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Valve-regulated lead-acid batteries for stop-and-go applications

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Abstract

Increasing levels of demand for electrical power for vehicles have prompted a considerable level of research into higher voltage systems. This has resulted in the definition of preliminary standards for 36/42 V systems. The implementation costs for these systems are high and this has led to improvements in 12/14 V power architectures. In particular, alternator power outputs at 14 V have increased and the need for lower emission levels and fuel economy is stimulating a demand for stop-and-go systems. In this type of application, the engine is stopped each time the vehicle comes to a halt, and is restarted when the accelerator is pressed again. The duty cycle that this applies to the battery is quite onerous with many shallow discharge cycles. Flooded lead-acid batteries are unable to meet the requirements and valve-regulated lead-acid (VRLA) batteries are essential to meet the demands applied. The background to stop-and-go battery applications is considered and test results on practical batteries are presented to show that under a simulated duty cycle, good performance can be achieved. There is also a need for a higher level of battery management for stop-and-go systems. A practical approach to battery condition monitoring to assess the state-of-charge and state-of-health of the battery is described.

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Keywords: Valve-regulated lead-acid; 36/42 V PowerNet systems; PowerNet; State-of-charge; State-of-health; Vehicles

1. Introduction

The electrical power requirements for vehicles are continuing to increase and to meet this demand, there has been a considerable amount of research and development activity applied to 42 V PowerNet systems [1–3]. There is no doubt that in the longer term as current demands increase, there will be a shift to higher voltages, but in the near term, the costs of implementing 42 V systems are inhibiting the exploitation of this technology. The requirements for higher electrical power, lower emission levels and improved fuel economy remain, however, in the forefront of vehicle manufacturer's requirements. This has led to the development of higher power alternators operating at 12/14 V, the deployment of dual-battery systems, and to the introduction of stop-and-go systems. In stop-and-go applications, the engine is stopped each time the vehicle comes to a halt and is started as soon as the accelerator is pressed again. This places new and heavy demands on the battery and a valve-regulated lead-acid (VRLA) battery is essential to meet the duty cycle. In this paper, the background to this requirement is discussed and test results for practical batteries under a simulated duty cycle are presented. This type of application also increases the need for battery management to ensure that the system is fully reliable. A practical approach to battery condition monitoring to assess state-of-charge (SoC) and state-of-health (SoH) is also described.

The different levels of requirement for advanced automotive batteries are summarized in Table 1 [4]. At the first level, higher power demands and the need for additional security when using drive-by-wire or brake-by-wire are leading to the use of two batteries on cars. The function of the main battery is unaltered, but the auxiliary battery will serve as a reserve power supply and will be controlled by a battery-management system to ensure that power is always available for critical functions. At the next level, stop-and-go is required, possibly with a limited use of regenerative braking. Higher voltage batteries at 36 V may be used initially for increased power, but will not be extensively applied until increased functionality is needed. They can provide power for stop-and-go capability and this can include launch assist or a greater level of power assistance to increase fuel efficiency. Valve-regulated lead-acid batteries are capable of meeting all of these requirements, but for higher voltage batteries used in full hybrid electric vehicles (HEVs), nickel−metal-hydride is the system of choice in the near term, with lithium batteries in prospect for the future. Nonetheless, HEVs need specific power rather than specific energy and lead-acid re-

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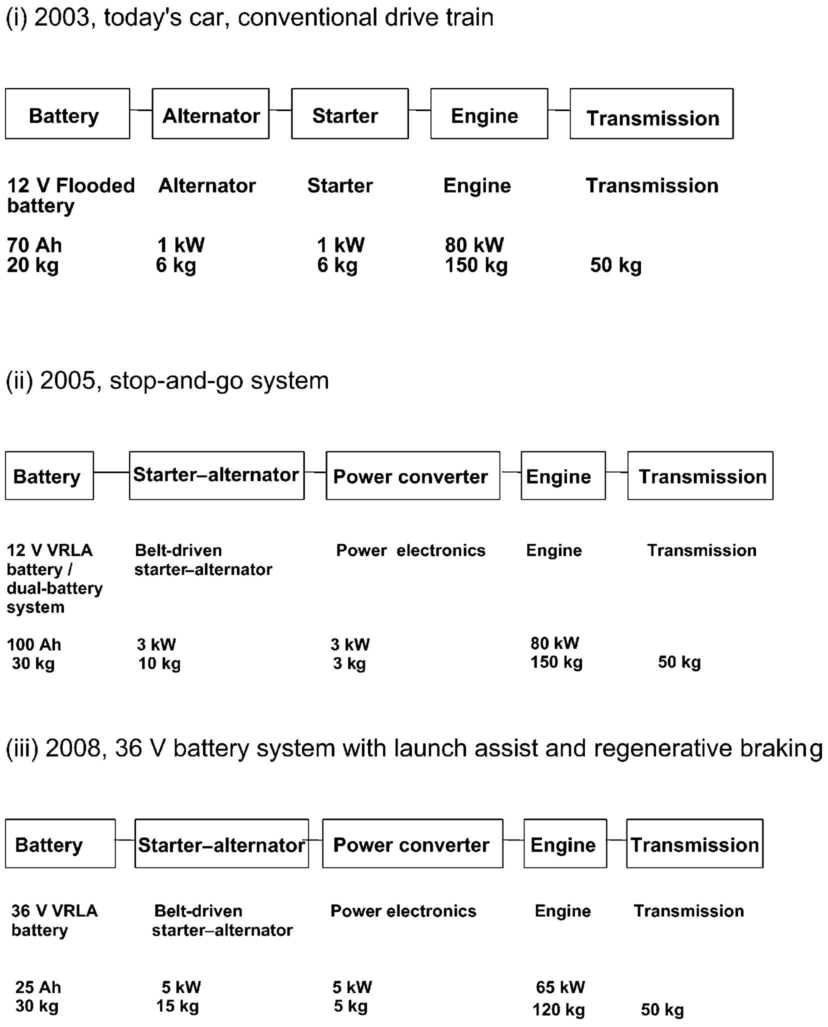
Table 1
Summary of the different levels of requirement for advanced automotive batteries

Type	
1	12 V dual-battery system for electrically-powered ancillaries
2	12 V stop-and-go, single- or dual-battery, regenerative braking
3	36 V larger automotive battery for higher power
4	36 V battery with stop-and-go
5	36 V battery with launch assist only (‘soft’ hybrid)
6	36 V battery with power assist (‘mild’ hybrid)
7	Higher voltage battery with power assist (‘full’ hybrid)
8	Full hybrid with electric only range

mains the most cost-effective system in terms of watts per dollar. Lead-acid is capable of meeting these requirements with specific improvements targetted at this type of duty cycle. Furthermore, the use of VRLA batteries in association with supercapacitors may be a good way of exploiting the best characteristics of each type of energy-storage device.

The key elements of drive-trains evolving from a conventional application, through a stop-and-go system to a drive-train with launch assist and regenerative braking are shown schematically in Fig. 1. In today’s cars, the battery is normally a flooded type and the alternator will have a power output of the order of 1 kW. The starter is separately installed and whilst it may have a higher instantaneous power rating, it is a relatively small machine. For stop-and-go, the starter and alternator become a single machine that is capable of producing a higher power output with power conversion to use the battery to start the vehicle and to derive a dc output. Combined starter—alternators are belt driven rather than being integrated into the engine. The more intensive shallow cycling duty on the battery is met by a VRLA battery which may need to have a higher capacity. Regenerative braking may be an option, but the energy recovery will be modest. Stop-and-go will provide a fuel saving of around 5%, but the reduction in city-centre emissions will be more dramatic at up to 30%. At the next level, with a limited amount of power used for launch assist, higher voltages are needed, a higher power starter—alternator-generator integrated on to the main engine shaft is used, but the engine can be downsized and overall economy is significantly improved. In


(i) 2003, today's car, conventional drive train

(ii) 2005, stop-and-go system

(iii) 2008, 36 V battery system with launch assist and regenerative braking

Fig. 1. Evolution of drive-trains and power system architectures.

Europe, a standard in terms of carbon dioxide emissions has been set at 140 g km^{-1} by 2008 as an overall level. This can be met with a mix of vehicles including stop-and-go, but the next step to 120 g km^{-1} will require an increased proportion of HEVs of various types.

2. Duty cycles

The duty cycle for batteries for stop-and-go applications requires large numbers of shallow high-rate discharges where the battery may not be regularly returned to a fully-charged condition. This high-rate partial state-of-charge (HRPSoC) operation is challenging for lead-acid and the test regime needs to simulate the requirement. The Advanced battery consortium in the USA (USABC) has proposed a zero power assist (ZPA) test cycle to provide a SoC neutral pulse profile for stop-and-go with a 90% round trip efficiency. Each cycle takes 3 min and reference capacity checks are made at intervals of 10 000 cycles. Similarly, EUCAR has a power assist profile for cycle-life testing with a 2-min cycle, with a high-power pulse and then a two-step charge to simulate regenerative braking and intermediate rests. This test also uses capacity checks at intervals of 10 000 cycles to validate performance.

The above tests do not replicate a more complex driving pattern and a more elaborate regime has been selected in the present study to be more representative whilst avoiding highly detailed drive-cycle tests. The test regime is shown in Table 2. The key features are a two-step discharge with a short peak current and longer lower level of current repeated 10 times, followed by periods of charging for various durations. This is considered to reflect more precisely the duty cycle. Reference capacity checks are made at intervals. The full cycle takes 3 h and has 60 discharge cycles. It has been estimated that 24 000 discharge cycles represents 1 year of use.

In addition to the duty cycle required for repeated engine starting, the battery also needs to perform all the requirements for normal service. This includes normal cold-starting performance at −18 °C or as low as −30 °C for extreme environments, to have sufficient reserve capacity for key-off use of the vehicle and emergency duties, to support long periods of stand with low drains, to have a high charge acceptance and to withstand high service temperatures. Valve-regulated lead−acid batteries display good behaviour over a wide range of service temperatures. At the high end, 60 °C can be tolerated for short periods, but for long service life 40 °C is a more reasonable maximum. In an application where there is regular cycling, internal heat generation will be more severe and thermal management will be important. Battery location in the vehicle has a strong influence as the engine compartment is very hot. Shielding and thermal barriers can be used with good effect. Active cooling is not favoured because of cost and complexity. A battery-management system can also be used to control temperature by reducing the number of stop-and-go cycles if the temperature exceeds a critical level. Low-temperature performance of VRLA batteries is generally excellent and will be as low as −40 °C in a fully-charged condition, but for PSoC operation, if the battery is permitted to remain in a partially-charged state, low-temperature performance will be reduced.

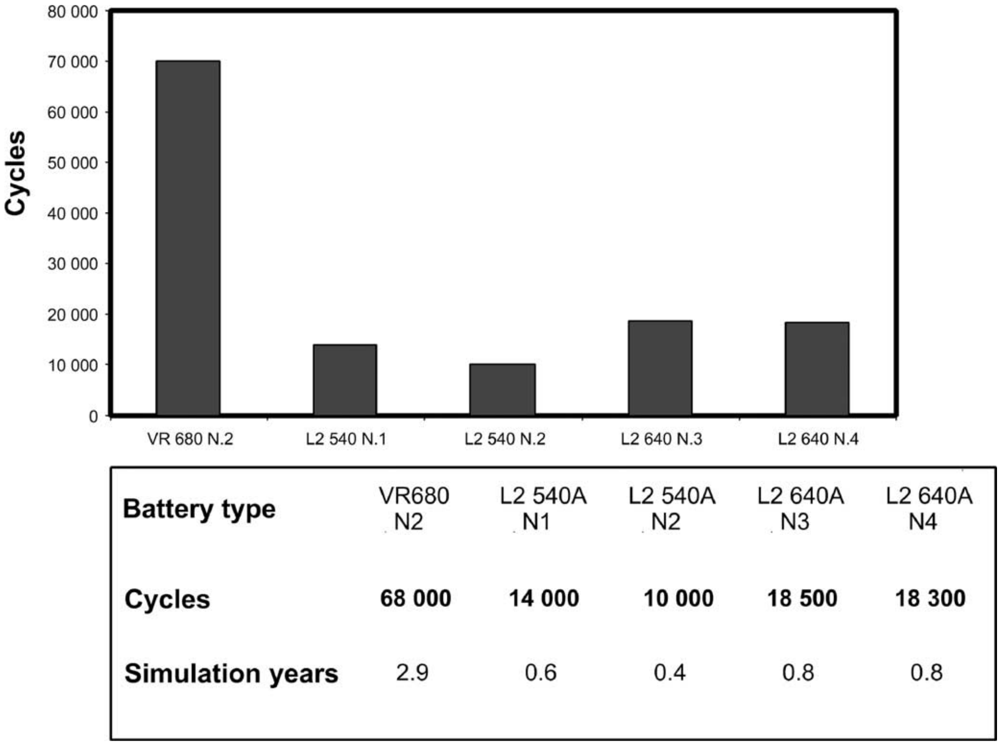
For stop-and-go applications without regeneration, the battery can be returned to a fully-charged state, but if regeneration is needed then a margin between the actual SoC and a full charge is needed. Operational strategies to return the battery to a fully-charged condition at end of use and then allow it to be discharged in use are correct in principle but flawed in practice as the end of a journey can never be predicted. Reserve capacity for VRLA batteries is simply a matter of battery sizing. For longer discharges, VRLA has good charge retention with low levels of self-discharge so that several months of standing presents no difficulty. Low levels of key-off discharge are also acceptable provided that the battery is not taken below 50% SoC in order to be able to retain an adequate cold-cranking performance. Overall, VRLA batteries offer good performance for all aspects of normal automotive service and can be adapted to the needs of stop-and-go applications.

3. Battery requirements and construction

The specific requirement for the application was for a 55 Ah battery with a cold-cranking rating of 640 A to EN

Table 2
Test regime for VR 680 battery in simulated stop-and-go cycling

Test regime	Charging modes are only to fixed charging times and not to any charging factor. Every daily cycle is made of 60 discharge and charge cycles divided into six microcycles as below.
1st microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 5 min
2nd microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 30 min
3rd microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 15 min
4th microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 5 min
5th microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 3 min
6th microcycle	10 repeated discharge cycles, with $I = 100$ A for 2 s, $I = 25$ A for 60 s, charge at 14.4 V, 50 A initial current limit for 60 min
Requirement	Every complete cycle (60 discharge−charge cycles) takes 3 h, so that 8 units or 480 total cycles are made daily. The requirement is for 20−24 000 cycles per year, and therefore 60−72 000 cycles to simulate a 3-year life.



Battery type	VR680 N2	L2 540A N1	L2 540A N2	L2 640A N3	L2 640A N4
Cycles	**68 000**	**14 000**	**10 000**	**18 500**	**18 300**
Simulation years	2.9	0.6	0.4	0.8	0.8

Fig. 2. Test results on simulated stop-and-go cycling.

in an L2 package. This was met with a specially-designed battery using a polypropylene container designed to withstand internal pressure and maintain high pack compression in service. Each cell was separately vented with a simple Bunsen valve. The grids were cast in lead–calcium–tin alloys and the active mass was optimized for continuous charge–discharge duty. The plates were wrapped in an absorptive glass mat (AGM) separator. The battery performed well to a normal automotive specification and was able to provide high performance over an extended life, as well as withstanding high temperatures.

Grid alloys should have low corrosion rates. This was achieved by selecting lead–calcium–tin alloys with lower levels of calcium and higher levels of tin. The tin level was sufficient to form a good interfacial layer between the grid and the positive active-mass. The paste density had to be slightly higher to give good durability on cycling. The expander addition was optimized for high-rate performance and plate processing and formation were designed to retain the integrity of the expander. The AGM separator selected had a thickness and grammage to ensure that a high stack compression was retained in the wet state and a had good ability to be processed. Battery assembly followed normal automotive practice with extrusion/fusion inter-cell welding and a heat-sealed cover. The battery case was specially designed with ribbed and reinforced end-walls to maintain uniform compression. Acid filling was carried out under controlled conditions and formation followed with careful attention to the current input levels and temperature.

4. Test results

The test results are summarized in Fig. 2 and compared with those for flooded battery types which failed within a year of simulated life. The VRLA stop-and-go battery reached 68 000 cycles, equivalent to nearly 3 years of service. Trials are now in progress to further optimize the performance of the battery and incorporate various approaches to improve cyclic behaviour and the sulfation behaviour of the negative plate.

The separator plays a key role in the performance of VRLA cells, and the formulation of the material to reduce the diffusivity of oxygen to the negative plate can reduce the reduction in potential caused by higher rates of recombination. The use of different forms of carbon in the negative plate is important. Very finely divided forms of carbon im-

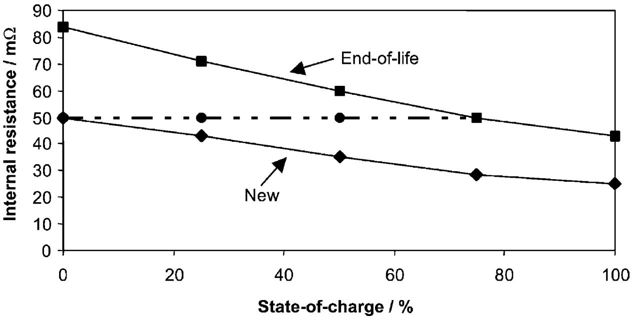


Fig. 3. Variation of internal resistance with battery age and SoC.

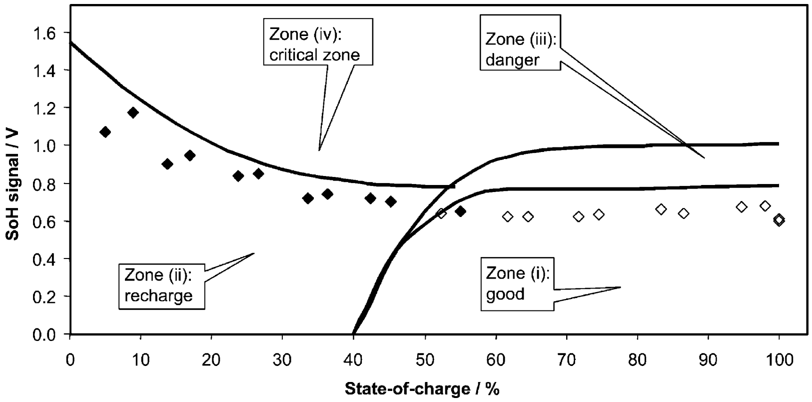


Fig. 4. Analysis of battery SoC and SoH by measurement of open-circuit voltage and voltage response on discharge. The four zones are: (i) area above 50% SoC where SoH signal is small and battery is in good condition; (ii) area where SoC is below 50% and SoH signal increases because battery has a lower SoC; (iii) area of concern where SoH signal is increased but SoC is above 50% and (iv) critical zone where SoH signal is high irrespective of SoC.

prove the conductivity, but larger graphitic particles provide better particle-to-particle contact. Conductivity is improved more effectively on an equivalent weight basis. This is being trialled with encouraging results.

5. Battery condition monitoring

Battery condition monitoring is being carried out by measuring the SoC and SoH of the battery in order to determine the state-of-function (SoF), which is defined as the ability of the battery to carry out specific or critical parts of the duty cycle. For example, the use of the battery would be curtailed for stop-and-go cycling if the ability of the battery to restart the vehicle was impaired by intensive use that takes the battery to a low SoC. Battery condition monitoring and an associated management system is essential to assure reliability and optimize service life. It will also provide an incidental benefit in reducing warranty returns for batteries simply with a low SoC.

The methodology adopted to measure SoC is based on measuring the open-circuit voltage (OCV) when the vehicle is not in use (key-off). The SoH is measured by analyzing the voltage dip on starting (key-on) and the voltage response to small fixed load applied every few hours when the vehicle is not operating (key-off). Operational loads are also determined. The SoH measurement records the internal resistance of the battery. This varies with the life of the battery at any given SoC (Fig. 3). The results are analyzed by using a look-up table for each battery type to give an indication of the SoC and SoH. The results are presented in Fig. 4. The relationship has four zones: (i) an area above 50% SoC where the SoH signal is small and the battery is in good condition; (ii) an area where the SoC is below 50% and the SoH signal increases because the battery has a lower SoC; (iii) an area of concern where the SoH signal is increased but the SoC is above 50% and (iv) a critical zone where the SoH signal is high irrespective of SoC. In zone (ii), battery operation would be curtailed to ensure the charge balance was positive; in zone (iii), an intermediate alarm or service indicator would be activated and battery use reduced; in zone (iv), an immediate action alarm would be activated.

6. Summary and conclusions

The requirements for stop-and-go applications for automotive service can be met with VRLA batteries. These have an intensive duty cycle and need to be constructed to optimize performance in HRPSoC operation (especially for cyclic performance) through good separator design, the use of active materials with higher integrity on cycling and by optimising the behaviour of the negative plates. Testing under a simulated duty cycle has shown that good service lives can be achieved.

Improvements in HRPSoC operation will open the way to applications where there is a need to provide power for launch or power assist. This will improve the prospects for 36/42 V systems with VRLA batteries as fuel economy and emission control regulations become more stringent.

Measurements of SoC and SoH are critical if reliability standards are to be achieved. Intensive battery operation cannot prejudice overall vehicle reliability. Simple measurement techniques will give good quality data that can be used to manage the battery as part of the electrical system on the vehicle and achieve the necessary standards.

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