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VRLA automotive batteries for stop&go and dual battery systems

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Abstract

The electrical power requirements for vehicles are continuing to increase and evolve. A substantial amount of effort has been directed towards the development of 36/42 V systems as a route to higher power with reduced current levels but high implementation costs have resulted in the introduction of these systems becoming deferred. In the interim, however, alternator power outputs at 14 V are being increased substantially and at the same time the requirements for batteries are becoming more intensive. In particular, stop&go systems and wire-based vehicle systems are resulting in new demands. For stop&go, the engine is stopped each time the vehicle comes to rest and is restarted when the accelerator is pressed again. This results in an onerous duty cycle with many shallow discharge cycles. Flooded lead–acid batteries cannot meet this duty cycle and valve-regulated lead–acid (VRLA) batteries are needed to meet the demands that are applied. For wire-based systems, such as brake-by-wire or steer-by-wire, electrical power has become more critical and although the alternator and battery provide double redundancy, triple redundancy with a small reserve battery is specified. In this case, a small VRLA battery can be used and is optimised for standby service rather than for repeated discharges. The background to these applications is considered and test results under simulated operating conditions are discussed. Good performance can be obtained in batteries adapted for both applications. Battery management is also critical for both applications: in stop&go service, the state-of-charge (SOC) and state-of-health (SOH) need to be monitored to ensure that the vehicle can be restarted; for reserve or back-up batteries, the SOC and SOH are monitored to verify that the battery is always capable of carrying out the duty cycle if required. Practical methods of battery condition monitoring will be described.

Keywords: Lead–acid; Battery; Valve-regulated; Battery monitoring; State-of-charge; State-of-health

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1. Introduction

A substantial and continuing increase in the electrical power requirements for vehicles has lead to a number of solutions. A substantial effort directed towards the development of 42 V PowerNet systems [1–3] has resulted in new types of battery and vehicle electrical networks to exploit the benefits this offers but the costs of implementing 42 V systems have put a halt to the exploitation of this technology in the short term. Nonetheless, the need for more electrical power, for lower emission levels and for improved fuel economy remain high priorities for vehicle manufacturers. Automakers are seeking to build cars that will meet the emission and fuel consumption challenges that are being promoted by the European Union and are attractive to consumers. The automotive industry has responded to the challenge by defining targets for greenhouse gas emission reductions. The Association des Constructeurs Europeenne d'Automobiles (ACEA) is looking to the industry to reduce CO_2 emissions by up to 25% by 2008.

One of the routes to this target is the use of stop and start or stop&go systems. The concept is simple; the engine is automatically cut off when the vehicle comes to a halt and is automatically restarted when the driver engages a gear or for an automatic transmission, when the driver releases the brake. Fuel economy is improved by up to 5% and city centre emissions are reduced by up to 30% but the duty cycle for the battery becomes more intense. As a result a valve-regulated lead–acid (VRLA) battery is essential.

In addition to the development of stop&go systems and a general trend to higher electrical power, a number of vehicle systems have become fully dependent on electrical power. Drive-by-wire or brake-by-wire require the additional secu-

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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&go, single or dual battery, regenerative braking
3	36 V larger SLI battery for higher power
4	36 V battery with stop&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

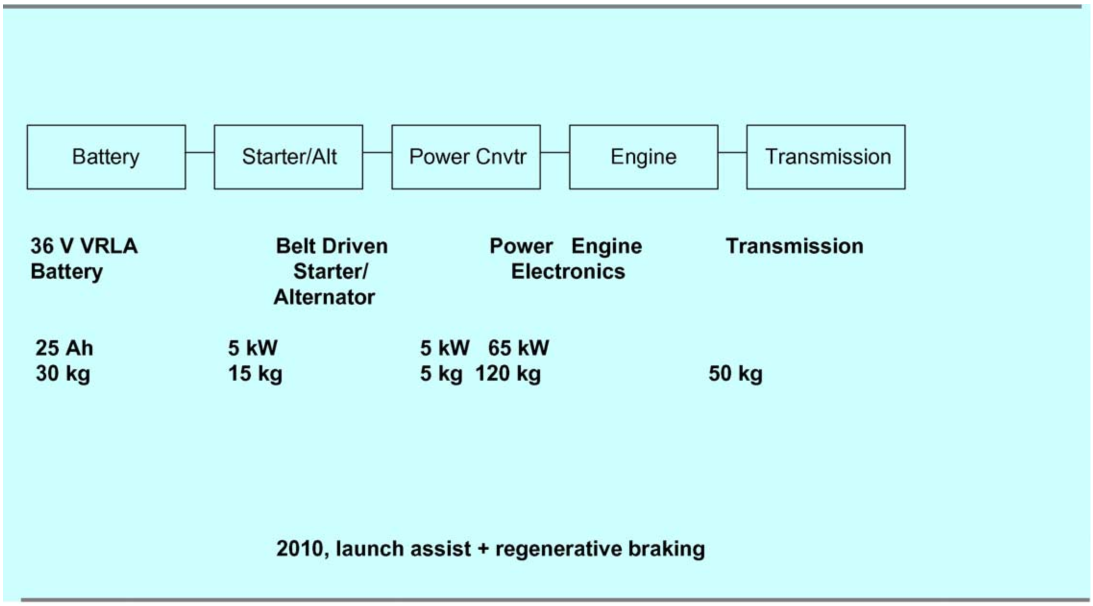
rity of a reserve power source and the use of small capacity VRLA batteries for standby power is emerging.

In this paper, the background to the requirements for batteries for stop&go applications and for back-up power will be discussed and the performance of practical batteries will be summarised. Both applications demand high levels of reliability and battery management becomes a vital tool to be certain that the batteries will perform correctly. A system for battery condition monitoring to assess state-of-charge (SOC) and state-of-health (SOH) will be described.

2. Evolution of battery requirements

The different levels of battery requirement for advanced automotive batteries are shown in summary form in Table 1 [4]. At an initial level, the need for higher power is met by a larger alternator and a larger battery; additional security for drive-by-wire or brake-by-wire is leading to the use of two batteries. The auxiliary battery serves only as a reserve power supply and is controlled by a battery management system to be certain that power is always available for critical functions. The next level brings stop&go functionality into play and the possibility of a limited amount of regenerative braking can also be realised. Higher voltages at 36 V may be used for increased power but in order to get full value, increased functionality is required, either for launch assist or a greater level of power assistance to increase fuel efficiency. Attempts to apply 36/42 V systems for launch assist have not demonstrated a high level of benefit and the transition to a full hybrid has become the next step. For this type of hybrid electric vehicle (HEV) nickel/metal hydride (Ni/MH) batteries have become the system of choice using higher voltage systems. The second generation Toyota Prius uses a 274 V Ni/MH battery and a bi-directional DC/AC converter to double the voltage to ∼500 V for the electric motor. Longer term, lithium batteries are likely to be used for HEVs. The requirement for HEVs is power density rather than energy density and lead–acid is the most cost effective system in terms of W/$. Improvements in lead–acid batteries, initially directed towards stop&go applications will make lead–acid more competitive for this type of duty cycle and the use of supercapacitors along with VRLA batteries may be a useful way of exploiting the best characteristics of each type of energy storage device.

Various types of drive train are shown in Fig. 1 starting with a conventional application, then a stop&go system and finally a drive train with launch assist and regenerative braking. For conventional applications, flooded batteries are used and the power output of the alternator is 1.0–1.5 kW. The starter is a separate machine to the alternator. In a stop&go system, the starter and the alternator become a single machine



(iii) 2010, 36 V battery system with launch assist and regenerative braking

Fig. 1. Evolution of drive trains and power system architectures: (i) 2004, conventional drive train; (ii) 2005, stop&go system; (iii) 2010, 36 V battery system with launch assist and regenerative braking.

as an integrated starter generator (ISG). The power output is higher and a power converter is used both to provide a DC output and to use the battery to start the vehicle. The unit is belt driven which makes it easier to adapt to existing drive trains rather than being concentric with the main engine shaft. The duty cycle is much more intensive than for a normal SLI battery and a VRLA battery is essential to obtain an adequate service life. At the final level, power from the battery is used for launch assist and for limited driving in an all-electric mode. Higher voltages are needed and the starter/alternator generator is integrated onto the main engine shaft. In the Prius, the electric motor has an output of 50 kW at 1400 rpm and the petrol engine an output of 57 kW at 4000 rpm. Similarly, maximum torque for the electric motor is 400 N m from 0 to 1200 rpm whereas the petrol engine provides only 115 N m at 4000 rpm. The combination permits both power sources to be operated where they are most effective and produces a 0–100 kph performance of less than 11 s with a combined cycle fuel economy of 4.3 l/100 km. The CO_2 emissions are 104 g km^{-1} which is much lower than the ACEA target for 2008 and also below the next target of 120 g km^{-1} which is under consideration.

Stop&go systems are available with power generation capability of up to 3 kW and 20% efficiency gains. They are capable of delivering 2 kW of warm cranking power and 65 N m of machine torque when cold making them capable of starting petrol engines up to 3 l in capacity and diesel engines up to 2 l in capacity at −30 °C. The machines may be liquid or air-cooled and the power electronics integrated in the machine or in a separate package. Warm engine starts are achieved in 400 ms from stationary to idle making the system virtually undetectable to the driver. A separate starter motor is not needed and the ring gear on the engine can be eliminated. Operating the air conditioning while the engine is stopped is not possible if the compressor is belt driven from the engine and an electrically powered compressor would be a significant load. The solution that is being proposed is to have part of the system as a thermal store containing cooled material that will in turn cool the air drawn over it by the fan while the air conditioning compressor is cut off to provide a few minutes of additional cooling. Fig. 2 shows the configuration of a stop&go system in a typical vehicle.

Auxiliary VRLA batteries are being fitted to some cars as a back-up or service unit to provide power to particular devices on the vehicle, either to protect the main SLI battery from discharge or to provide a back-up for various critical functions. For example, if the vehicle has brake-by-wire, steer-by-wire, electrically actuated brakes or other devices that need additional redundancy in the event of failure of the main power system, an auxiliary battery may be fitted. There may also be a need to power the locking mechanism or electric windows if the main battery has failed or alternatively, the vehicle can be configured such that an auxiliary battery provides the hotel load and another unit starts the car. In this case, the starting battery can be separated from the other loads so that starting is never compromised. In this paper, smaller VRLA batteries used to back-up critical functions are discussed.

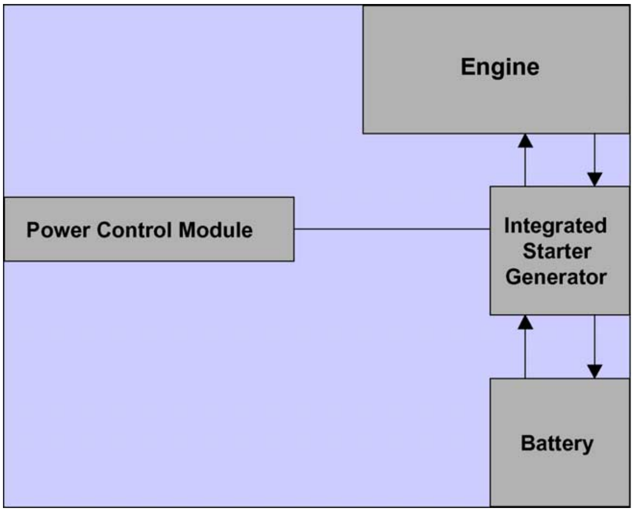


Fig. 2. Schematic diagram of a stop&go system with a belt-driven integrated starter generator (ISG) with a power control module to deliver 14 V DC to vehicle loads and to the battery.

3. Batteries for stop&go applications

The application requirement under consideration was for a 50–55 Ah battery with a CCA rating of 640 A to EN standards in an L2 package. A polypropylene container specifically designed not to distort under internal pressure and to maintain a uniform high compression on the cell pack in service through the use of end wall ribbing was used. Simple Bunsen valves were selected for venting, fitted to each cell on the cover with a vent strip to secure them in place. The grids were cast in Pb–Ca–Sn alloys and the active mass was optimised for continuous charge/discharge behaviour. The plates were wrapped in an absorptive glass mat (AGM) separator. This battery performs well to a normal automotive duty cycle and will give high performance over an extended life in addition to having good resistance to high temperatures. It is used for automotive original equipment as well as being in development as a battery for stop&go applications.

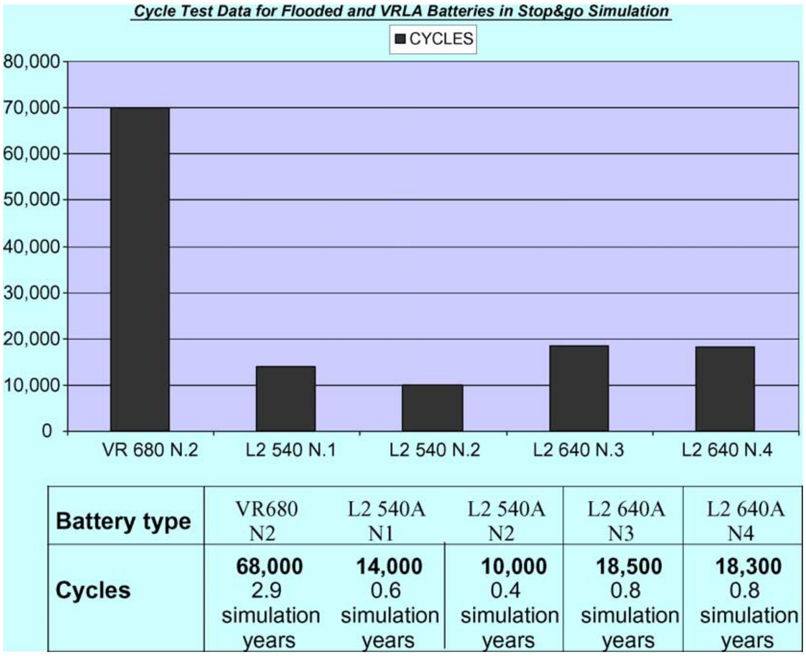
The grid alloys were selected to have good corrosion resistance through the use of Pb–Ca–Sn alloys with lower levels of Ca and higher levels of Sn. The Sn level also confers a good cyclic performance by ensuring a conductive and cohesive interfacial layer between the grid and the active material. The expander addition was optimised for high-rate performance but at this stage of development did not contain any special levels or types of carbon additives in the negative other than a normal level of carbon black. The plate processing used was developed to improve the cyclic behaviour of the positive active material whilst not compromising the integrity of the expander. The AGM separator was specified to have a thickness and grammage sufficient to retain high stack com-

Table 2
Test regime for VR 680 battery in simulated stop&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:
First 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 m.
Second 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 m.
Third 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 m.
Fourth 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 m
Fifth 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 m.
Sixth 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 m.
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.

pression in the wet state and be readily processed. Battery assembly was conventional with extrusion/fusion inter-cell welding and a heat sealed cover. Acid filling was carried by volume under controlled conditions and formation followed directly with care taken regarding current input levels and temperature.

A simulated duty cycle for batteries for stop&go applications needs careful consideration: the fundamental requirement is for a large number of shallow high-rate cycles where the battery may not be returned to a fully charged condition at the end each cycle or group of cycles. The United States advanced battery consortium (USABC) has proposed a zero power assist (ZPA) test cycle to provide a SOC neutral pulse profile for stop&go with a 90% round trip efficiency. Each cycle takes 3 min and capacity checks are made at 10,000 cycle intervals. The European car manufacturers consortium (EUCAR) has a power assist profile for cycle life testing with a 2 min cycle using a high power pulse, followed by a two-step charge to simulate regenerative braking with intermediate rests. This test also uses capacity checks at 10,000 cycle intervals to validate performance. These tests, however, do not replicate a more complex driving pattern and so a somewhat more elaborate regime was selected to better represent actual practice whilst avoiding highly detailed drive cycle tests. The regime selected is shown in Table 2. The principal features are a two-step discharge with a short peak current and a longer lower level of current repeated 10 times followed by charging periods of varying durations. This represents the



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

Fig. 3. Test results on simulated stop&go cycling.

duty cycle more precisely. Capacity checks are made at intervals and the full cycle takes 3 h with 60 discharge cycles. As a guide, 24,000 discharge cycles are estimated to be equivalent to 1 year of service.

The results of the tests are shown in Fig. 3 and compared to flooded batteries which failed within a year of simulated life. The nominal capacities of the flooded units were 60 Ah compared to 52 Ah for the VRLA unit. The VRLA stop&go battery reached 68,000 cycles, equivalent to nearly 3 years of service. Trials are continuing to further optimise battery performance by adopting strategies to optimise the cyclic behaviour and to make the negative plate more resistant to sulphation.

The results may be considered by reference to Ah turnover. The total Ah turnover in this test in shallow cycling is very much higher than the deep cycle turnover for the same design of battery. Numerical comparisons tend to be misleading because the relationship is highly non-linear and other shallow cycling tests give different Ah turnover results depending on the regime selected but the performance is significantly better than expected. Comparisons with flooded batteries under the same conditions may be made more directly. For example with a 17.5% partial state of charge (PSoC) test, there is a requirement for VRLA batteries to have a cyclic endurance of at least three times the flooded equivalent. These batteries exceed this requirement.

The tests that are continuing are focusing on the behaviour of the separator and the conductivity of the negative plate. The separator plays a key role in the behaviour of VRLA cells and the formulation of the material to reduce the diffusivity of oxygen to the negative plate may reduce the reduction in potential caused by higher rates of oxygen recombination. The use of different forms of carbon in the negative plate is important. Very finely divided forms of carbon improve the conductivity but larger graphitic particles provide better particle to particle contacts. As a result, conductivity is improved more effectively on a specific weight basis.

Irrespective of the duty cycle for repeated engine starting, the battery also needs to have all the characteristics needed for normal service. Cold starting is required at −18 °C and as low as −30 °C for extreme conditions. Sufficient reserve capacity is needed for key-off use of the vehicle and for emergencies and to support long periods of stand with low drains. Excellent charge acceptance is needed and the battery needs to be able to be operated under a wide range of temperatures. VRLA batteries have good characteristics over wide range of service temperatures. 60 °C can be tolerated for short periods but for normal operation, 40 °C is a more acceptable maximum. Heat generation under intensive cycling needs to be considered and thermal management needs to be considered. Battery location is important; the engine compartment will be very hot although thermal barriers can be used to good effect. Active cooling is not realistic because of cost and complexity. Battery management is important and can be used to control the battery temperature by limiting the number of stop&go cycles if the battery temperature exceeds a specified level. Low temperature performance of VRLA batteries is excellent but whilst useful capacity can be achieved as low as −40 °C in a fully charged condition, PSoC operation results in the battery being below a full charge and this needs to be considered for low temperature operation. If there is no requirement for regeneration, the battery can be fully recharged but if regeneration is needed, a margin between the actual SOC and a full charge needs to remain. Operational strategies to return the battery to a fully charged condition at the end of a period of use and then allow it to be discharged in use may be correct in principle but flawed in practice as the end of a journey can never be predicted. For longer discharges, VRLA has good charge retention and low levels of self-discharge so that months of standing present no difficulty. Low levels of key-off discharge are acceptable provided that the battery is not taken below 50% SOC in order to be able to provide an adequate cold cranking performance. Reserve capacity is simply a matter of battery sizing taking into account whether there is a single or dual battery installed. VRLA batteries can be adapted to meet the needs of stop&go applications and offer good performance for the other service requirements.

4. Batteries for dual battery systems

Auxiliary VRLA batteries are derived from small standby or motorcycle batteries and Table 3 shows some of the battery types that are being used for this application but the particular type that will be described is a 14 Ah battery used for back-up energy in a current production vehicle. This battery (Fig. 4) has a specified reserve capacity and a high-rate performance (not for engine starting) in order to provide power for certain critical functions on the vehicle. The design adopted uses cast Pb–Ca–Sn grids, conventionally pasted with an acrylonitrile butadiene styrene (ABS) copolymer case and lid. ABS was specified as it is more rigid and provides more uniform stack

Table 3
Auxiliary VRLA battery types

Battery type	C20 (Ah)	CCA (EN)	Weight (kg)	Ah kg^{-1}	l (mm)	w (mm)	h (mm)	Case	Terminals
FG 20201	2.1	23	0.9	2.3	178	34	65	ABS	4.8 mm faston
F4-12B	3.8	40	1.6	2.4	113	70	85	ABS	4.8 mm faston/M5
F7-12B	6.8	70	2.7	2.5	113	70	130	ABS	4.8 mm faston/M5
GTX14-12B-1	12	170	4.7	2.6	150	87	145	PP	M6
GTX14-12B-2	14	180	5.0	2.8	150	87	145	ABS	Special M6 bolt
F19-12B	19	200	6.5	2.9	181	76	167	ABS	Special M5 bolt

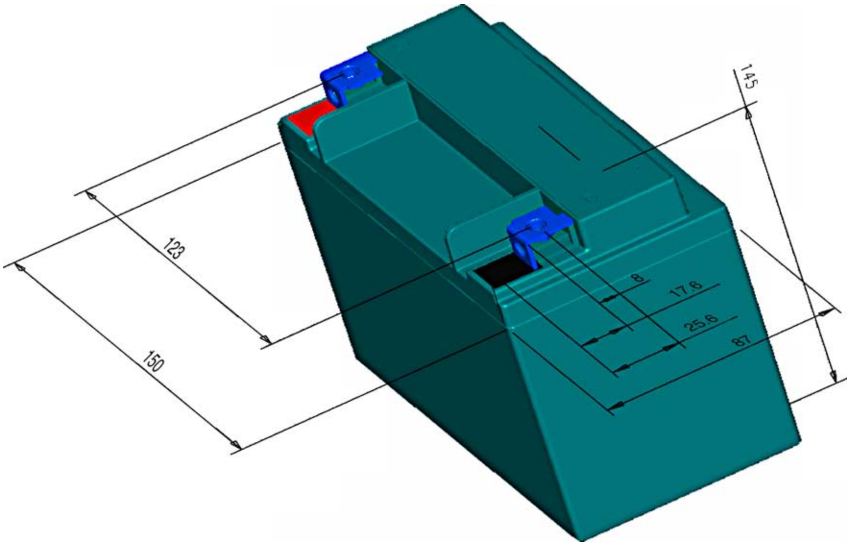


Fig. 4. VRLA auxiliary battery.

compression over a wide range of temperatures. The element groups and the inter-cell connectors are welded together in a single operation and encapsulated in epoxy resin which is also used to make the lid-to-case seal. This provides a very high integrity construction. A secondary cover is used above individual cell vents and this is ultrasonically welded in place. Specially designed L-shaped nickel and tin-plated brass terminals are used with a pre-welded nut for ease of installation. For a small unit the energy and power density are high and a long service life is assured. In view of the functions that this battery has to support, condition monitoring is essential to ensure that the duty cycle can always be performed.

5. Battery condition monitoring

Battery condition may be monitored by measuring the SOC and SOH of the battery in order to determine the state-of-function (SOF) defined as the ability of the battery to carry out specific or critical parts of the duty cycle. For stop&go cycling the use of the battery would be curtailed if the ability of the battery were to be impaired by intensive use taking the battery to an unacceptably low SOC. For an auxiliary battery, a safety warning would be made if the SOF for a critical function was such that vehicle safety was compromised. Battery condition monitoring and an associated management system are essential to assure reliability and optimise life. It also has the incidental benefit of reducing warranty returns for batteries that simply have a low SOC.

The methodology adopted to measure SOC and SOH is based on measuring open circuit voltage (OCV) when the vehicle is not in use (key-off) to check SOC. SOH is measured by analysing 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 measures the internal resistance of the battery which varies with life of the battery at any given state-of-charge (Fig. 5). The results are analysed using a look-up table for each battery type to give an indication of the SOC and SOH which is presented

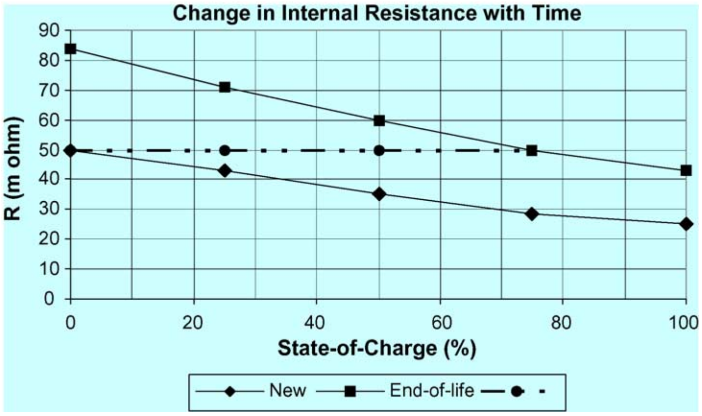


Fig. 5. Variation of internal resistance with battery age and state-of-charge.

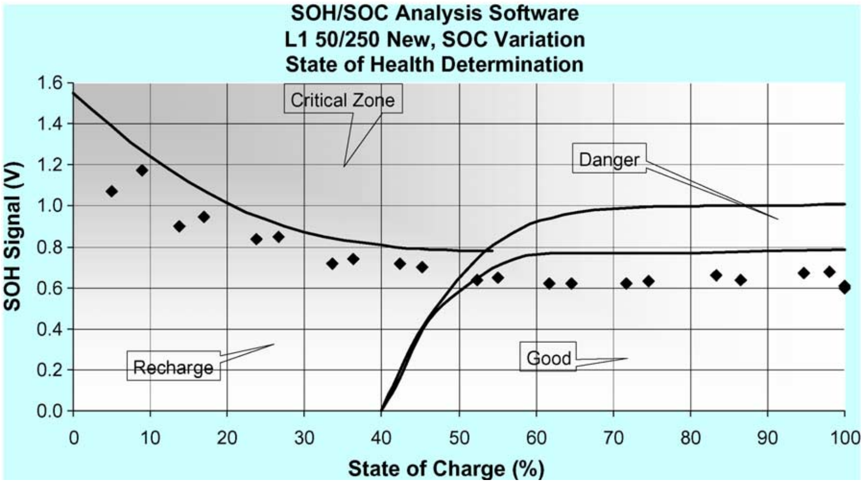


Fig. 6. Analysis of state-of-charge (SOC) and state-of-health (SOH) by measurement of open circuit voltage and voltage response on discharge. The four zones are: (i) an area above 50% SOC where the SOH signal is small and the battery is in good condition; (ii) an area where the SOC is below 50% and the 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 Fig. 6. This 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; and in zone (iv), an immediate action alarm would be activated.

6. Summary and conclusions

The requirements for stop&go applications for automotive service can be met with VRLA batteries. These have an intensive duty cycle and need to be constructed to optimise performance in PSoC 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. Simulated duty cycle testing has shown that good service lives are achieved.

Improvements in PSoC operation will open the way to applications where there is a need to provide power for launch or power assist and improve the prospect for the use of lead–acid batteries for advanced systems as fuel economy and emission control regulations become more stringent.

VRLA batteries are also being deployed as auxiliary batteries to support critical electrical loads as vehicle systems become more dependent on a secure electrical power supply.

SOC and SOH measurements 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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