Energy Storage Options for Hybrid Diesel Electric Shunting Locomotives

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ABSTRACT

Shunting locomotives are required to produce high powers during shunting operations but may be idle for many hours each day. A key issue with a hybrid conversion is battery life. Shunting locomotives are required to develop typically 1000hp to 2000hp for periods of perhaps a few minutes and the battery is sized for its capacity to deliver instantaneous power. This paper will examine typical shunting duty cycles for a 1000 hp case study where a 520Ah 880V battery is applied. Methods of estimating battery life based on amp-hours exchanged with correction factors for time duration and peak currents are explored. Alternate storage devices such as ultra capacitors can provide methods of significantly reducing the peak battery discharge current and could potentially halve the battery mass.

1. INTRODUCTION

Recent advances in battery and power electronics technology combined with demands for low cost innovative locomotive power solutions have provided the opportunity to evaluate the adaptation of hybrid technology for shunting service, [1]. The hybrid solution secures very significant fuel savings and savings of tens of kilolitres annually are possible.

Most railway operators have a stock of obsolete locomotives, typically more than 30 years old, which can become economic targets for conversion. Figure 1 shows a 1720 class 1000hp locomotive which is suitable for conversion. This particular Queensland Rail locomotive is No. 1723, manufactured by Clyde Engineering, Eagle Farm, Queensland in November 1966. Known as “Frank Archer” is one of the few named locomotives in the QR fleet and is named for an early Rockhampton region explorer, [2].

Apart from fuel savings, hybrid locomotives offer many other advantages. It is common practice to retire older main line locomotives to shunting towards the end of their lives. These locomotives, because of age, may not meet the requirements of national environmental protection agencies, in terms of noise and particulate emissions and this has been a driving factor in the removal of older locomotives from this service. Large diesels do not run efficiently or cleanly at light loads and maintenance is high. When locomotives are in shunting service they may be periodically cycled into heavier service to clean out engine deposits. Oil spillage is a problem internationally. Shunting yards can become contaminated sites due to lubricating oil losses from locomotives. The conversion of an obsolete diesel electric locomotive to hybrid battery electric, (HBE), service would require:

- The removal of the main engine, which normally would be at the end of its design life, and the generator;
- The addition of a large battery bank and a packaged alternator;
- The addition of a power electronic chopper to power the existing traction motors, these are often series DC machines in older locomotives.

Figure 1: The 1720 Class Queensland Rail Locomotive “Frank Archer”, [2].

This paper considers the energy storage requirements for a generic 1000hp hybrid battery electric design that has the following features:

- Industry standard driver control performances - locomotives operate with throttle notch positions that approximate constant power operation at the levels shown in Table 1;
- An operational cycle that is similar to that observed in US heavy duty operations with times in various notches as given in Table 2, [1], shunting duties consist of short periods of activity interposed with idle periods;
- Retention of the existing traction motors and replacement of the generator system by a chopper controlled DC drive capable of the full current range of the alternator/rectifier of that class which ensures the same tractive effort, typical currents are 0-1800Adc range;

- A nominal main battery voltage that allows a suitable maximum speed, in this case a nominal 880Vdc battery is applied;
- A battery or energy storage mass limit of 15 tons, this is compatible with the mass of a 1000hp locomotive which weighs approximately 75 tons; the allowable volume limit is 8m^3;
- A 100kW charging system.

Throttle Setting	Chopper Power
Idle	0
Notch 1	38 kW
Notch 2	128 kW
Notch 3	218 kW
Notch 4	315 kW
Notch 5	412 kW
Notch 6	510 kW
Notch 7	622 kW
Notch 8	750 kW

Table 1: Locomotive Power for Various Notch Settings

Throttle Setting	Heavy Duty	Standard Duty
Idle	85%	86%
Notch 1	2%	7%
Notch 2	4%	3%
Notch 3	3%	2%
Notch 4	3%	1%
Notch 5	1%	0%
Notch 6	0%	0%
Notch 7	0%	0%
Notch 8	2%	1%

Table 2: Typical Times in Notches for US Shunting Engines, [1].

The HBE locomotive control strategies will keep the energy efficiency of the locomotive as high as possible by minimizing the energy cycled through the battery. This avoids a charge/discharge energy efficiency penalty and prolongs life. The chopper runs off the traction battery alone until the battery depletes to approximately 60% of its full charge. At this point, an energy management system automatically starts charging alternator. Typically the alternator will remain operating at it optimum fuel efficiency point until the battery reaches 80% charge. These charge points are selected to optimize the battery cycle life. For time to time the energy management system will raise the battery to higher charge states to force the equalization of charge in the many series connected battery cells. The locomotive will not include regenerative braking for the following reasons:

- The presence of regenerative braking complicates the chopper design and increases the technical risk unnecessarily during the prototype phase;
- Older locomotive classes typically use series wound motors – these require additional contactors to achieve regeneration;
- The lack of independent field control limits the range of regeneration that can be achieved with a series motor;
- The available energy from regenerative braking is normally less than ten percent of the energy involved in the cycle;
- Regeneration complicates the braking system.

2. THE ENERGY STORAGE TASK

HBE locomotives secure fuel savings by avoiding the operation of large diesels at low power or idle. At idle a 1000hp diesel will consume approximately 12 litres an hour. Shunting duty features short periods of intense activity and long periods of light load or idle operation. The energy storage device must satisfy three criteria:

- Peak power capability – the peak discharge power can reach 750kW;
- Adequate energy storage capacity;
- An economic operating life.

The peak power rating does need further qualification in terms of time for which this can be maintained. Reliability and robustness would dictate that this peak power should be maintainable for some minutes. Most battery manufacturers supply high rate discharge data that result in relatively low cell voltages at the end of the discharge. From a life cycle viewpoint this is very unlikely to be acceptable as these batteries are subject to many high rate discharges. The batteries used must be able discharge at this rate for a few minutes and not be damaged. Consequently, for batteries at least, a target of 20 minutes endurance at this rate is set. In energy terms this is 250kWh which will be shown to be significant. For energy storage devices other than batteries this endurance can be reduced if it can be shown life time is not adversely affected.

Table 3 shows the hours spent in each notch over a 24 hour period, together with the maximum discharge power in each notch, assuming the alternator is running for the 3.6 hours when the locomotive is not in idle, and the total energy storage required over a full day. The total energy storage requirement, 653 kWh, represents the total power exchange performed by the energy storage over 24 hours. Shunting operations will occur several times per day and short periods of work, perhaps 30 to 60 minutes long will be interposed with idle periods or similar lengths. The capacity of the storage can be much less than 653kWh, as many opportunities exist for recovery. Figure 2 shows the experience of US operations and three periods of shunt activity occur in approximately 6 hours. If this extended over 24 hours approximately 12 cycles of activity would occur and the energy storage capacity required could be less than 55kWh. The issues relating to the production and storage of energy will be assed in terms of economics and technical capacity.

3. ALTERNATOR RATING

A key issue for any hybrid design is the relative sizing of the charging alternator and the energy store. Larger diesels have progressively higher fuel consumptions at idle. A 1000hp diesel can readily consume 12 litres per hour at idle. The major fuel saving advantages accrue by the use of a smaller alternator that is better matched to the average load and by only operating that alternator at its optimal loading point.

The total storage requirement, 653 kWh must be replaced by the alternator, if this is done exclusively in the idle periods the average battery recharge, net of charging losses, is 32 kW. Allowing for an 80% charge efficiency the average power input to the charger will be 40kW. The alternator rating should be higher than this as the optimal fuel efficiency point is likely to be between 50% and 80% of rating. In this case a 100kW rating will provide a margin that will accommodate the additional demands within a locomotive for auxiliaries, such as air conditioning, forced cooling air and compressed air. These are fluctuating loads that may range up to 20kW. It also will provide enough power for continuous operation in notch one. This would allow a HBE locomotive to travel a speed indefinitely if moving between shunting locations. Lighter loadings are easily accommodated by turning the alternator off and running for a period on battery power. This will avoid ring and bore glazing.

Subject to the load acceptance limits of the alternator while cold immediately after starting, a sensible operating strategy is to:

- Fully load the alternator at throttle notch two and higher to minimise the battery discharge and to avoid the battery charge/discharge losses and prolong the battery cycle life;
- Load the alternator to at least its optimum efficiency point while charging in throttle notch one or below;
- Allow the battery to cycle through a limited depth of discharge, (DOD), to extend battery life, but large enough to require a run time of several hours from the alternator; a 20% discharge is a good compromise.

It will be later shown that the battery capacity will be in the order of 450kWh. To replace a 20% discharge, an input of approximately 110kWh will be required. As the HBE locomotive may be operating and requiring a portion of the alternator output power this will require at least a two hour run time. It would be expected that the alternator would need to run four or five times per day. The alternator cycle time can be greatly extended by reducing the alternator output for throttle notch one and below. The best battery life scenario is to have the alternator running for as long as possible and directly meeting load without battery cycling. The run time can be extended by reducing the alternator output to the lower limits imposed by fuel efficiency and cylinder bore glazing.

4. LEAD ACID BATTERIES

Locomotives that might be considered targets for conversion, such as the 1720 class, typically utilize DC motors. There is a requirement to travel at reasonable speeds between working locations which forces the use of a battery voltage similar to that applied in the original designs. Applied voltages range up 1000Vdc, the upper limit of the low voltage, (LV), classification within the Australian AS 3000 family of standards. Operationally it is useful to arrange batteries in groups that do not exceed the AS3000 extra low voltage, (ELV), limit of 120Vdc which can be individually isolated as this allows easy access for work. For a lead acid battery chemistry 384 cells (880V nominal at 2.3volts per cell), packaged as 8 groups of 48 cells (110V nominal) is an arrangement which stays within these limits even at the upper battery cell voltages.

Throttle Setting	Heavy Duty	Discharge Power	Energy
Idle	85% 20.4h	nil	0
Notch 1	2% 0.48h	nil	0
Notch 2	4% 0.96h	28kW	27kWh
Notch 3	3% 0.72h	118kW	85kWh
Notch 4	3% 0.72h	215kW	154kWh
Notch 5	1% 0.24hr	312kW	75kWh
Notch 6	0% 0h	410kW	0
Notch 7	0% 0h	522kW	0
Notch 8	2% 0.48h	650kW	312kWh
Total	**100% 24h**		**653kWh**

Table 3: Energy Storage Requirements over 24h Continuous Operation.

A peak discharge power of 750 kW equates to 1.95 kW per cell. It is difficult to achieve this with the weight constraint. For example, if a standard deep cycle battery for UPS applications such as Absolyte IIP, [3], is used to realise a 384 cell battery, the largest cell size that can be accommodated within the mass constraint is 344 Ah. At a 20 minute rate these cells will deliver 675W with a final cell voltage of 1.6V. This is a very hard discharge. Even at 5 minutes this cell will only deliver 851W.

The peak power constraint forces the adoption of spiral wound lead acid battery technologies as adopted by the Enersys Cyclon range, [4], the Enersys Hawker Armasafe range, [5] or the Optima Batteries Yellow Top range, [6-7]. These feature extremely high discharge capabilities but the standard commercial offerings are somewhat limited in size with the largest Cyclon offering being 25Ah for a single cell, Optima Battery offering 75Ah at 12V and the Enersys Hawker offering the Armasafe battery which is 120Ah at 12V. All are capable of supplying the discharge power requirement and all offer very similar peak discharge current capabilities in proportion to their ampere-hour capacity. Earlier versions of the Optima Yellow Top battery, which where only rated at 52Ah in 1996, were tested at discharge rates up to 500A for 10 seconds, [6]. This is

9.6 times the ampere-hour capacity or 9.6C, and was considered to be representative of the worst loading cases in an electric vehicle, (EV).

To achieve 750kW for 20 minutes from spiral wound batteries, a total capacity of 520Ah would be required. This corresponds to a mass of 12.2 tons. The ampere-hour capacity is four times larger than the Enersys Armasafe battery which is intended for starting armoured vehicles, or seven times larger than the Optima battery which is intended for electric vehicles, so a customised design would be required. Proportionally the discharge current in this application, 852A at 880Vdc, is only 1.64C. The EV application is more than five times more severe. An interesting feature of this design is the internal resistance. Optima batteries have internal resistances of 2.5 mΩ, constructing a bank of seven parallel by 64 series connected batteries yields 23mΩ total resistance and a prospective fault current of 38kA. Such a battery raises significant protection issues. DC circuit breakers are readily available for 1500Vdc railway traction applications but these fault levels are testing.

As an indication of price an equivalent mass of the Optima batteries are estimated to cost $83 000USD. The nominal energy storage capacity is 450kWh and this posses no operational constraint. The operating life is now considered.

The duty imposed in this application is less arduous than that imposed in electric vehicle designs where peak powers are up to five times higher, [7]. The Ford Company conducted life cycle tests with the Ranger electric vehicle battery which achieves a 20 000Ah cycle life with an 82Ah monoblock VRLA battery in continuous deep cycle laboratory tests with service temperatures of 45C, [8]. The ampere-hour life measure was 243 times the battery amp hour rating. The Ford experiences showed that with better battery and thermal management life could be extended to 37 000Ah or 451 times the battery ampere-hour rating. The highest cycle lives for VRLA batteries have been achieved using specialised charging algorithms developed by Optima under funding from the Advanced Lead Acid Battery Consortium, (ALABC), [9]. These methods termed Partial State of Recharge, (PSOR) and Current Interrupt, (CI) in combination achieved a 38 580Ah life for a 52Ah Optima cell. This corresponds to 741 deep cycles with 12V nominal batteries discharged to 10.5V under electric vehicle loading regimes.

In both cases the batteries where subject to deep cycles which is in the context of an electric vehicle was 60% to 80% of battery capacity. In the locomotive application the cycle depths will be 20% which suggests a longer life. These changes in depth of discharge will extend the battery life time in both the number of cycles and the total amp hour lifetime. The peak discharge rates are also lower and will additionally extend life. Estimates of how battery life changes can be made using three premises developed by Symons, [10-11]. These are:

Premise 1: Each Cell has a finite life as measured by the sum of the effective ampere-hours throughput during its useful life.

$$T_r = L_r D_r C_r \qquad [1]$$

Where:

- T_r is the rated charge life;
- C_r is the rated amp hour capacity at a rated discharge current I_r;
- D_r is the depth of discharge for which the rated cycle life was determined;
- L_r is the cycle life at the rated depth of discharge and discharge current.

Premise 2: The charge life (total ampere-hours throughput) will always be less than T_r when a battery is cycled more deeply than a reference DOD and will be greater than T_r when the battery is cycled less deeply.

This premise can be applied by fitting the following expression to manufacturer's data:

$$L = u_2 \left(\frac{D_r}{D} \right)^{u_0} e^{u_1 \left(1 - \frac{D}{D_r} \right)} \qquad [2]$$

The three parameters u_0, u_1 and u_2 allow considerable flexibility in fitting this result to the available data. As a customised design might be necessary for the cell sizes required this data is not immediately available. Drouilhet and Johnson, [10], suggest that some cases do exist where manufacturer's data does not align with Symon's second premise. While the number of cycles always increases with a lower DOD, the effect on total ampere-hour life may be very weak or possibly negative.

In the absence of explicit data, this premise does generally indicate that the DOD should be limited. Given the cell size is determined by the discharge capacity, the energy capacity is much larger than needed. The depth of discharge is controllable by adjusting the frequency of the alternator starting. It is reasonable to limit the depth of discharge to 20% which is significantly less than seen in the electric vehicle application. It is also useful to operate the battery at states of charge below the recombination area, [8], to avoid water loss and a corrosion mechanism that occurs in the high states of charge. It would be beneficial to operate the battery between 60% and 80% of charge. In a long series connection of cells operating in this mode periodic equalisation will be necessary.

Premise 3: The charge life of a cell will be decreased when ever the cell is discharged at a rate faster than the rated rate.

$$d_{eff} = \left(\frac{C_r}{C} \right)^{v_0} e^{v_1 \left(1 - \frac{C}{C_r} \right)} d_{actual} \qquad [3]$$

Again three parameters v_0, v_1 and v_2 allow considerable flexibility in fitting this result to the available data. Once more it can be difficult to secure adequate data to perform this exercise. In our application it would be necessary to have a representative set of operating data available to develop a series of equivalent discharge events to determine the overall effect. Given the relatively adverse conditions for EV batteries, a good life time gain is possible.

While the data limitations exist, Symon's three premises can be used to give a indicative range of the battery cycle life for the HBE locomotive application. The best life for VRLA batteries is 741 times the ampere-hour rating suggesting that under similar conditions a 520Ah battery a total charge life of 385 000Ah could be achieved. As this life time figure for EV batteries was obtained at higher depths of discharge and at higher relative rates of discharge the HBE locomotive battery life will further increase. If adequate manufacturer's data, or experimental data, is available the above expressions could be fitted to extrapolate for the additional life time.

The total battery exchange of 653 kWh over 24 hours equates to 31 ampere-hours per hour. The charge throughput rate indicates a life time of 12 500 hours. Fuel saving studies suggest that this would be enough to justify the battery cost through fuel savings, [1].

5. OTHER BATTERY CHEMISTRIES

Nickel cadmium batteries are often considered as a battery of choice for high discharge rate applications. Saft, for example offers the SRX range of steel cased batteries for high rate railway applications and these have ratings for discharges as short as one minute, [12]. To deliver 750 kW for 20 minutes at a nominal bank voltage of 880Vdc, a 440Ah bank of 656 cells would be required. This bank weighs 14.9 tons and is at the upper acceptable weight range.

Lithium ion cells are also capable of the discharge power requirements. Thunder Sky, for example produces a range of large cells for vehicle and submarine applications with capacities to 9 000Ah. For this application a bank of 216 1000Ah cells, [13], will provide a 750kW by 20 minute capacity with a bank mass of 7.4 tons. This battery is fully specified for continuous discharge at 1000A, slightly higher than the currents required at 750 kW. It is rated at 300 cycles at 80% and DOD and 500 cycles at 70% DOD. Symon's second premise appears strongly with these batteries. The ampere-hour lifetimes equate to 240 000Ah and to 350 000Ah respectively. The life figures at 70% DOD are comparable to the lead acid lifetime. As it is possible to operate at significantly lower depths of discharge it is possible much longer life times will result.

While these battery chemistries offer alternatives and potential life time improvements cost is an issue. As an indication nickel cadmium cells are likely to cost twice that of lead acid and lithium ion cells may be five to ten times the lead acid cost.

6. SUPERCAPACITORS

The discharge capability of a particular battery determines the battery size in all cases. Figure 2, reproduced from [1], illustrates the impulsive nature of the battery loading. A shunting event of 30 to 60 minutes duration, will normally consist of many smaller operations as wagons are added to or removed from partial trains or consists. The earlier estimate of energy storage required for a 30-60 minute shunting event was 55 kWh. However the nature of the task is such that an energy storage of capable of supplying 50% of the load at notch eight, would be valuable. This might halve the peak discharge power of the battery and halve its mass. One minute at 375 kW corresponds to 6.25kWh or 22.5MJ.

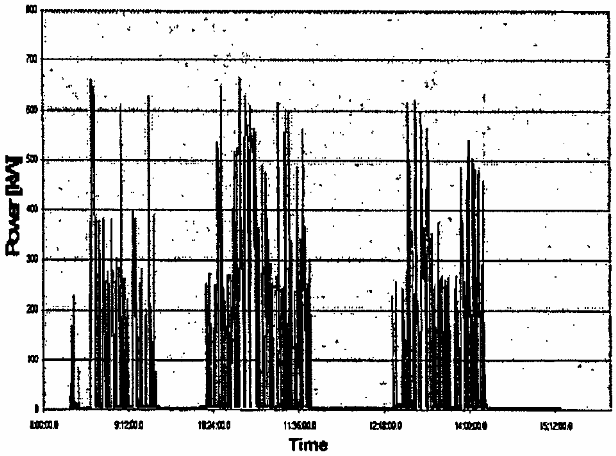

Figure 2: Shunting Power Requirements Reproduced from [1].

Supercapacitors have already found applications in electric vehicle applications where their high discharge capacity and better charge discharge efficiency can potentially improve performance, [14-16]. The largest supercapacitors, 4500F at 2.7 V, appear to be manufactured by Skeleton Nanolaboratory, [17]. Supercapacitors can be interfaced to the DC bus of a locomotive via a DC-DC converter which in this case would need to have a discharge rating of 375kW. The charge rating can be much less and 100kW, the alternator rating, would be the upper limit. Similar powers have been achieved in a crane application where supercapacitors were used to average the hoisting power requirement, [18].

In order to extract the large part of the stored energy from the capacitor bank its voltage needs to vary widely. The top voltage will correspond to 880Vdc, the nominal battery voltage as it will be charged with a buck converter. Discharge will be performed by a boost converter. Under discharge, the bottom voltage will be limited to 440Vdc as this corresponds to a maximum current 852Adc. Lower discharge voltages will force either a higher current rating or reduced power. At 440Vdc 75% of the energy is extracted. A bank of 350 series by six parallel connected capacitors will achieve this level of storage. The total bank capacity is 77.5F at 880Vdc which represents 30MJ in total, of which 22.5MJ are recovered in the discharge mode. The mass is 1.4 tons and the volume is 1.04m^3. The rated current is 4 800Adc. The equivalent series resistance is 13 mΩ. The cycle life is specified as 250 000 cycles for 300A discharges. This will give a service life in the order of ten to twenty thousand hours which will be comparable to the expected battery lives. The current pricing of supercapacitors, is in the order of $6USD/kJ, [19]. This capacitor bank is valued at $270 000USD and is currently more expensive than the battery it replaces.

7. CONCLUSIONS

Several battery storage technologies exist that allow 1000hp class locomotives to be converted to a hybrid battery electric operation. A battery life in the order of 12 500 hours, and probably more, can be achieved with spiral grid wound lead acid cells. There is an economic case for conversions based on the current fuel prices.

Lead acid batteries offer cost advantages. While nickel cadmium and lithium ion batteries are capable of performing in this role the price differential is difficult to justify. Lithium ion produces a much lighter solution but this is not a large advantage in this application. Railway operations use steel wheels on steel rails and offer an order of magnitude rolling resistance advantage over rubber tyres. Shunting yards, at least in Australia, are never constructed with significant grades. The mass saving does not justify a price premium.

Supercapacitor technology is an interesting possibility that technically, but not economically, could halve the required battery size. This is a technology, which like lithium ion battery development, is being driven by the electric vehicle sector. It may well emerge as a realistic alternative if volumes reduce price.

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