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Automatic Monitoring of Electrical System Health

Developed by the Technology & Maintenance Council's (TMC) Sensor Enhanced Maintenance Task Force

ABSTRACT

TMC's Future Truck Committee charged its Sensor Enhanced Maintenance Task Force to evaluate and state a position on the feasibility of automatic monitoring of electrical system health. The finding of that task force is that automatic monitoring of electrical system health is achievable by combining onboard circuit analysis with Testing for Statistical Significance (TSS). When paired together, these two fundamentally sound sciences quantify the state of health (SOH) for batteries, alternators, starters, and electrical cables. The use of the SAE J1939 communication network allows for downloading of data, scheduling of maintenance and integration with fleet management systems.

INTRODUCTION

Currently there are no onboard diagnostics or means of knowing a battery state of health relative to electrical power demands. Except for battery voltage, there are no indicators to identify when maintenance is required for the battery or any of the components in the primary electrical system. The methods and analysis described herein are important in defining the next generation; automatic monitoring of electrical system health.

Electrical system maintenance is performed as part of a preventive maintenance program. This is usually done on a regular time- or mileage-based interval. If the intervals are too short, unnecessary maintenance is being performed. If the maintenance intervals are too long, the electrical system and vehicle, as a whole, are put at risk. Field failures may occur and may also result in vehicle having to be towed. The onboard diagnostic methods described in this paper would enable preventive maintenance to be performed in a timely manner before a hard failure, while avoiding excessive maintenance.

THE PRIMARY ELECTRICAL SYSTEM

Vehicle manufacturers select the battery size and the number of batteries based on the cranking requirements of the engine and to some

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extent upon customer specifications. The batteries must provide the required cold cranking amperage (CCA) and reserve capacity (RC) to ensure day-to-day operation and support for defined parasitic loads. Likewise, the alternator must provide for 100 percent charging during a normal duty cycle while providing power for all the electrical systems and devices.

Lead acid (Pb-Acid) batteries are the most commonly used on ground vehicles. There are millions of vehicles in use today using Pb-Acid batteries. There are three basic types: wet cell (flooded), absorption glass mat (AGM) and gel-cell.

Batteries are further categorized by the intended application. Starting batteries are designed to provide high current surges for short durations. Starting batteries should be kept fully charged between cycles to prevent sulfation. Deep cycle batteries are designed for application where they are regularly discharged. They deliver less peak current than flooded batteries but are capable of withstanding regular discharging to low voltage levels.

Electrochemical capacitors (ECs) are also seeing widespread adoption for starting commercial vehicles. ECs offer high power for cranking, but low energy as compared to batteries. ECs are integrated in conjunction with batteries to provide high cranking power to start the engine allowing the batteries to focus on only supplying the electrical loads. With an EC providing the cranking power the battery voltage will not drop during the engine starting cycle.

Figure 1 is representative of a typical heavy-duty configuration with starting and deep cycle batteries (See TMC RP 136B, *Managed/ Isolated Battery Systems for Electric Start Systems*). A normally open solenoid switch keeps the two battery types separated when the engine is off or the alternator output is low. It closes when the alternator output is high enough to charge the batteries.

MAINTENANCE PRACTICES

Onboard diagnostics are very limited. Typically, there is a gauge or digital display. There may be a red zone on the guage, and/or a low-voltage indicator light, with or without an audible alarm. The scaling could be in volts or state of charge (SOC). The gauge or display has minimal value. Its primary purpose is to let the driver know the electrical system is in good operating condition. The red zone or alert indicates corrective maintenance is required. If maintenance isn't performed there is a high risk the vehicle will not complete the intended

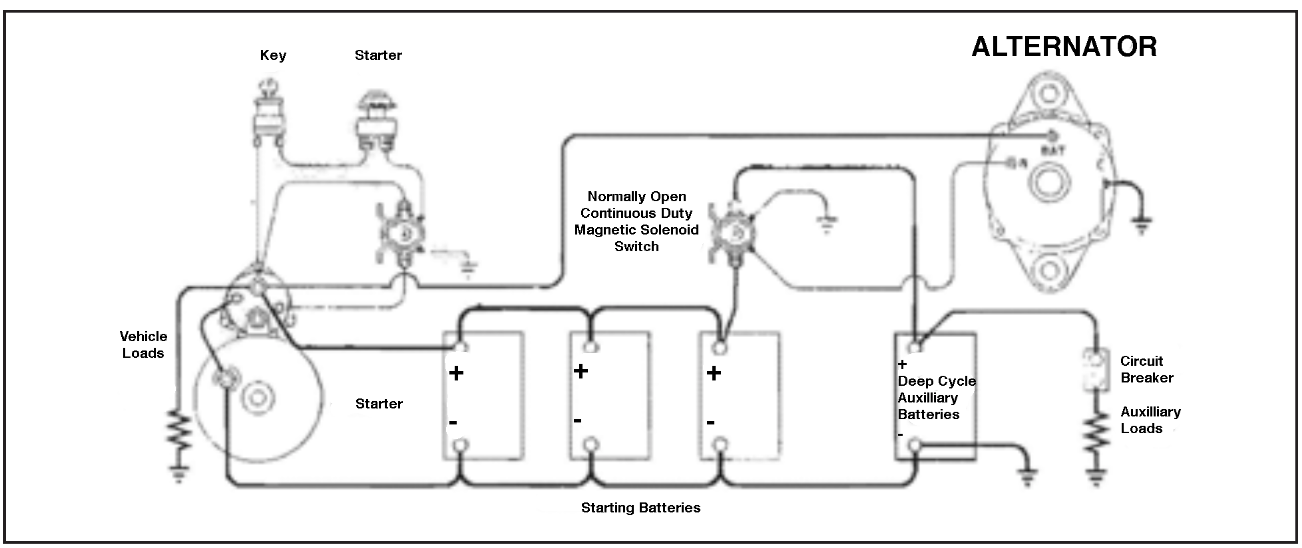

Figure 1: Typical Primary Electrical System

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mission. What is lacking in the current generation of vehicles is a condition-based alert to have a maintenance scheduled before a red zone or alert occurs.

Offboard diagnostic procedures are used to evaluate the health of each component independently. There are industry-wide standard test methods and diagnostic equipment for batteries, starters, alternators and cables. This has been the traditional practice used for decades. Maintenance is performed when either a component has failed in service, or as part of a routine maintenance. All corrective maintenance is too late. Failures disrupt the operation and the vehicle cannot reliably complete its missions. This means that service must be performed in the field or the vehicle must be towed to a maintenance facility.

Routine maintenance, commonly called preventive maintenance, is a good practice for electrical systems but it may take place too soon or too late. If too soon, unnecessary maintenance is performed and the vehicle is pulled out of service too often.

BENEFITS OF CBM

There are three categories of maintenance in use today: corrective maintenance (CM), preventive maintenance (PM) and condition-based maintenance (CBM). They each have attributes that serve the needs of the maintenance community. When used in conjunction with each other they provide for the optimal level of maintenance.

CM can be characterized as “if it's broke, fix it.” It is carried out on any item that shows substantial wear or has already failed. Roadside breakdowns are a common result of only using corrective maintenance practices.

Preventive maintenance can be characterized as “replace it before it breaks.” PMs are the standard maintenance practice in most operations. Scheduled maintenance is based on an interval of miles driven or interval of hours of operation. PMs ensure reliability and reduce the risk of field failure. Regularly scheduled PMs are more cost effective than just doing corrective maintenance. The downside of PM practices is that they can be too frequent resulting in excessive maintenance, cost, and out-of-service hours. If PMs are scheduled too late, the maintenance is ineffective. Components will fail while in service resulting in additional cost and failure to complete missions.

CBM can be characterized as the optimal level of maintenance because it’s performed at the right time. It uses real-time data to prioritize and optimize maintenance requirements. CBM determines the SOH of components or systems, and alerts when maintenance is necessary. Batteries and electrical systems in general can benefit from using CBM techniques to improve up-time, as well as reduce the cost of maintenance. Specifically, CBM can reduce the cost of doing excessive maintenance while ensuring there is ample time to replace components before they fail.

Take for example a new fleet purchase of 100 vehicles. For simplicity, this example is limited solely to a discussion of batteries rather than the entire electrical system.

Presume that the vehicles are to be maintained for 10 years. Weibull analyses and previous experience suggest failures will occur between Years 2 and 3. A preventive maintenance program is established to replace the batteries every two years. Each vehicle in the fleet has a three-battery pack. This equates to a replacement of 1,500 batteries over 10 years (10 years ÷ 2 x 3 batteries x 100 vehicles). With CBM, the total numbers of batteries replaced would be reduced based on their SOH. The net savings is in replacing fewer than 1,500 batteries. Batteries are replaced only when requred. The result might be 1,200 or 1,125 (respectively a 20 or 25 percent reduction) or some other quantity less than 1,500 battery replacements. The annual cost savings is directly proportional to the number of batteries that are not needlessly replaced that year.

This example does not imply that the batteries which are not replaced on a PM schedule will last another two years. They may well not last that long. Fleets have PM schedules for other inspections and repairs that take place more routinely than every two years. It's during one of these PMs that the batteries are replaced if the CMB alert has been set. On a CBM program, the batteries remain in service longer and are replaced prior to their failure, as opposed to every two years even if they still have effective service life remaining.

OPERATING MODES

The primary electrical system shown in **Figure 1** has several modes of operation, or logic states. Each of these has a unique identity that is used for doing circuit analysis. There are four basic modes and several fault modes. The four basic modes are depicted in **Figure 2**.

- **Key OFF State:** With the key off, the internal combustion engine (ICE) is off and there is no alternator output. The starter battery pack may have a small load for electronic equipment that must operate under all conditions. This would include systems like anti-theft or telematics systems. On vehicles requiring more devices or auxiliary equipment, an auxiliary battery is used allowing the starter battery pack to be in its most relaxed state.
- **Key ON and Engine OFF:** In this mode of operation, there is voltage at the key that is slightly below battery voltage. The difference between the two voltages is directly related to the amperage (electrical load) being drawn from the electrical distribution panel. This is many times the case with alternative-powered vehicle including hybrids.
- **Start Cycle:** The characteristics of the start cycle are easily identified. There is a significant power surge that begins when the magnetic starter switch pulls in. All of the voltages, including the battery voltage drop significantly. The key voltage and starter voltage both being lower that the battery voltage because of the high current through the battery cable to the starter. At the end of the start cycles voltage begin to recover relatively quickly even if the engine does not start.
- **Alternator Output:** The alternator output can only be present with the Key ON and engine running. The voltages at the key and the battery are at elevated levels above the batteries' 100 percent state of charge value. Typically the alternator output is regulated at 14.1 volts or more for 12-volt systems and 28.2 volts or more for a 24-volt system.

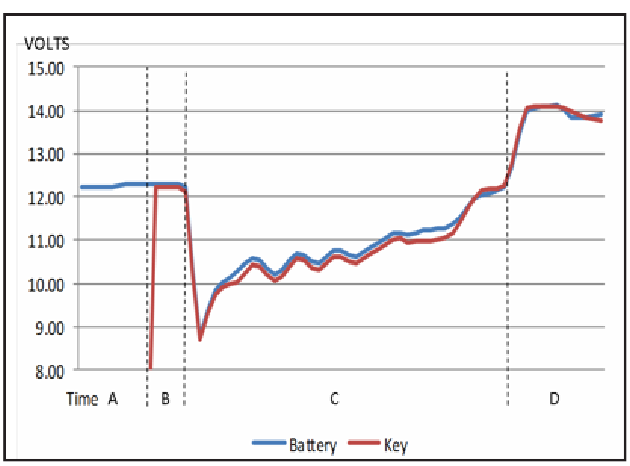

Figure 2: Voltages for Electrical System Four Operating Modes

Once the operation mode is identified, the circuit analysis can be performed. Values of parameters (some measured and some calculated) can be compared with expected values and limits. Storing a historical record is beneficial for evaluation using statistical methods.

STARTER CIRCUIT ANALYSIS

Circuit analysis is the primary method of doing onboard diagnostics. It is a method of determining the condition of a component without doing the intrusive diagnostic tests typically

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done during PMs. When applied to the starter circuit, the internal resistance of the battery pack and impedance of the starter motor can be estimated fairly accurately and repeatedly. Changes in these values over time are key indicators that maintenance is required. This is the essence of CBM.

One method of measuring the current in the circuit is to use the battery cable as a shunt resistor. This eliminates the need for an in-line shunt or a clamp on current sensor. For example, a 4/0 AWG copper cable five feet in length has a resistance of 250μ-ohms at 20C°. The resistance value changes with temperature. This intrinsic material property is referred to as the coefficient of resistivity. For automotive grade copper, there is correction factor of 0.00393 per C°. Resistance increases as temperature increases and decreases as temperature decreases. Thus, the value of the shunt resistor is determined by wire gauge, length and temperature.

This method of using the battery cable as a shunt is only valid when all the circuit components are at ambient temperature. This requires the vehicle to be stationary with the engine off for an adequate time so that the engine cools down to ambient temperature. Thus, each end of the cable, as well as the battery and starter motor are all at ambient temperature. The current through the starter circuit is calculated using the voltage drop across the cable (battery terminal voltage minus starter motor voltage) and the battery cable resistance at ambient temperature.

STATISTICAL ANALYSIS

Another important part of CBM is applying statistical analysis to compare each sample data set with baseline data.

The data sets have a mathematical relationship with the circuit model in terms of volts, amps, power and energy. However, in normal daily operation a statistical analysis is negated by the temperature differences between components and outside disturbance that effect engine cranking time. For example, the starter motor windings and the battery temperature may be substantially different when the vehicle has repeated start/stop cycles. In these cases, a rigorous analysis is not possible.

Analysis can only be done on a qualified start cycle where certain preconditions are met. These are usually after the vehicle has been stationary with the engine off for adequate time for all components to cool to ambient temperature. This same time allows any surface charge on the batteries to dissipate. Hence, the battery terminal volt can be estimated as the open circuit voltage (OCV). The next start cycle is designated as a qualified start cycle for doing statistical analysis. All of the components are at ambient temperature and the OCV is known.

All data sets, when corrected for temperature, have a distribution pattern centered on the mean value (arithmetic average) for each parameter being recorded. This is true until there is a significant change due to aging, wear, abrasion, corrosion, or complete failure. These are the conditions that warrant maintenance and trigger a CBM alert.

A reasonable assumption is the parametric values of a new system are at 100 percent SOH. Vehicles are built to known specification with approved components that meet the intended quality standards set by the manufacturers. Once a vehicle has passed final inspection and/or end of line testing, it is put into service. Normal operation is expected for hundreds and even thousands of daily cycles. If, in fact, the starting and charging systems operate satisfactorily for the end user on a daily basis, then the SOH of each parameter value is scaled to 100 percent.

Anticipating that the parametric values are stored in a history file, and the mean values and standard deviations calculated, the initial data sets of 30 to 100 qualified start cycles represent the baseline data. This baseline could then be used throughout the life of the system/vehicle to evaluate all qualified start cycles. Deviations that are outside of preset limits would be expected to trigger a CBM alert.

Parameters of specific importance include the mean value and standard deviations for:

- **Internal resistance of the battery.** As internal resistance increases the cold cranking ability decreases.
- **Impedance of the starter.** Changes signal internal faults (e.g., windings, brushes, commutator, etc.).
- **Efficiency of the starter cable.** This is a clear indicator of corrosion or loose connection.
- **Power delivered from batteries during initial time interval.** Batteries are not being charged properly, indicating irreversible aging.
- **Power into the starter during initial time interval**. Indicates circuit integrity compromised, external disturbance.
- **Mean value of charging voltage.** Changes signal internal faults of alternator, regulator or loose belt.

Hypothesis testing can be used in determining the SOH for the components. A t-test is a statistical examination of two sample means. A paired-sample t-test examines whether two means from the same group are statistically different at two time intervals and is commonly used when the variances of two normal distributions are unknown and when an experiment uses a small sample size.

For CBM applications, one sample mean employs the data obtained from a new battery and compares it to the mean of the same battery over time in order to identify statistically significant impairment. The same method would be used for starters, alternators and battery cables. In the case of battery cables a difference in t-test scores is an indication of corrosion, abrasion, chafing or a loose connection.

A linear method of determining when CBM is required could be accomplished by scaling each parametric to where it falls in terms of deviation from the mean baseline value. For example, the mean value can be scaled to 100 percent SOH and the limit scaled to 10 percent SOH. The CBM alert can set at 10 percent or some other arbitrary percentage based on experience and correlation with offboard diagnostics practices. When offboard diagnostic tests do not substantiate that a component needs replaced, then the CBM alert level should be adjusted accordingly.

Use of these or similar techniques can detect irreversible battery aging, reduction of CCA, current leakage, cable corrosion, loose connection, and starter motor and alternator degradation due normal wear resulting from hours of service, number of cycles and thermal stress. As conditions change, the circuit parameters move away from the mean values of the baseline data. Maintenance alerts are set if the data is outside of the confidence interval.

STARTER CABLE MONITOR

The gauge and length of a wire determines its resistance at 20C°. A correction factor is applied because resistance of copper is a function of temperature. This principle is applied to the cable connecting the battery to the starter. Knowing this resistance and the voltages on each end of the cable allows the instantaneous amperage during a start cycle to be calculated.

Further calculations yield the power and energy draw from the batteries. Efficiency of the cable is calculated as:

$$Eff = \frac{\text{Power Out}}{\text{Power In}} = \frac{\text{Power Delivered to Starter Motor}}{\text{Battery Power Out}}$$

Efficiency for each start cycle, when corrected for temperature, should be within one standard

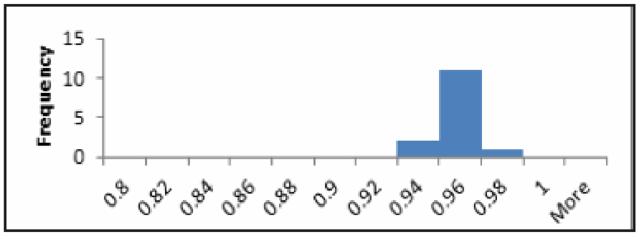

Figure 3: Battery Cable Efficiency

deviation of the mean unless influenced by physical disturbance such as a loose connection or corrosion. In either case, the efficiency of the cable decreases, implying the voltage drop per amp crossed the cable has increased. This becomes a maintenance issue at some point. Typically, heavy-duty systems have a failure threshold of 0.1 volts per 100 amps (see **Figure 3**). This equates to an efficiency of greater than 92 percent in most heavy-duty systems.

BATTERY SOH MONITOR

The service life of a battery is adversely affected by internal leakage and sulfation of the plates, both of which lead to irreversible aging. Internal leakage results in energy loss and the inability to hold a charge while in an open circuit mode. Sulfation results in the internal resistance increasing (See **Figure 4**). This manifests itself in reduced CCA and RC. Both internal leakage and sulfation can be detected by using circuit analysis techniques and statistical methods. A CBM alert could certainly be triggered accordingly.

The state of health can be expressed as a percentage, "% SOH." A new battery is assigned a value of 100 percent SOH. A scaling factor is used to decrease the SOH with increasing degradation. For example, a doubling of internal resistance results in substantial loss of CCAs and is reason to replace the battery. This would be assigned a value of 10 pecent SOH and should trigger a CBM alert.

SOH easily verified by a technician using standard diagnostic methods. The CBM alert with the technician's verification justifies replacement of the battery. Without a CBM alert the technician would not need to perform the diagnostic procedure.

DATA STRORAGE & PROCSSING

Once filtering and triggering has been activated, the next consideration is how to store the data. There are two methods to be considered for data storage: simple ASCII, and binary. If data storage in binary form is chosen, any file captured and transferred would mandate post-processing to make it human readable. The other method is to store a data log in a human readable ASCII format, which can be immediately interpreted. The file could also be marked (timestamp, data bus, message header, etc.) in such a way that it would be easy to write a post-processing PC-based application to parse and store the data for later predictive maintenance or further CBM analysis.

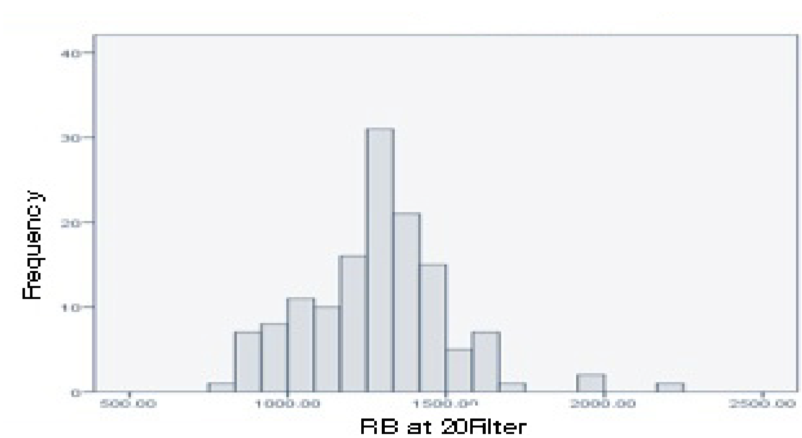

Figure 4: Battery Internal Resitance Corrected to 20°C

The files could be stored on a removable Flash memory card or similar media for file transfers.

SUMMARY

Predominantly, today's maintenance practices related to electrical systems do not employ CBM techniques. There is no known onboard monitoring or diagnostic run for batteries or the primary electrical system. While the voltage and current measurements are readily available, and used for other functions, they are not used for maintenance purposes. At best, maintenance is done on a regular PM schedule. There is a high risk of hard failures of batteries, cables, starters or alternators that disrupt operations and significantly drive up maintenance costs.

The concepts laid out in this paper are for the next generation CBM. The objective is to improve overall vehicle readiness while reducing the total cost of maintenance. No additional sensors are required. The voltage sensing and ambient temperature sensor are already on board. CBM could utilize a dedicated electrical system monitor or be embedded within an existing ECU. The circuit analysis and related testing for statistical significance could be done on-board during normal operation.

The uses of diagnostic fault codes or tell-tale indicators alert the maintenance community only when preventive maintenance is required. Under CBM, a service technician validates the condition using standard diagnostics procedures and makes the necessary repair (See **Table 1**). The result would acheive the optimum level of maintenance during the lifecycle of the vehicle, while protecting against premature failures that are otherwise missed.

TABLE 1: NEXT GENERATION CBM-FUNCTION OVERVIEW

Battery	State of Health (as a function of internal resistance. State of Charge (as a function of OCV).
Current	Abnormalities. Internal battery leakage. Parasitic in the relaxed state.
Starter	Power and Energy Profile, Trend Analysis Cycle Count and Total Time
Cables	Change in Efficiency (Power to Starter from Battery). Corrosion or loose connections.
Alternator	Over/under charging and abnormal waveform
Alerts	J1939 fault message
Data Output	File transfers via J1939

REFERENCES

- TMC RP 109A, *Battery Ratings and Engine Cranking Requirements*
- TMC RP 129, *Heavy-Duty Vehicle Cranking And Charging Troubleshooting: 12-Volt Systems*
- TMC RP 132B, *Battery Charging, Testing, and Handling*
- TMC RP 136B, *Managed/Isolated Battery Systems for Electric Start Systems*
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