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NEXT GENERATION CONDITION BASED MAINTENANCE (CBM) AND ON-BOARD DIAGNOSTICS FOR VEHICLE BATTERIES AND ELECTRICAL SYSTEMS

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ABSTRACT

Predictive analysis of vehicle electrical systems is achievable by combining condition based maintenance (CBM) techniques and 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 systems. The use of a communication protocol such as SAE J1939 allows for scheduling maintenance based on condition and not a traditional time schedule.

INTRODUCTION

Currently there are no on board 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 CBM and on board diagnostics for batteries and electrical systems.

Electrical system maintenance is performed as part of a preventive maintenance program. This is usually done on a regular time or mileage 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 on board diagnostic methods described in this paper will allow preventive maintenance to be performed in a timely manner before a hard failure and without doing 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. The batteries must provide the required cold cranking amperage (CCA) and reserve capacity (RC) to ensure day to day operation. Likewise the alternator must provide for 100% charging during a normal duty while providing power for all the electrical systems and devices.

Lead acid (Pad-Acid) batteries are the most commonly used on ground vehicles. There are millions of vehicles in use today using Pad-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 but are capable of withstanding regular discharging to low voltage levels. Figure 1 is representative of a typical heavy-duty configuration with starting and deep cycle batteries. 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.

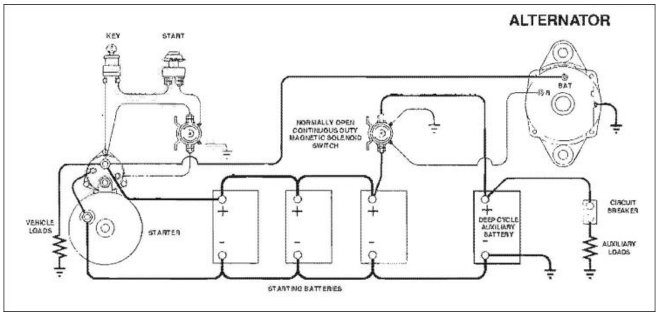

Figure 1: Typical Primary Electrical System [1]

MAINTENANCE PRACTICES

On-board diagnostics are very limited. There is typically a gauge or digital display. There could be a red zone, and/or a low voltage tell-tail light or 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 mission. What is lacking in this current generation of vehicles is a condition based alert to have a maintenance scheduled before a red zone or alert occurs.

Off-board 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 is 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 the missions. 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 it is 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. Road 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. It is based on scheduling maintenance 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 it is ineffective. Components will fail while in service resulting in additional cost and mission failure.

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 state of health (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.
The vehicles are to be maintained for 10 years. The batteries are known to fail in much less time. A preventive maintenance program is established to replace the batteries every two years. Each vehicle in the fleet has a 4 battery pack. This equates a purchase of 2000 batteries over 10 years (10 years ÷ 2 x 4 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 only some of the 2000 batteries. It might be 1000, or 1500 or some quantity less than 2000. Only the required batteries are replaced.

OPERATING MODES

The primary electrical system as 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. This is usually the case with alternative powered vehicle including hybrids. 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 vehicle 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.

- 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 an engine running. The voltages at the key and the battery are at elevated levels above the batteries' 100% 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.

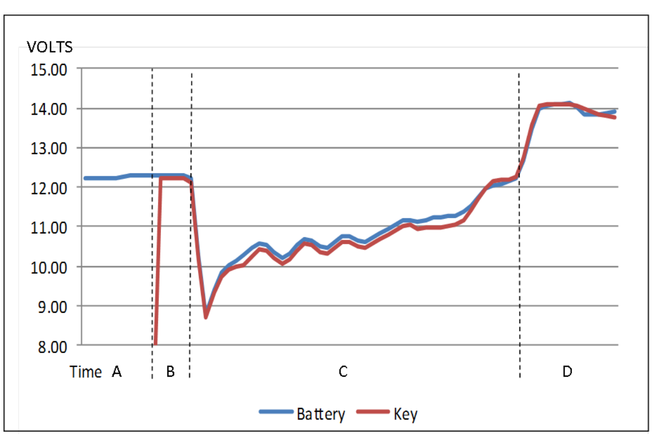

Figure 2: Four Operating Modes: A-Key On, B-Key Off, C-Start Cycle, D-Alternator Output

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 on board diagnostics. It's a method of determining the condition of a component without doing intrusive diagnostic tests as is typically 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 inline shunt or a clamp on current sensor. For example a 4/0 AWG copper cable five feet in length has a resistance of 250 μ-ohms at 20 C°. The resistance of copper 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 increase as temperature increases and decreases as temperature decreases. Hence the value of the shunt resistor is determined by wire gauge, length and temperature.

The method is valid when all the circuit components are at ambient temperature. This implies that the vehicle must be stationary with the engine off for an adequate time for the engine to cool 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 – 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 substantial different when the vehicle has repeated start/stop cycles. In these cases a rigorous analysis isn't 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 settle at ambient temperature. During this same time any surface charge on the batteries will have time 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 significate 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% 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 thousands of daily cycles. If in fact the starting and charging systems operate satisfactorily for the end user on a daily bases, then the SOH of each parameter value is scaled to 100%.

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 is used throughout the life of the system/vehicle to evaluate all qualified start cycles. Deviations that are outside of pre-set limits 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-c*hanges signal internal faults (i.e. windings, brushes, commutator, etc.).*
- Efficiency of the starter cable-a *clear indicator of corrosion of loose connection*
- Power delivered from batteries during initial time interval-n*ot being charged properly, irreversible aging*
- Power into the starter during initial time interval-c*ircuit integrity compromised, external disturbance.*
- Mean value of charging voltage-c*hanges signal internal faults of alternator, regulator or loose belt.*

Hypothesis testing can be employed 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 is 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 is 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% SOH and the limit scaled to 10% SOH. The CBM alert can set at 10% or some other arbitrary percentage based on experience and correlation with off-board diagnostics practices. When off-board 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 serves, number of cycle and thermal stress. As conditions change the circuit parameters move away from the mean values of the model and baseline vehicle. Maintenance alerts are set if the data is outside of the confidence interval.

STARTER CABLE MONITOR

A given wire gauge and wire length determines the resistance or the cable at 20 C°. 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,

$$\text{Efficiency} = \frac{\text{Power Into the starter}}{\text{Power Out of the batteries}}$$

Efficiency for each start cycle, when corrected for temperature, should be within one standard 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. This equates to an efficiency of greater than 92% in most heavy-duty systems.

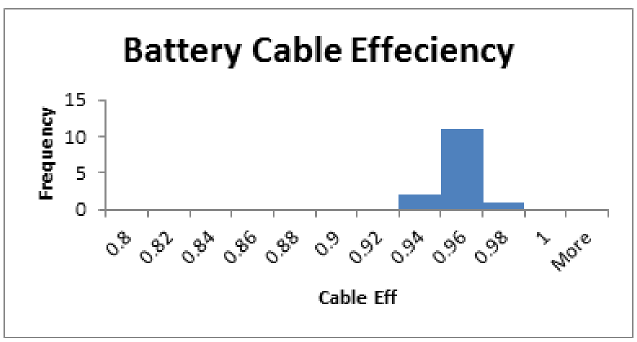

Figure 3: Battery Cable Efficiency

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 charge while in an open circuit mode. Sulfation result in the internal resistance increasing. 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 can be triggered accordingly.

The state of health can be expressed as a percentage, % SOH. A new battery is assigned a value of 100% 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% SOH and trigger a CBM alert. This is 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 does not need to perform the diagnostic procedure.

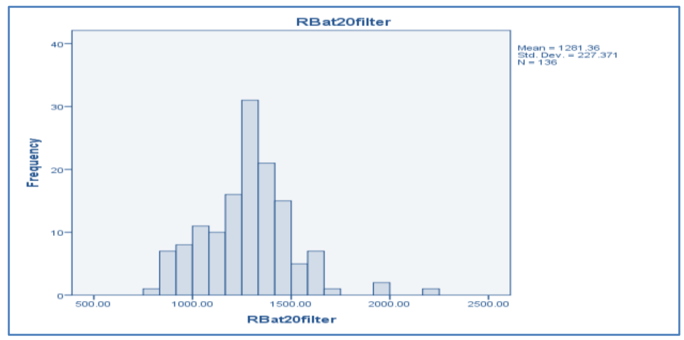

Figure 4: Battery Internal Resistance corrected for 20 C°

FLEET MANAGEMENT SYSTEMS (FMS)

A fleet management application is an application used by vehicle fleet managers to track and maintain the health of all the vehicles in their fleet. The fleet management software closely integrates with the vehicle diagnostics data and proves additional features including:

- Vehicle fleet health monitoring
- Vehicle maintenance scheduling and tracking
- Prognostics and Condition Based Maintenance (CBM+)
- Fleet reports
- Interface to parts order processing applications
- Geo-fencing & delivery documentation

Currently batteries and electrical systems are not included in fleet management for tracking and maintaining their health. By add the CBM principles outlined in this paper, it is possible to include batteries and the electrical system as part of the fleet management program.

J1939 DATA LOGGING, DATA DOWNLOAD AND CBM DATA ANALYSIS: MINI-VCS (Mini-Vehicle Computer System)

A data logger is a standalone device or embedded memory of another device that stores data on board. In this case for batteries and electrical systems it would store the data sets to form a historical record. Once the data is downloaded it can be used for fleet level CBM and prognostics. The SAE J1939 protocol is adhered to as the industry standard.

There are several implementations for doing a data logger:

- Dedicated battery management / electrical system monitor (i.e. E-Trak, Figure 5). This is a dedicated device that implements the algorithms used for circuit and statistical analysis, tracks, and store data, and triggers the CBM maintenance alerts.

Figure 5: Battery Management/Electrical System Monitor

- Embedded within an existing vehicle ECU. This would require embedding the software algorithms into an engine or vehicle ECU, storing, analysis and downloading data similar manner as a dedicated electrical system monitor

- Dedicated vehicle computer system (i.e. Mini-VCS, Figure 6). Vehicle Computer Systems (VSC) are designed to withstand the rugged environments found in vehicle applications. The Mini-VCS shown in Figure 6 is a device that will support many of the VCS applications (including CBM), while attached to the vehicle's J1939 diagnostics connector. The Mini-VCS is a low cost small package device based on the US Army's SWICE program. Applications of the Mini-VCS include support for vehicle J1939 Diagnostics and Vehicle Data Logging for CBM. The Mini-VCS also supports remote diagnostics using secure wireless link to the vehicle.

Figure 6: Mini-VCS with Security Authentication

Among the many Mini-VCS functional attributes, the Mini-VCS also includes the ability to function as a real-time data logger which is important to next generation CBM efforts. A data logger in the short-term can assist fleet operators in enhancing predictive maintenance schedules, with the long-term end-goal of platform-level CBM. The Mini-VCS provides a powerful and sophisticated, yet easy to configure platform for data logging.

Since the Mini-VCS has the ability to connect and communicate on any of the vehicle networks, it can also store copies of any of the messages it finds on a network in to a disk "file" in Mini-VCS's memory. This file can then be uploaded for pattern and trend analysis (prognostics) or it can be used to play back a scenario seen in the field by an technician or engineer investigating vehicle performance issues, for example, "rough shifting".

FILTERS AND TRIGGERS

One negative aspect of data logging, the most commonly seen, is that of information overload. Too much data can be overwhelming, and very time consuming to analyze. Eventually, the data gets pared down to meet the exact need. To pare the information down to the right level, two tools can be deployed in the Mini-VCS, filtering and triggers.

Simple filtering allows only specific messages of interest (possibly carrying more than one data item of interest) to be recorded at an appropriate time interval. This requires more post-processing work on an external PC to extract the data points from the messages. In complex filtering, data value(s) inside a message are used when selecting what information to store. This is done internally by the Mini-VCS, making for less post-processing work, and is the preferred method.

As filters tend to be based on values or time intervals, the Mini-VCS also employs a more powerful feature called "triggers". A trigger can best be described as an "event-based" reason for logging of data. Triggers differ from filters in that when a specific data value meets a trigger condition (i.e. the "event"), a pre-described action takes place. Actions may include starting/stopping logging, logging x minutes before or after the trigger, applying a set of filters, sending a message, or just writing an event to the data log. Triggers can also activate other triggers, a term called "stacked triggers". A very popular trigger condition in commercial fleets is one for "hard braking" (an x mph/second deceleration of the vehicle).

A PC-based graphical user interface (GUI, Figure 7) makes the Mini-VCS easy to configure, including filters and triggers. To simplify the process, and to allow for more detailed hands-on configuration, filters and triggers are defined in an XML language file that can be hand edited, and can be deployed to other Mini-VCS systems. Once the file has been created, the file is downloaded to the Mini-VCS and from there, the logging and triggering operations are automatic.

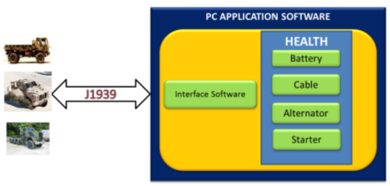

Figure 7: API and GUI for Next Generation CBM

DATA STRORAGE & PROCSSING

Once filtering and triggering has been activated, the next consideration is how to store the data. There are two camps when it comes to data storage, simple ASCII and binary. The Mini-VCS team chose not to implement the data storage in binary form, as any file captured and transferred would mandate post-processing to make it human readable. Instead, the Mini-VCS captures and stores the data log in a human readable ASCII format, which can be immediately interpreted. The file is also marked (i.e. 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 in a database for later predictive maintenance or further CBM analysis.

The files stored on the Mini-VCS are on a removable Flash memory card. When the Mini-VCS is configured to perform data logging functions, one of the parameters is how much memory to set aside for storage of these data log files. When the end of storage nears, the Mini-VCS can be configured to overwrite the oldest data, or to stop collecting data entirely. When the memory is full, a trigger can be set to perform other actions.

SUMMARY

Today's maintenance practice does not employ CBM techniques. While the voltage and current measurements are readily available, and used for other functions, they are not monitored for preventive maintenance. There is no on-board monitor or diagnostic run for batteries or the primary electrical system. At best, maintenance is done on a regularly PM schedule. In many cases there are hard failures of batteries, cables, starters or alternators that disrupt operations and significantly drive up maintenance costs.

The concepts laid out in this paper provide condition based maintenance that improve overall vehicle readiness and reduce the total cost of maintenance. No additional sensors are required. The voltage sensing and ambient temperature sensor are already on board. CBM can be included in a dedicated battery management/electrical system monitor or embedded with other ECU functions. The circuit analysis and related testing for statistical analysis are algorithms conducted during normal operation. The uses of diagnostic fault codes or tell-tale indicators alert the maintenance community only when preventive maintenance is required. A service technician validated the condition using standard diagnostics procedures and makes the repair. These results in a reduced level of maintenance during the lifecycle of the vehicle while protecting against premature failures that are otherwise missed.

Component	Function
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

Figure 8: Next Generation CBM-Function Overview

REFERENCES

[1] TMC RP136 A