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Field Results of Battery Management Technology Integration into a Vehicle Application (inGEN®)

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ABSTRACT

This paper presents advanced battery monitoring technology developed for integration into the vehicle system to enable true battery power diagnostics and management. As an update of SAE paper 2001-01-2715 from the 2001 SAE Truck and Bus Conference[i], the paper examines battery parameters measured and the diagnostics produced to determine the health, charge condition and deliverable power of the battery. Diagnostics, whose methodology to accurately calculate true state-of-charge (SOC) and state-of-health (SOH) for SLI lead-acid batteries was previously reported, are further explored for application with military high capacity VRLA batteries, similar in cell type to batteries anticipated to be deployed in 42 volt architectures. Furthermore, the system and technology is examined in dynamic field-testing of actual drive cycle data acquired in vehicle under hood environments. Finally, the paper explores how improved battery data and diagnostics can lead to improved electrical system and vehicle performance.

INTRODUCTION

Effectively and efficiently computing the State-of-Charge and State-of-Health of a vehicle battery or batteries in a dynamic, under hood environment has remained an elusive objective, especially for lead-acid battery designs. The need for these measurements becomes even more important as the battery becomes a more critical safety element in vehicles with increased loads. Electrical system demands for comfort, convenience, and telematics are growing drastically. New developments for fuel, cost and safety improvements are incorporating X-by-wire designs, idle start-stop systems, and other applications requiring higher voltage systems. These developments are driving the movement to 42-volt, deep cycle and HEV applications, and making the battery a critical element for both performance and safety. Calculation of the battery's ability to delivery power at any moment, and understanding of its requirement to accept charge and its state of health are needed. A battery monitoring system becomes essential to ensure vehicle operation.

Previous SAE session 01TB-128 (2001) demonstrated how a new vehicle integrated battery management technology, or **inGEN®**, can accurately predict the true state-of-charge and state-of-health of the battery through continuous and automatic measurements of the battery voltage, temperature, current flow and conductance over time.

InGEN derives state-of-health and state-of-charge diagnostics through the intelligence gathered in the above measurements. These SOH and SOC measurements provide a continuous and real-time assessment of the battery's ability to provide reliable starting and reserve power. Moreover, they can be utilized to provide optimized charging to the battery. The diagnostics can be used to eliminate overcharging/undercharging the battery, reducing fuel consumption and the burden on the alternator. The same diagnostics can be used for intelligent load shedding and calculation of exactly how and when particular applications affect the battery.

ESSENTIAL PARAMETERS TO BE MONITORED

To establish meaningful diagnostics, inGEN technology measures the following parameters, previously detailed:

1. Voltage (AC and DC)
2. Current
3. Battery Temperature
4. Time
5. Battery Conductance

Whereas parameters 1-4 above are common variables for a battery charging system to measure, inGEN adds the measurement of internal battery conductance. The conductance measurements are the key element to enable accurate and meaningful diagnostics. To summarize many previous presentations[ii] and the 2001 SAE paper, a battery's measured conductance correlates linearly with its ability to deliver current. As conductance declines over time or due to other faults, so does a battery's ability to meet its specified capacity and supply energy.

BATTERY DIAGNOSTICS

The initial under hood version of inGEN produces two significant diagnostic measurements:

1. State-of-charge (SOC)
2. State-of-health (SOH)

These calculations are significant, since by themselves, conductance, voltage, temperature, and current measured, recorded and reported continuously over time will provide a battery operator with key performance information; however, these diagnostic classifications can further be refined and mathematically manipulated to equate to definitions of deliverable energy and charge requirement as specified for a particular application.

inGEN achieves these diagnostics by utilizing an adaptive learning algorithm based on the application requirements, not the battery's design parameters. The algorithm accounts for all of the relative measurements of conductance, voltage, temperature and current, and their relationships. Additionally, the algorithm accounts for the relationships and changes in the measurements of the SOC and SOH diagnostics themselves.

The diagnostic measurements themselves and the methodology used to verify and correlate the accuracy are detailed.

STATE-OF-CHARGE (SOC)

The definition of SOC used with inGEN is the definition of relative SOC as indicated by the battery's Specific Gravity (as indicated by voltage), in comparison with the battery's design Specific Gravity. More simply, a battery that has lost 50% of its full charge capacity can still achieve a SOC of 100%, in as much as that 100% SOC battery is capable of delivering only a diminished capacity. Midtronics is extending its algorithms to predict and learn the actual low rate capacity, which will further refine the SOC calculation.

SOC is calculated and expressed from 0% to 100%, and becomes an indicator of the amount of energy that is available in a particular battery. As the battery is discharged and charged, SOC will indicate the relative amount of energy that has been removed or added into the battery. SOC is calculated based on all the battery and system measurements and their relationships discussed above. Figure 1 and Figure 2 represent SOC calculations obtained during winter field-testing in similar vehicles with vastly different driving patterns. The dramatic differences in SOC measurements, and resulting battery issues, for nearly identical battery and vehicle types indicate the imperative requirement to monitor battery condition.

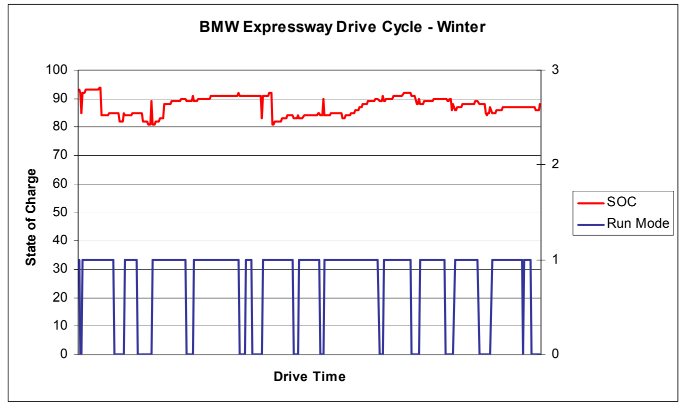

Figure 1: State of Charge Measurements – Vehicle used primarily in expressway driving.
Dual axis chart: Left axis notes the SOC%. Right axis notes the corresponding charge/discharge cycle (discharge is key off quiescent current draw only)
Complete timeframe is 14 days

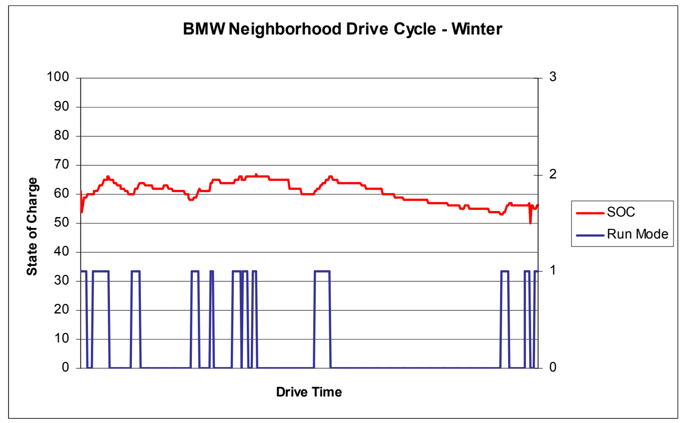

Figure 2: State of Charge Measurements – Vehicle used primarily in short trip driving.
Dual axis chart: Left axis notes the SOC%. Right axis notes the corresponding charge/discharge cycle (discharge is key off quiescent current draw only)
Complete timeframe is 14 days

The SOC measurements for Figure 3 were taken utilizing a military specified tank battery and manipulated to reproduce charging and discharging cycles similar to the vehicle application.

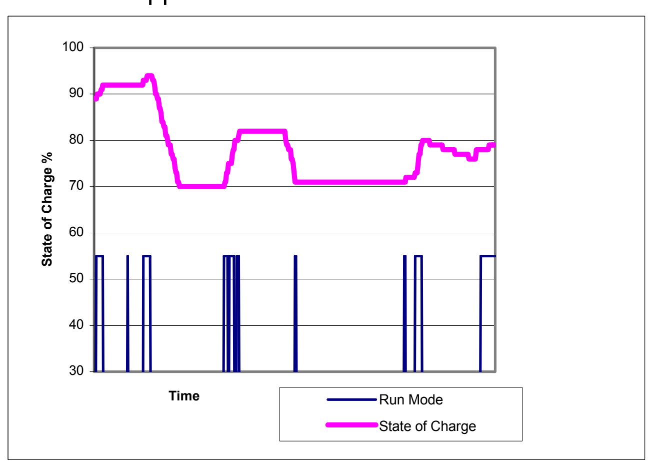

Figure 3: State of Charge Measurements
Lead-acid flooded Military Application Battery -- RC of 270 minutes

Figure 4 shows the extreme effects of an idle-stop (start/stop) driving pattern on the SOC of the battery in comparison with conventional operation, again illustrating the necessity to monitor and control the battery condition and environment in such an application.

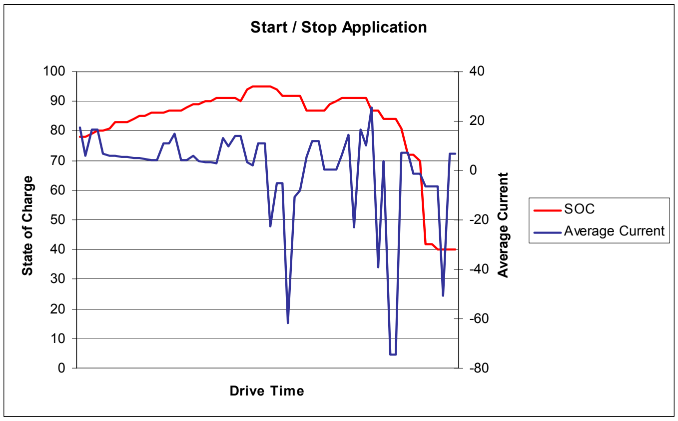

Figure 4: Start / Stop Driving Sequence
This chart shows a simulated loading pattern for a Jeep that was run in a conventional pattern in the first half of the sequence (1 hour) and then run with a heavy stop / start pattern for the remainder (1 hour)

STATE-OF-HEALTH – (SOH)

Calculating SOC is an important component, but is not sufficient on its own. As the battery ages or its environment and condition changes, this measure can become less important since a SOC measurement will often not reveal a faulty battery on its own. To complete the necessary diagnostics, it is essential to calculate a measurement of the battery's ability to deliver its energy, or its State-of-Health (SOH). In vehicle applications, the State-of-Health (SOH) determines the ability of the battery to supply essential power to the vehicle. SOH is expressed in percent, from 0% - 100%, based on following equations:

<u>SOH Definition</u>:

We define SOH as {CCAcomp - CCAmin} / {CCAnew - CCAmin}, where:

CCAcomp is the real time cranking power of the battery, compensated for temperature and State-of-Charge.

CCAnew is the predicted cranking power of the battery when new, and at 100% State-of-Charge.

CCAmin is the minimum cranking power required by and the vehicle application as specified by the vehicle manufacturer.

An accurate SOH measurement equates to the ability of the battery to deliver its energy, at a given point in time. As a battery declines over time, develops faults, or is subject to adverse conditions, the SOH will decline.

Figures 5-6 display SOH measurements compared to the actual cranking power. Figure 5 represents the relationship between the dynamically measured CCA and the SOH calculation as it relates to the vehicle-cranking requirement. Figure 6 displays the use of inGEN parameters to predict the cranking voltage of a battery. This extends the usefulness of inGEN to be able to predict with certainty the starting ability of the battery under vastly different conditions. inGEN can also learn load levels of vehicle starting so that impending problems can be averted.

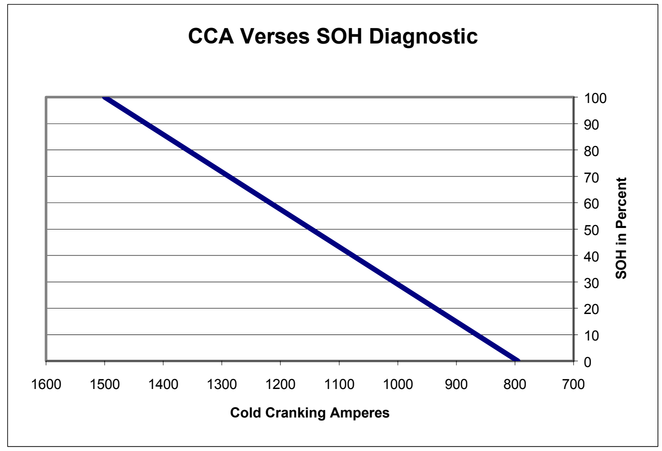

Figure 5: Cranking Capacity (CCA) versus SOH Diagnostic Calculations
Lead-acid flooded Military Battery (270 RC minutes), 795 CCA minimum required

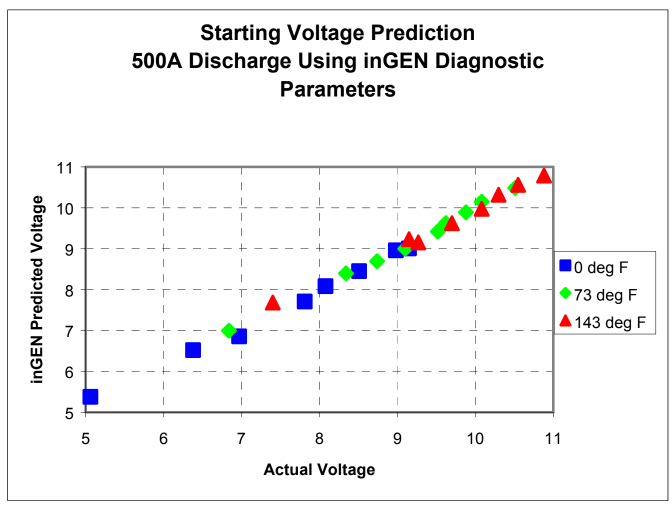

Figure 6: Cranking Voltage Prediction Using inGEN Parameters versus Actual Voltage at a 500A discharge.
Various size and age lead-acid batteries at three different temperatures

Midtronics has demonstrated that the dynamic conductance of a fully charged lead acid battery, compensated for temperature, is proportional to the cold cranking characteristics of the battery. The standard test method to determine the "real" cranking capacity (CCA) of the battery is as follows:

The CCA (Cold Cranking Amps) is the amount of discharge current that a battery at 0^{o} F (-18^{o} C) will support for 30 seconds while maintaining a minimum voltage of 1.2V/cell.

inGEN focuses on the initial part of this cranking discharge since it better relates to actual start sequences.

Combined, the measurements of SOC and SOH provide the elements to determine, at any moment, the battery's power level and its ability to deliver that power upon demand in real time. By themselves, they offer battery measurements that have never been achieved for real-time, continuous monitoring of a battery's condition and the elements affecting that condition. They enable a new level of onboard monitoring and power management.

ALGORITHM CALCULATIONS

The inGEN algorithms begin by making certain reasonable assumptions about the unknown variables, recognizing that their actual values may in reality be quite different from the assumed state. As the battery is exercised, meaning that a change occurs in any of the fundamental measured physical properties, differential changes in the parameters are plotted against the assumptions. Error terms are created as a by-product of the process, and are driven to zero resulting in a convergence to the present state of the battery. As the battery state changes (either SOC or SOH), the parameters re-converge on the present solution.

<u>Use of diagnostics for battery monitoring</u>

The inGEN parameters and diagnostics provide immediate benefit to vehicle operators and technicians. The inGEN measurements can be used to immediately alert the operator to a specific battery problem or issue. The measurements can be incorporated into a vehicle control unit or other systems to send diagnostic messages to displays for operators, to diagnostic frames for technicians, to store data and information for analysis, and provide any number of advanced warning mechanisms to improve system reliability. The power management system can signal a problem before it becomes an emergency, so that it can be detected and corrected before the battery is stressed or fails.

<u>Use of diagnostics for optimized charging</u>

In addition to providing valuable measurements for battery monitoring and analysis, this paper proposes that the SOC and SOH measurements can form the backbone of real-time information that can be utilized to control the charging system output to the battery. Such a system could vastly decrease battery failure and extend battery life by optimally charging the batteries according to the SOC, SOH and other inGEN measurements.

Battery life and performance is normally maximized when the battery is maintained at or near a fully charged condition. The battery in a vehicle, however, is often subjected to wide excursions of charge and discharge due to different driving patterns, vehicle electrical loads and severe temperatures[iii].

The charging system is called upon to recharge the battery as quickly as possible under extremely divergent temperature conditions without overcharging the battery, thereby degrading its life. Balancing these two opposing functions—maximum charge with minimal overcharge—makes the normal regulator settings somewhat of an arbitrary compromise. It is clearly seen that more information from the battery is needed to allow the charging system and battery to work together at their highest efficiency while maintaining optimum battery performance and life. inGEN can supply this critical information.

SUMMARY

The purpose of this paper was to present additional data on emerging inGEN technology, which will dramatically improve battery intelligence and battery power management. The inGEN methodology incorporates the complex battery and vehicle system relationships through an adaptive intelligence, where the inGEN algorithms learn and differentiate the specific battery or batteries in the vehicle application. This technology requires minimal inputs for complete integration into a vehicle system, and quickly adapts to provide continuous real-time state-of-charge monitoring which can provide many benefits. Expected benefits from full integration of this technology include improved battery life, reliability of battery power for start and for electric loads, improved fuel economy, improved charging algorithms, a possible reduction in battery weight, advanced warning of impending battery failure, and diagnostic charging intelligence. Additionally, the technology should produce benefits in other applications including motive power, EV/HEV, heavy-duty, military, recreation, and marine.

REFERENCES

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