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Electrochemical Capacitor Powered Automated Guided Vehicles (AGVs)

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Summary

The majority of Automated Guided Vehicles (AGVs) are powered by on-board battery storage systems, lead-acid batteries being the most common technology. Although electrochemical capacitors store considerably less energy than batteries and are much more expensive, they can often provide lower ownership costs in AGV applications, primarily because of their very high cycle life and extremely long operational life. We examine application requirements needed to support economic use of electrochemical capacitor storage in AGVs. Performance details are reported for an AGV demonstration system that is powered by electrochemical capacitors.

Key words: Automated Vehicles, Battery, cycle life, Electric Double Layer Capacitor, EDLC

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1 Introduction

Automated Guided Vehicles (AGVs) are widely used in manufacturing and warehousing because they help reduce labor costs, improve efficiency, increase dependability and thus can provide an overall economic benefit. Generally an AGV is powered by an on-board energy storage system that periodically is recharged. Lead acid batteries were historically chosen for the storage system because of their low initial cost. Standard flooded designs were used first and then later the more-advanced maintenance-free sealed lead acid designs because they do not require watering and generally have higher cycle life and longer operating life. Irrespective, advanced lead acid batteries are still heavy, have low efficiency, and demand long charge times. Nickel metal hydride battery systems have been used more recently to power some AGVs. This type battery offers still higher cycle life and higher charge rates (shorter charge times) but it is more expensive. Additional mass reductions and still higher charge rates have been realized by using lithium ion batteries in the energy storage system. Their cost is still greater but they offer even higher cycle life. Lithium ion battery safety has improved significantly in recent years (due to growth of the electric automobile industry), which today removes safety as a primary factor when considering this battery technology.

Electrochemical capacitors (ECs), sometimes referred to as supercapacitors or ultracapacitors, have been proposed for use in some AGV applications. EC energy storage technology is safe and offers essentially unlimited cycle life (>1,000,000 charge/discharge cycles), long operational life, and extremely high charge rates. EC energy density, however, is substantially below the value of every battery technology. But due to its high cycle life and rapid charge capability, this attribute is not limiting for AGV applications provided frequent charging is possible, which generally is the case in the majority of AGV applications.
This paper describes results from our investigation of EC storage technology used to power an AGV located at the Nippon Chemi-Con Nagaoka factory in Japan.

2 Electrochemical capacitor powered AGV

Figure 1 shows a photograph of an AGV that uses electrochemical capacitor energy storage. This AGV is used in the Chemi-Con manufacturing plant in Nagaoka, Japan. Vehicle mass with work load is ~325 kg and the mass of the electrochemical capacitor module used to power the AGV is ~12 kg. The capacitor module in this AGV, shown in **Figure 2**, is comprised of twelve series-connected model DXE 3600-F Nippon Chemi-Con electrochemical capacitor cells. It operates between 30 V and 15 V and can deliver ~100 kJ of energy, equivalent to ~28 Wh. The AGV capacitor module was designed to provide 2.5 round trips plus have a margin of one round trip for operation with an average load of 325 kg.

Figure 1: Photograph of capacitor-powered AGV located at the Nippon Chemi-Con factory in Nagaoka, Japan.

Figure 2: Electrochemical capacitor module used to power the AGV shown in Figure 1. Twelve model DXE 3600-F Nippon Chemi-Con electrochemical capacitors are connected in series. The module is rated at 30 V and can deliver ~100 kJ (28 Wh) with discharge to 15 V.

A block diagram of the capacitor power system, including the charging transmitter, is shown in **Figure 3**. The capacitor is charged wirelessly at a dedicated charging station. Charging time to 30 V (with 30 A current) ranges from 30 seconds to ~150 seconds, depending on initial module voltage.

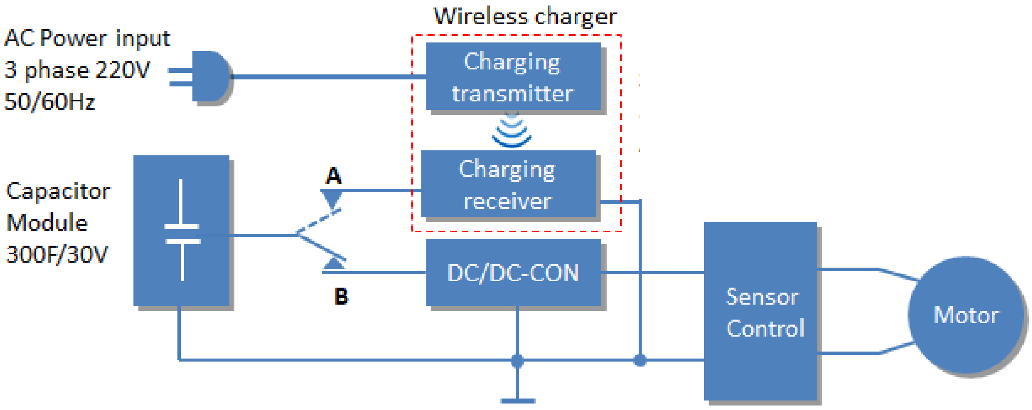

Figure 3: Block diagram of the capacitor energy storage system used to power the AGV. Wireless charging takes place at a base station in the factory. Switch position **A** is for charging the capacitor module and position **B** is for AGV operation.

Figure 4 shows a power profile for a fully loaded capacitor-powered AGV along with capacitor module voltage and current. The power level depends on operating activity, for instance cruising, steering, or standby idle. For this power profile, the AGV returns to the wireless charging station after ~380 s where it is charged with 30 A current from 22.5 V to 28 V in 45 s.

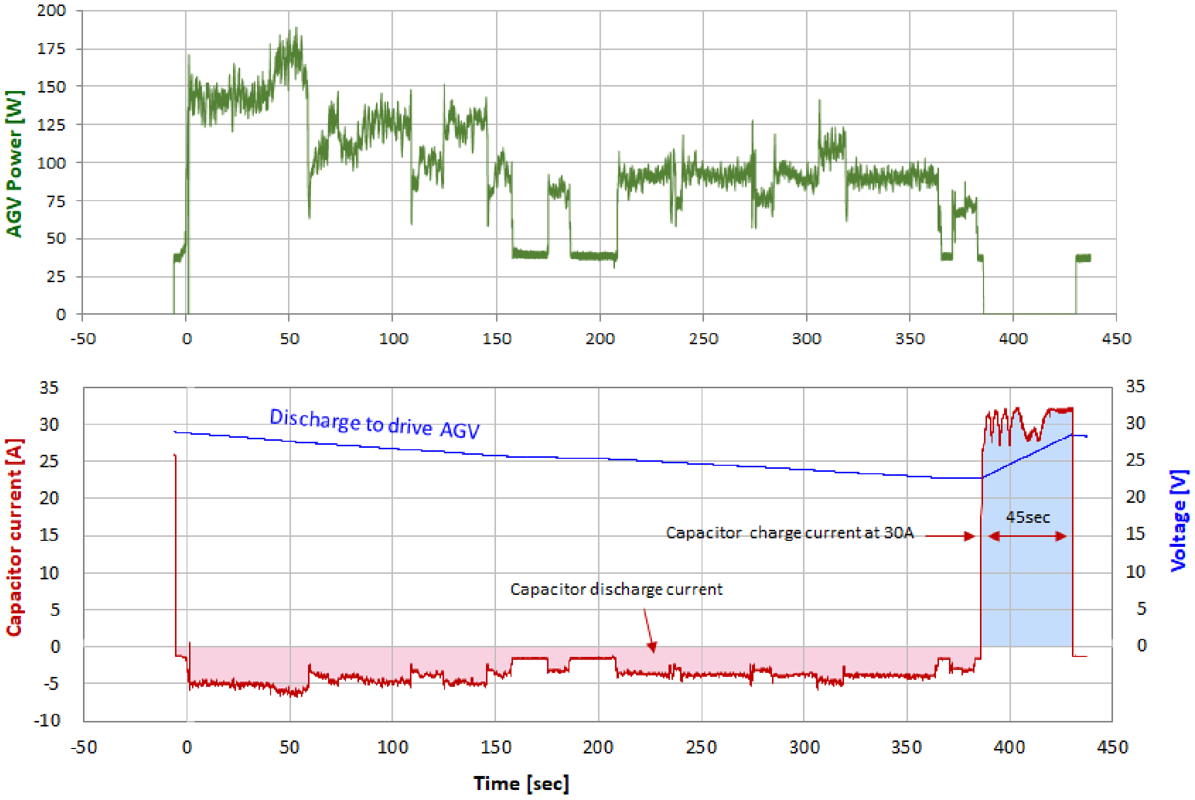

Figure 4: AGV power profile is shown in the upper graph and capacitor module voltage and current is shown in the lower graph. With 30-A current, the capacitor module is charged from 22.5 V to 28 V in ~45seconds (blue shaded region).

3 Life analysis

3.1 Cycle Life at Room Temperature

The minimum life expected today for an AGV is 10 years during which time its energy storage system may be charge/discharge cycled 350,000 times. This number was calculated assuming continuous AGV operation seven-day-a-week with four charge/discharge cycles every hour. **Figure 5** shows cycle-life performance of a Nippon Chemi-Con electrochemical capacitor similar to the type used in the AGV, which was cycled at constant-current between V_{max} and $0.5 \bullet V_{max}$ using a 30-second cycle. As shown, during two million cycles the discharge capacitance decreased less than 12% and the internal resistance increased less than 40%. Importantly, property fade was gradual and predictable. Batteries are not able to match this level of cycle performance. Cycle-life predictions for a typical lead acid battery are shown in **Figure 6** [1]. As shown, shallow depths of discharge will increase battery cycle life. Correspondingly, this will also reduce the effective energy density of battery. For example, battery energy density must be reduced by more than ten times to reach 10,000 charge/discharge cycles. Achieving this level of cycle life, however, can never be certain with batteries because they experience random catastrophic failures. Such failures are extremely rare with electrochemical capacitor technology. Irrespective of reliability issues, periodic battery replacements is needed to reach the design goal of 350,000 cycles. And such replacements, of course, increase operating expenses. The cycle life plots shown in Figures 5 and 6 are for normal ambient temperature conditions of 20 to 25 °C.

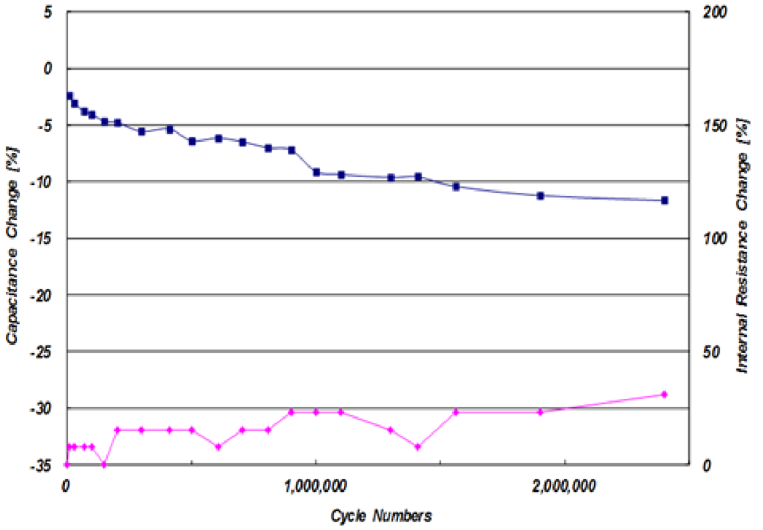

Figure 5: Room-temperature electrochemical capacitor cycle-life. As shown, stored energy fade was <12% after 2,000,000 cycles.

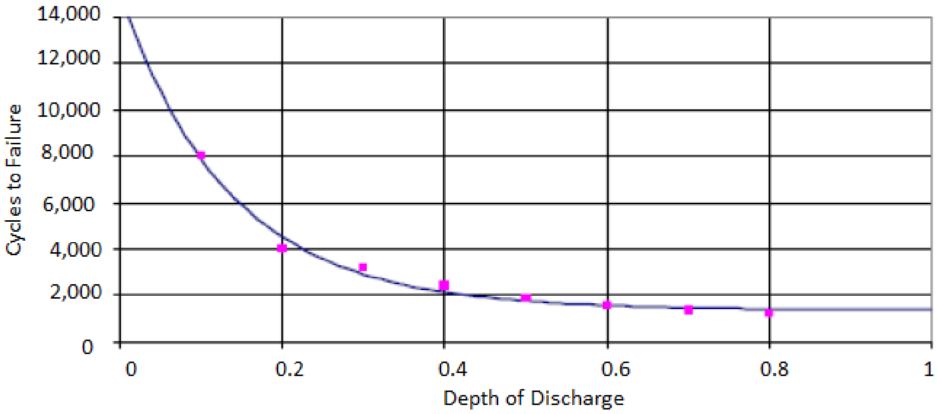

Figure 6: Typical cycle life performance of a lead acid battery at room-temperature, which shows that high cycle life requires shallow depths of discharge. However, this correspondingly reduces its effective energy density.

3.2 Cycle Life at Elevated Temperature

Electrochemical capacitor cycle life at room temperature greatly exceeds one million cycles and thus it should readily meet the ten-year cycle-life requirement. However, electrochemical capacitor cycle-life is reduced at high temperatures, which may be encountered, for instance, in unconditioned warehouse space at some locations. **Figure 7** shows average high and low temperatures over one year in Phoenix, Arizona, USA, a local known for its hot climate. As shown, the average high temperature peaked at 104 ^{0}F (40 ^{o}C) in July.

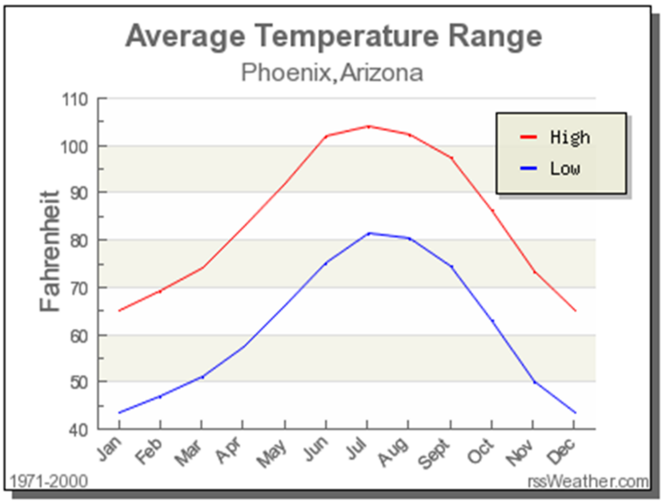

Figure 7: Average temperature distribution for YR 1971 to 2004 [2]

To determine the maximum capacitor temperature in the AGV application, self-heating must be calculated. Capacitor temperature will equal the ambient temperature T_a plus ΔT caused by self-heating, which is due to internal losses. These internal losses are calculated as i^2R where I is the RMS current shown in the lower part of Figure 4 (10.3 A) and R is the internal resistance, which is equal to 0.27 mΩ. Thermal resistance of these capacitors is 7.5 °C/W. Then the calculated self-heating temperature increase ΔT will be:

$$\Delta T = \left(7.5\ {}^{o}C/_{W}\right) * (10.3\ A)^2 * (0.27\ mOhm) = 0.2\ {}^{o}C \qquad (1)$$

This value is small and can be safely ignored in capacitor life calculations.

AGV capacitor storage system life can be predicted by following a sequence of steps and assuming the temperature follows the Figure 7 temperature profile. First, Figure 7 is approximated as shown in **Table I** where only three temperatures are used to represent the average high-temperature curve. This greatly simplifies later computations. Thus maximum average high temperatures during the first three months of a year is set at 20 °C, the next two months set at 30 °C, the following four months set at 40 °C, etc.

Table I: Approximation of the Figure 7 average high-temperature plot. During one year (8760 hours), 3600 hours would be at 20 ℃, 2280 hours at 30 ℃, and 2880 hours at 40 ℃.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Highest (°C)	18.3	20.8	23.5	28.3	33.3	38.9	40.1	29.1	36.3	30.2	22.9	18.3
Approximation (°C)	20			30		40				30	20	

Second, life estimates (**Table II)** are made for the time at each of the three simplifying temperature levels. Listed life estimates are based on extensive test data and models developed by Nippon Chemi-Con for its electrochemical capacitor cells.   Also listed in this table is the ratio of time spent at each of the three temperatures to the time in one year. Column 2, for example, covers Jan to Mar and Nov to Dec and lists 3600 hours, which represents R_n=3600/8760=0.41 of the year.

Table II. Life estimates at each of the three temperatures of the simplified temperature profile. Also listed is R_n, which is the ratio of time at each temperature T to the time in one year.

Period	Jan to Mar, Nov to Dec	Apr to May, Oct	Jun to-Sep
Estimated time (hours)	3600	2280	2880
Capacitor temperature T (℃)	20	30	40
Predicted life at temperature T (hr)	120500	88140	65760
R_n= ratio of temperature T time	0.41	0.26	0.33

Miner's Rule [3] can be used to estimate capacitor life since it is maintained for different lengths of times at each of the three temperatures. This rule is:

$$L = \sum_{n=1}^{n} \frac{Rn}{Ln} \tag{2}$$

where L is the predicted life, n is the number of temperature levels, L_n is the life at each temperature level, and R_n is the ratio of number of hours at each temperature to the number of hours in one year. Using Miner's Rule with Table II data yields AGV capacitor life for operation in unconditioned space in Phoenix, Arizona.

$$L = \frac{1}{(\frac{0.41}{120500}+\frac{0.26}{88140}+\frac{0.33}{65760})} = 87{,}950\ hours\ \approx 10\ years \tag{3}$$

Life values at each temperature were based on the definition that capacitance loss of 30% represented the end-of-life. The AVG at the Nippon Chemi-Con Nagaoka-plant successfully operates with a capacitance value equal to a 40% reduction in capacitance. This translates to a predicted life of ~18 years for the electrochemical capacitors in the AGV, the projection relying on extensive life test data and models developed by Nippon Chemi-Con.

4 Economic discussion

Simply based on the costs of energy delivered during a single discharge cycle, an electrochemical capacitor storage system is much more expensive than a battery storage system. However, electrochemical capacitor storage system costs may be lower than battery storage system costs on a long-term basis. This arises from several factors including the high cycle life of a capacitor, its long and maintenance-free operational life, and its rapid charge time. Rapid charging, for example the 45-second-charge-time shown in Figure 4, can create fewer process-flow disturbances in the work place and provide great value.

Lead acid batteries have much lower initial cost than electrochemical capacitors. However, they generally require daily service work and may require replacement every 1.5 years in the AGV application, which adds to ownership costs. Cost comparisons between the two energy storage systems, with assumptions, are listed in **Table III**. Charger costs for the capacitor are higher because it is a wireless system. This alleviates labor costs associated with storage system charging. On the other hand, two batteries are required when battery-powered, one to power the AGV and the second one being charged. Battery swapping is performed daily. **Figure 8** shows running costs. EC solution costs are estimated to equal battery solution costs at year five. For 18 years of operation, cumulative direct cost saving is estimated to be $14,000 for an electrochemical capacitor storage system compared with a lead acid battery storage system.

Table III: Cost comparison of the two energy storage technologies. Costs have been converted to US dollars.

TECHNOLOGY	Storage device cost ($)	Charger cost ($)	Maintenance cost ($)
Electrochemical capacitor	1100	5500	0
Lead-acid battery	650 1)	420	830 2)

1) Battery life is assumed to be 1.5 years. Labor costs for battery change-out are included.

2) Labor costs are associated with battery swapping and charging that is assumed to occur each day.

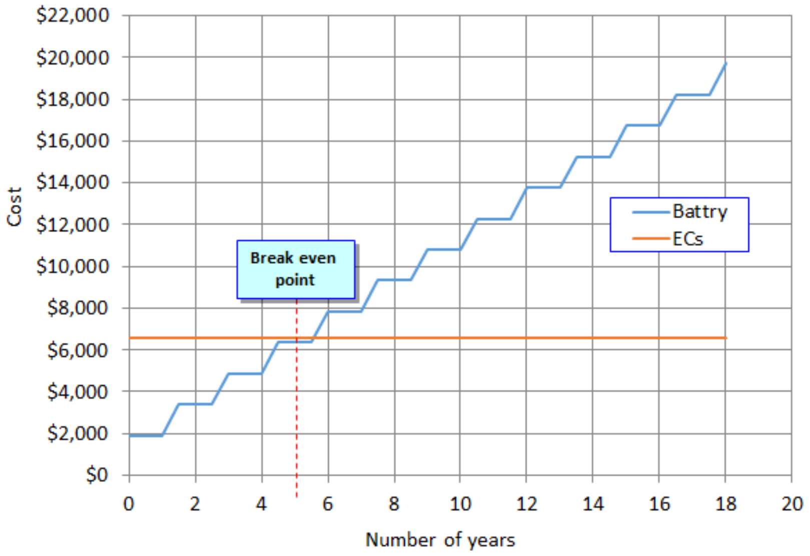

Figure 8: Predicted running cost for two energy storage systems used in an AGV—one using electrochemical capacitors and the other using lead acid batteries. The capacitor is wirelessly charged and operates maintenance-free for 18 years. Thus, its sole cost is the initial purchase. The battery, on the other hand, needs daily maintenance plus replacement every 1.5 years.

5 Summary

Automated Guided Vehicles powered by electrochemical capacitors have operational benefits over battery-powered vehicles. Significantly, AGVs powered by capacitors have lower long-term ownership costs than those powered by batteries.

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References

[1] http://www.power-thru.com/documents/The%20Truth%20About%20Batteries%20-%20POWERTHRU%20White%20Paper.pdf accessed on 6/27/2017
[2] http://www.rssweather.com/climate/Arizona/Phoenix accessed on 6/26/2017
[3] Nian-Zhong Chen, Ge Wang and C. GuedesSoares “Palmgren–Miner’s rule and fracture mechanics-based inspection planning”, Engineering Fracture Mechanics 78, pp 3166–3182 (Dec. 2011).

Author

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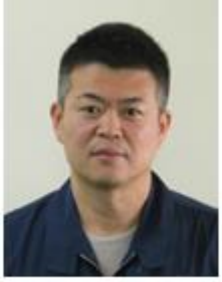

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