications, 2005, vol., no., pp.9

[3]Erb, D.C.; Onar, O.C.; Khaligh, A., "Bi-directional charging topologies for plug-in hybrid electric vehicles," APEC, 2010 pp.2066-2072,

[4] Mukherjee, N.; Strickland, D.; Cross, A.; Hung, W.; "Reliability estimation of second life battery system power electronic topologies for grid frequency response applications," PEMD, vol., no., pp.1-6, 27-29 March 2012.

[5] Department of US Defense, MIL-HDBK-217F Notice 2, Military Handbook-Reliability Prediction of Electronic Equipment, 1995.

[6] Feder, D.O. “Performance measurement and reliability of VRLA batteries” INTELEC '95., Page(s): 22 – 28

[8] Cantor, W.P.; Davis, E.L.; Feder, D.O.; Hlavac, M.J.”Performance measurement and reliability of VRLA batteries. II. The second generation” INTELEC. 1998 , Page(s): 369 - 380

[9] Feder, D.O.; Jones, W.E.M. “Gas evolution, dryout, and lifetime of VRLA cells an attempt to clarify fifteen years of confusion and misunderstanding”, INTELEC '96., , Page(s): 184 - 192

[10] MacDougall, R.E.; Bertolino, J.D.; Rodden, K.L.; Alger, E.T. “Lab testing of battery charge management systems for electric and hybrid electric vehicle battery packs to evaluate cycle life improvement” Battery Conference on Applications and Advances, 2000. Page(s): 237 – 242.

[11] Kervarrec, G.; Marquet, D.; "A realistic reliability and availability prediction methodology for power supply systems," INTELEC. 24th Annual International 2002 , pp. 279- 286.

[12] Selanger, P.A.; Johansson, A.O.; Lundqvist, K.; Oberger, K.; Humla, L.; "End-user experience of VRLA batteries," INTELEC '95, 17th International, , pp.143-147, 29 Oct-1 Nov 1995.

[13] Cooper, A.; Moseley, “VRLA Batteries Match the Performance of NiMH Batteries in Power-Assist Hybrids”P.T. Hybrid and Eco-Friendly Vehicle Conference, 2008. IET HEVC 2008 , Page(s): 1 – 4

[14] Weili Ke; Ning Zhang “Charging models & the performance of battery packs for electric bicycles” AUPEC 2007.,Page(s): 1 – 4

[15] Long Lam ; Bauer, P. “Practical Capacity Fading Model for Li-Ion Battery Cells in Electric Vehicles”, Power Electronics, IEEE Trans, Vol 28, 2013 , Page(s): 5910-18

[16] Yancheng Zhang ,Chao-Yang Wang; “Cycle-Life Characterization of Automotive Lithium-Ion Batteries with LiNiO2 Cathode”, Journal of The Electrochemical Society, 2009, Vol 156 , p527 -535

[17] Guena, T. ; Leblanc, P. “How Depth of Discharge Affects the Cycle Life of Lithium-Metal-Polymer Batteries”, INTELEC '06. Page(s): 1 - 8

[18] Dogger, J.D.; Roossien, B.; Nieuwenhout, F.D.J.; "Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage," Energy Conversion, IEEE Transactions on , vol.26, no.1, pp.256-263, March 2011.

[19]Brunarie, J.; Billard, A.-M.; Lansburg, S.; Belle, M.; "Lithium-ion (Li-ion) battery technology evolves to serve an extended range of telecom applications," INTELEC, 2011 IEEE 33rd International , vol., no., pp.1-9

[20] Haran, B.S.; Ramadass, P.; White, R.E.; Popov, B.N.; "Capacity fade of Li-ion cells cycled at different temperatures," Battery Conference on Applications and Advances, 2002. The Seventeenth Annual, pp.13-18

[21] Chan, F.; Calleja, H.; "Design Strategy to Optimize the Reliability of Grid-Connected PV Systems," IEEE Trans. on Industrial Electronics, vol.56, no.11, pp.4465-4472, Nov. 2009.

[22] Hirschmann, D.; Tissen, D.; Schroder, S.; De Doncker, R.W., "Reliability Prediction for Inverters in Hybrid Electrical Vehicles," *Power Electronics, IEEE Transactions on* , vol.22, no.6, pp.2511,2517, Nov. 2007.

[23] Kaigui Xie; Zefu Jiang; Wenyuan Li; "Effect of Wind Speed on Wind Turbine Power Converter Reliability," Energy Conversion, IEEE Transactions on , vol.27, no.1, pp.96-104, March 2012.

[24] Xiaoxiao Yu; Khambadkone, A.M.; "Reliability Analysis and Cost Optimization of Parallel-Inverter System," Industrial Electronics, IEEE Transactions on , vol.59, no.10, pp.3881-3889, Oct. 2012.