Eliminating Periodic Fluid Sampling - Deep Dive Into Next Generation Online Fluid Technology

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Abstract

Online fluid sensing technologies are making a big impact in operators' reliability programs. Utilizing this advanced sensing technology has proven to lead to higher uptime through lubrication health tracking and event detection, enabling informed, timely preventative maintenance. This leads to lower maintenance cost as operators are able to reduce failures and take corrective action earlier.

To replace the need for periodic oil sampling, a critical advancement in sensing technology was required. Sensors measuring single or even a few properties of the oil are not adequate to replace oil sampling. However, advances in sensor design utilizing Electrochemical Impedance Spectroscopy (EIS) have enabled the required deeper understanding of the oil properties needed by a comprehensive oil condition monitoring program. With these type of sensors operators are now able to know the current health of their oil, trend degradation, project fluid RUL, and significantly reduce overall oil consumption as part of a truly condition-based fluid change program.

Poseidon Systems' Trident QW3100 fluid quality sensor is the one such EIS based online fluid quality sensor. The Trident QW3100 derived from technology developed for the Department of Defense over a 15-year period. The advancements made in the last few years have allowed for its adoption as the standard for many fluid monitoring reliability programs; leading to significant savings for operators.

INTRODUCTION

Oil sampling analysis has been the backbone of all oil reliability programs for the past century. From early analysis technology used by oil labs to the more modern miniaturized benchtop equipment, these have transformed the way and speed to which we make decisions around preventative maintenance. The latest of these advancements has been new in-line, real-time oil quality monitoring sensors that deliver on the earlier promises of true online monitoring capabilities.

The value from oil samples are centered around oil health itself. Properties such as oxidation, TBN, TAN, additive packages, viscosity, water, fuel, soot, etc. are all used to assess the remaining-useful-life (RUL) and identify preventative, as well as corrective actions. A few notable challenges with oil sampling are the time delay between sample and results, access to remote and mobile assets, infrequency of sampling compared to reliability events, and high risk of human error. Because of these challenges, many operators are moving towards online fluid monitoring.

Typically, past online sensors were simple single point dielectric, conductivity, or permittivity measurement devices detecting rough oxidation of the oil with little sensitive to other key parameters. More recent sensor advancements are now capable of detecting degradation of not only overall quality, but estimating percent soot, total base number, relative humidity, additive depletion, etc. These new sensors can detect most, if not all, key oil events and project remaining useful life of the oil while the asset is in operation.

While these sensors cannot duplicate lab analysis results, they can provide the necessary insight to make preventative maintenance decisions before damage occurs. Online oil quality sensors are key enablers to shifting the oil sampling paradigm from periodic to true condition-based sampling. New sensor technologies utilize Electrochemical Impedance Spectroscopy (EIS), which cover a spectrum of properties of the oil and allow for sensitivity to most failure modes. Sensitivity to multiple failure modes is a critical characteristic to ensure adequate coverage of today’s complex oils and oil systems.

ENABLING TECHNOLOGY

A common sensing approach provides the real-time analysis of fluid properties in an online sensor based on electrochemical impedance spectroscopy (EIS). The EIS technology has been commercialized by multiple companies in on/off highway diesel engine applications as well as wind turbine gearbox, stationary power generation, and marine applications. Poseidon's approach to online EIS based oil condition monitoring is embodied in its Trident-QM/QW product lines.

Electrochemical impedance spectroscopy involves injecting an alternating current signal into a system over a range of interrogation frequencies and measuring the response in order to characterize the system. The impedance of the system is determined by analyzing the differences between the injection (excitation) and response signals, see *Figure 1*. By scanning across a wide-range of frequencies, the resulting data set that can be used to define multiple properties of the system under test. Impedance spectroscopy is a commonly applied sensing technique and has applications in corrosion monitoring, fuel cell monitoring, battery monitoring, film/coating characterization, and many others.

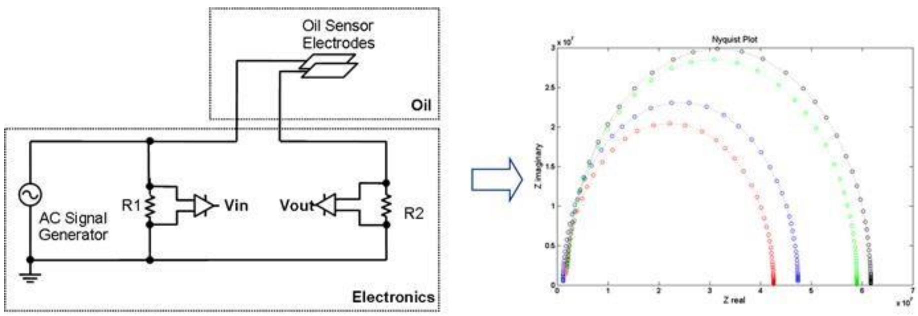

Figure 1: EIS Based Sensor Principle - use of Broadband Impedance Spectroscopy (such as Trident-QM)

Application of EIS to the characterization of lubricating oil is an area of significant recent development and advances. The technology provides the ability to measure multiple properties of a lubricant using a pair of simple electrodes immersed in the fluid of interest. The technique does not require any consumables or exotic materials and it is applicable to a wide range of fluid types. EIS based sensing is well suited for online applications and Poseidon is leading the industry in the development and commercialization of EIS-based oil condition sensing technologies.

EIS Technology Comparison

The primary advantage of EIS measurements over conventional dielectric or similar sensors is that an EIS measurement results in the simultaneous characterization of both the bulk solution and the interfacial properties of the lubricant. When high frequency interrogation signals are applied to a lubricant system, the response is dominated by polar additives, oxidation byproducts, and polar contaminants. At low frequencies, the response is dominated by the presence, type, and health of surface-active additives that form films on the electrode surfaces. By measuring both bulk and interfacial properties of a lubricant, EIS offers excellent insight into lubricant health and function. These measurements are described in more detail below.

Figure 2 shows a Nyquist representation (real vs imaginary impedance) of a typical diesel engine oil. Notice the impedance curve forms two distinct regions. Each of these regions can be independently characterized in terms of its resistive and capacitive properties. These properties are based on the measurement cell geometry, the fluid temperature, the base oil, the additive package, oxidation products, and oil contaminations. Because cell geometry is constant, fluid temperature is measured, and base oil is constant (for a given oil change interval), any changes in the impedance spectrum are due to changes in the additive package, oxidation products and/or contaminations.

In comparison with a dielectric or permittivity sensor, using impedance spectroscopy provides the ability to monitor multiple fluid properties simultaneously and better determine the driving failure modes. These more basic technologies only provide the equivalent of a single data point from the impedance spectrum, see Figure 3. They offer no ability to assess interfacial response, no ability to detect specific contaminants, and can easily be “fooled” into reporting healthy oil conditions when multiple contaminants or degradation modes are present simultaneously.

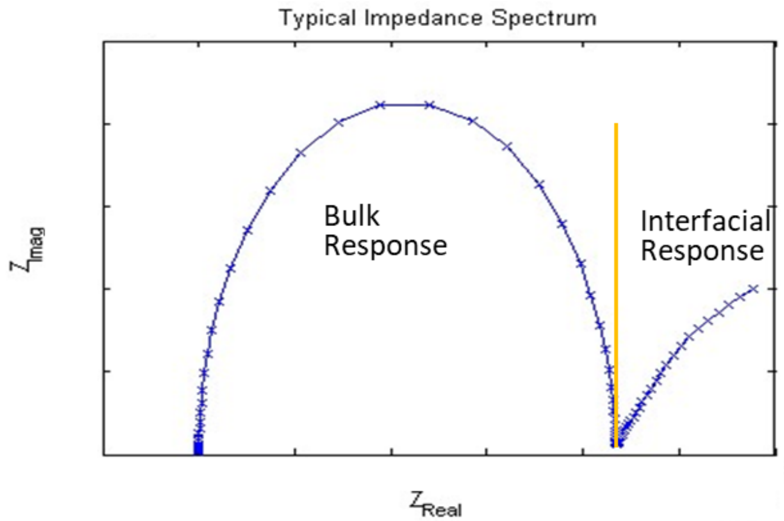

Figure 2: Example Impedance Spectrum (Nyquist Representation)

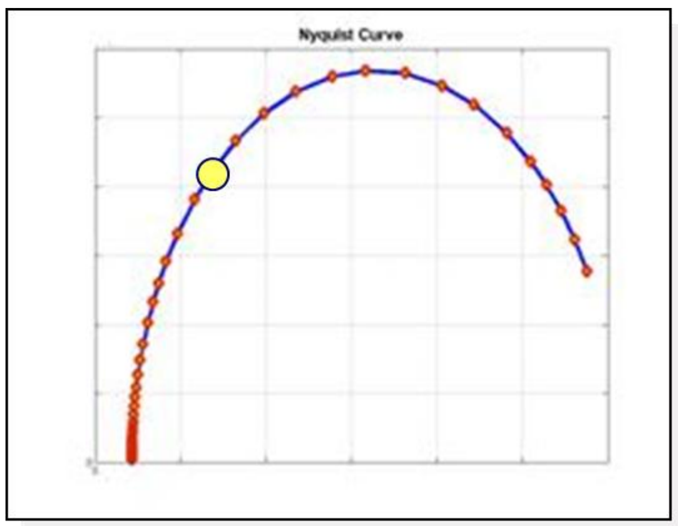

Figure 3: Illustrative Example of Single Frequency Measurement

As introduced above, one of the key measurements of an EIS based sensor is the Interfacial Impedance measurement. The very low frequencies of an EIS interrogation are affected by the interfacial properties of the oil. From the responses at these low frequencies, the health of surface protection additives and presence of contamination on the electrode surfaces can be assessed. The Interfacial Impedance rises during oil break-in and falls as surface protection additives deplete. The feature also provides very good free water detection with the impedance falling orders of magnitude when free water contacts the electrodes.

Bulk Resistance is the second important measurement of an online EIS based sensor. At low to medium interrogation frequencies an EIS sensor measures the bulk impedance of the oil. The Bulk Resistance is sensitive to oil polar additives, oxidation products, and other contaminants. Much like Interfacial Impedance, Bulk Resistance shows a rise in value as during oil break-in and a downward trend of is indicative of decreasing additive health as the oil naturally degrades with use. An accelerating negative slope is indicative of a contamination event as water, fuel, or coolant rapidly degrade the additive package health.

A third key measurement for any good EIS sensor is the High Frequency Bulk measurement. As the its name implies, the High Frequency Bulk measurement uses high frequencies to measure the capacitive properties of the oil. Dissolved/dispersed contaminants and oxidation products in the oil can be detected using these higher frequencies. Contrary to the other measurements, a downward trend, usually linear, is typically inversely proportional to contamination, especially soot in diesel applications. In other words, the High Frequency Bulk measurement decreases with an increase in soot. It is also sensitive to dissolved water and fuel.

APPLICATION EXAMPLES

Several compelling real applications of Poseidon's oil quality sensors are described below. These are a combination of in field applications and high-performance OEM test stands. In several of the examples the oil quality sensor readings can be directly compared to standard oil sample data.

Example 1 – Fuel Contamination

Figure 4 shows two features from the impedance spectrum in response to contamination events that occurred in large vehicle engine. The bulk resistance, shown in the top figure, is primarily impacted by changes to the additive package and to contaminations which significantly affect the fluid impedance. The interfacial impedance, shown on the bottom figure, indicates the strength of the surface protection additives.

The fuel contamination event is detected as a more rapid drop in bulk impedance due to the difference in the impedance of fuel and oil. Given enough time, the fuel would also accelerate oxidation and additive depletion leading to an accelerating decrease in bulk impedance. In the time frame of this test, fuel has no impact on the surface protection additives.

The response to water contamination is more dramatic. The impedance rise is due to the formation of inverse micelles by detergents surrounding water droplets. As the water is broken into ever smaller droplets and absorbed by the oil, the impedance drops off. After the event, the measured impedance level is lower due to the additive depletion caused by the contamination. Take note the contaminations can opposite influences on the impedance measurements. Therein lies the risk of using a single parameter device to attempt to characterize a complex system such as a degrading oil.

In terms of surface protection, the interfacial impedance drops immediately after the addition of water. This indicates the surface protection layer has been compromised as a result of water droplets hitting the surface of the electrodes and displacing the surface protection additives. The slow rise over time is a result of the recovery of the surface protection layer as water is stripped from the electrode surfaces through absorption and detergents.

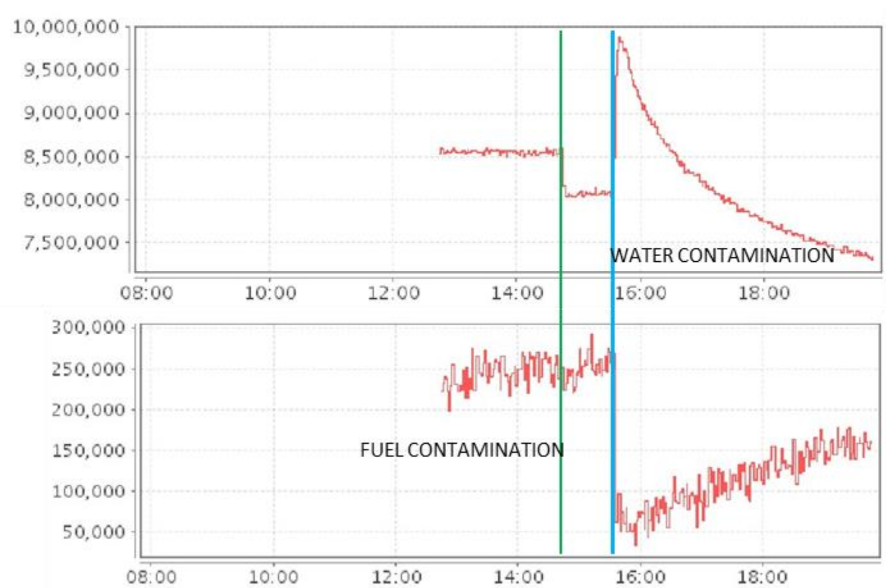

Figure 4: Bulk Resistance (Top) and Interfacial Impedance (Bottom) Response to Contamination

Through this multi-frequency / multi-feature approach, EIS offers the capability to provide protection against an array of fluid degradation modes in a single, robust, inexpensive package. The technology is unique in its ability to provide protection against contamination, oxidation, and additive depletion.

Example 2 – Mining Truck Coolant Contamination

In another notable application, an online oil quality sensor was installed on a diesel engine operating off highway. A several month trend of data from the installed sensor is shown in Figure 5. Note this is a detailed view of the data typically used by engineers, a more typical easier to interpret view is shown in Figure 6. There are two characteristic trends in the plot that commonly occur in almost every oil health monitoring application. First, after an oil change, there is a typical break-in period during which the quality reading peaks as shown in the first (left most) part of the plot. Second, as the equipment continues to operate, the sensor readings trend down as oil quality degrades, as shown in the middle part of the plot.

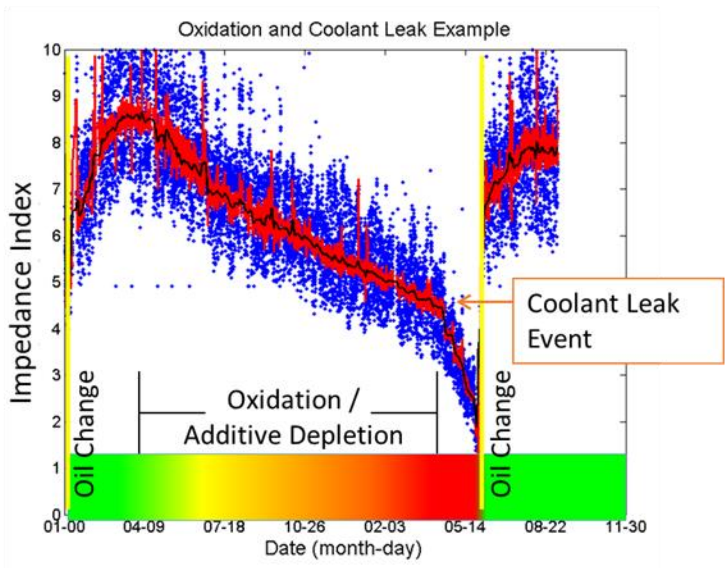

Figure 5: Online Impedance Spectroscopy Measurements from Mining Truck, Detailed Engineering Data

What is not expected is the more rapid decrease in the trend near the end of the more gradual trend. As shown Figure 6, the sensor data showed a significant decrease in the quality trendline and an increase in relative humidity detected by the sensor. The downward sensor trend increased in rate on approximately 05/05/17, which triggered an alert. The alert caused an inspection, during which a coolant leak was discovered. The coolant leak would have gone undetected and severely damaged the equipment forcing a full engine rebuild if the sensor had not been installed. The equipment was repaired, oil changed, and put back in service with minimal downtime compared to previous cases.

Using online oil quality sensors leads to earlier detection of fault conditions and enables preventative maintenance actions, before equipment is severely damaged.

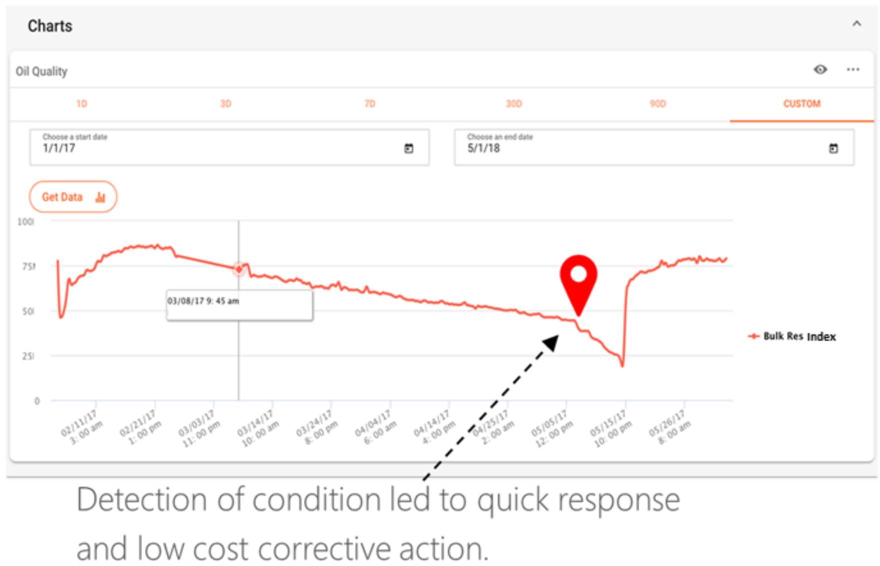

Figure 6: Typical User View

Example 3 – On Highway Diesel Engine

An oil quality sensor was installed in an on-highway diesel engine from which oil lab samples were also collected. Throughout this application, the engine components were subject to various abnormally high loads and temperatures. These high loads and temperatures resulted in rapid oil degradation and several oil changes over the duration of installation.

One of the raw sensor outputs, Bulk Resistance, is shown in Figure 7, compared to total base number (TBN) measure via standard lab analysis. Typically, additional processing is performed to simplify the result to make it easier to understand, however for the purposes of this technical whitepaper, a less processed sensor output is provided. Solid, black vertical lines represent times at which an oil change or oil replenishment (top offs) occurred. The sensor output, both filtered (blue solid line) and not (red dots), clearly show the characteristic response of EIS to new oil, a large increase followed by steady decrease. Usually the decrease in the sensor output would continue until a condemning limit is reached and an oil change would be recommended. However, the oil was changed due to extreme operating conditions.

The bulk resistance showed very good correlation with lab nitration, oxidation and TBN measurements, as shown by the green dots on the secondary (right) axes. The downward trends of the sensor mirrored the lab TBN measurements, indicating the sensor can accurately reflect the results from the more labor-intensive lab sampling.

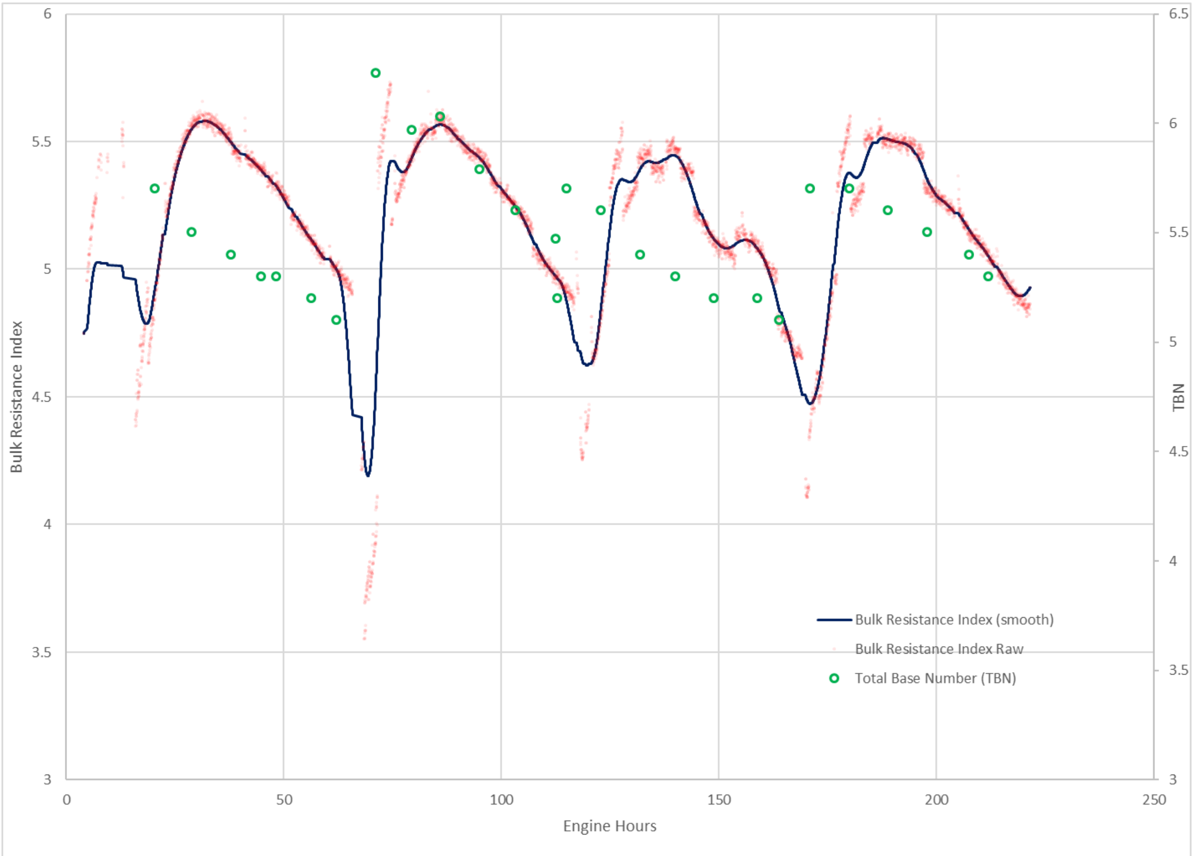

Figure 7: Diesel Engine Application, Raw Sensor Response and Laboratory Total Base Number

Another similar installation occurred for a much longer duration. As shown in Figure 8, the sensor had very good correlation between the sensor's bulk resistance and TBN from the oil lab samples. The sensor response trended extremely close to the lab measured TBN but was continuous over the entire duration, versus the periodic lab sampling. Both measuring techniques showed the aging oil over the duration, but the lab sampling was much more labor intense, which in this application occurred much more frequently than normal.

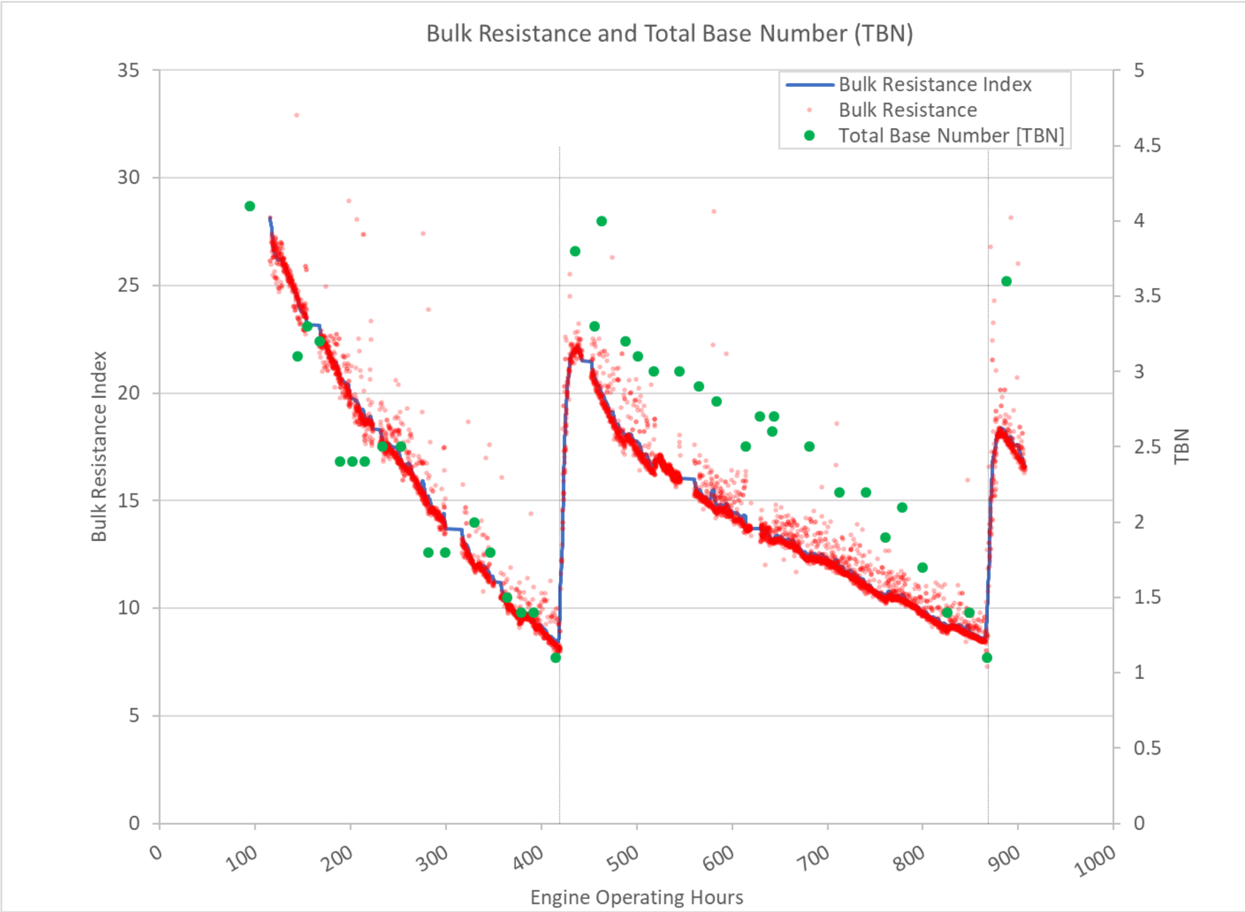

Figure 8: Sensor Response vs. TBN

Figure 9 compares the sensor readings to the lab measured soot content, with only the smoothed sensor measurements shown. This diesel engine application caused high levels of soot contamination in the oil. The High Frequency Impedance measurement trended inversely, as expected, with the increase diesel soot. Based on these results a High Frequency Impedance threshold could be set at a corresponding soot contamination level to ensure engines fielded with the online oil quality sensor would have real time monitoring to detect and alert the operator of the deteriorating oil prior to engine damage or significant loss of performance.

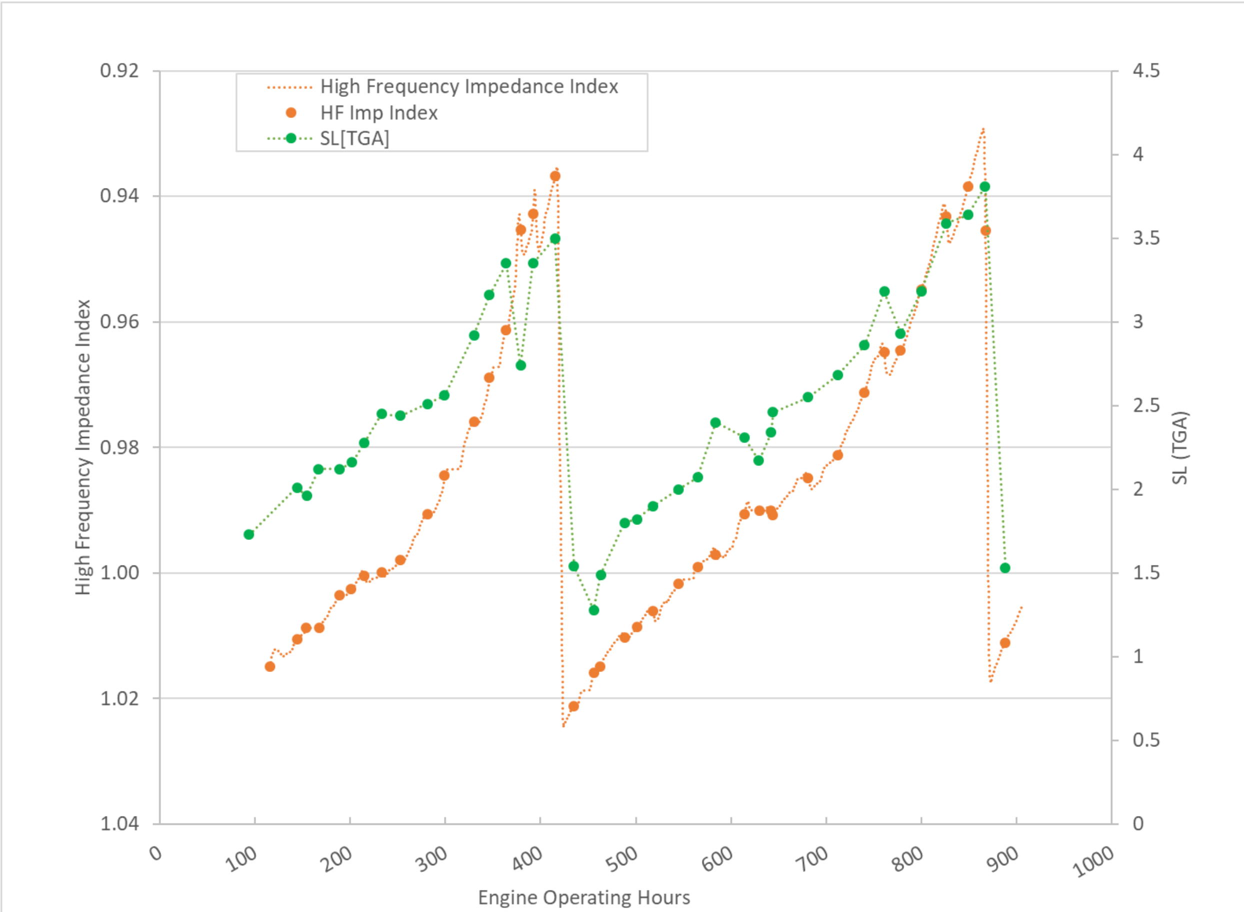

Figure 9: Sensor Response vs Soot (SL[TGA]) Increase

A further simplified view is typically presented to the customer, as shown in Figure 10. The data is viewable in real time by secure web portal so the responsible person, be it site manager or maintenance lead, can view the online oil quality sensor results at any time. There is no need to wait for lab results, the assets current oil health can quickly be accessed, even remotely.

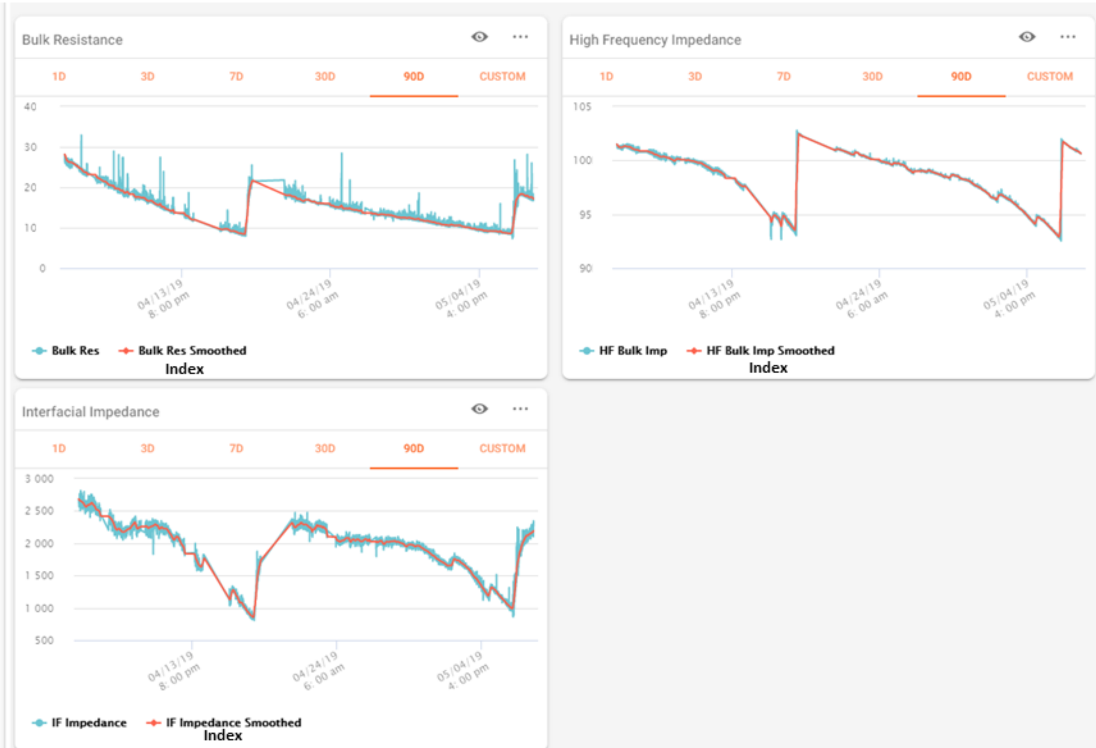

Figure 10: Typical Customer View

Example 4 – Diesel Engine Longer Term Endurance Application

A final set of diesel engine examples spanned even longer duration and had fewer intermittent oil changes or top offs, leading to more variability in the data due to large changes in temperature. Common practice is to apply various techniques to temperature compensate EIS readings in order to reduce measurement variability and error. These techniques typically involve normalizing or correcting the readings to a standard temperature to allow more direct comparison. Figure 11 plots the temperate compensated sensor Bulk resistance over the +1200-hour duration. The oil quality sensor readings agreed very well with the oil lab nitration, oxidation and TBN measurements. Like other applications, the High frequency Impedance showed good correlation with lab soot measurements as the engine ran for extended periods at high loads. The few comparatively few top-ups were evident in the data. The dashed red lines are theoretic thresholds (limits) that could be used on the corresponding EIS measurement. If the Bulk Resistance trended below its limit, it would indicate need to change the oil due to depleted additives or aged oil. If the High Frequency Impedance trended below its limit, it would indicate need to change the oil due to high levels of soot contamination. Either alarm indicator would be provided in real time during operation, as the asset is generating revenue, versus traditional lab sampling that would occur days if not weeks after the engine was subjected to the harmful conditions.

Not only does on-line real time monitoring expediate the oil monitoring process, it can help reduce costs by removing some of the conservatism in condemning criteria necessary in a lab sampling paradigm. Since the lab sampling inherently has a lag between measurement and remedial action, the condemning levels of used necessarily must be lower, more conservative, than a method that monitors the oil in real time. In other words, any actions taken based on lab sampling must take in to account the time between sample and action, since the asset continues to operate with that oil. It must be assumed the oil will continue to degrade during the time it takes to conduct the sampling, time during which the oil condition continues to worsen. Therefore, recommendations based on lab sampling are necessarily more conservative to reduce the risk to the asset. However, if monitoring the oil in real time, one could reduce the conservatism because there is no measurement lag time, and thereby reduce costs associated with replacing oil too soon.

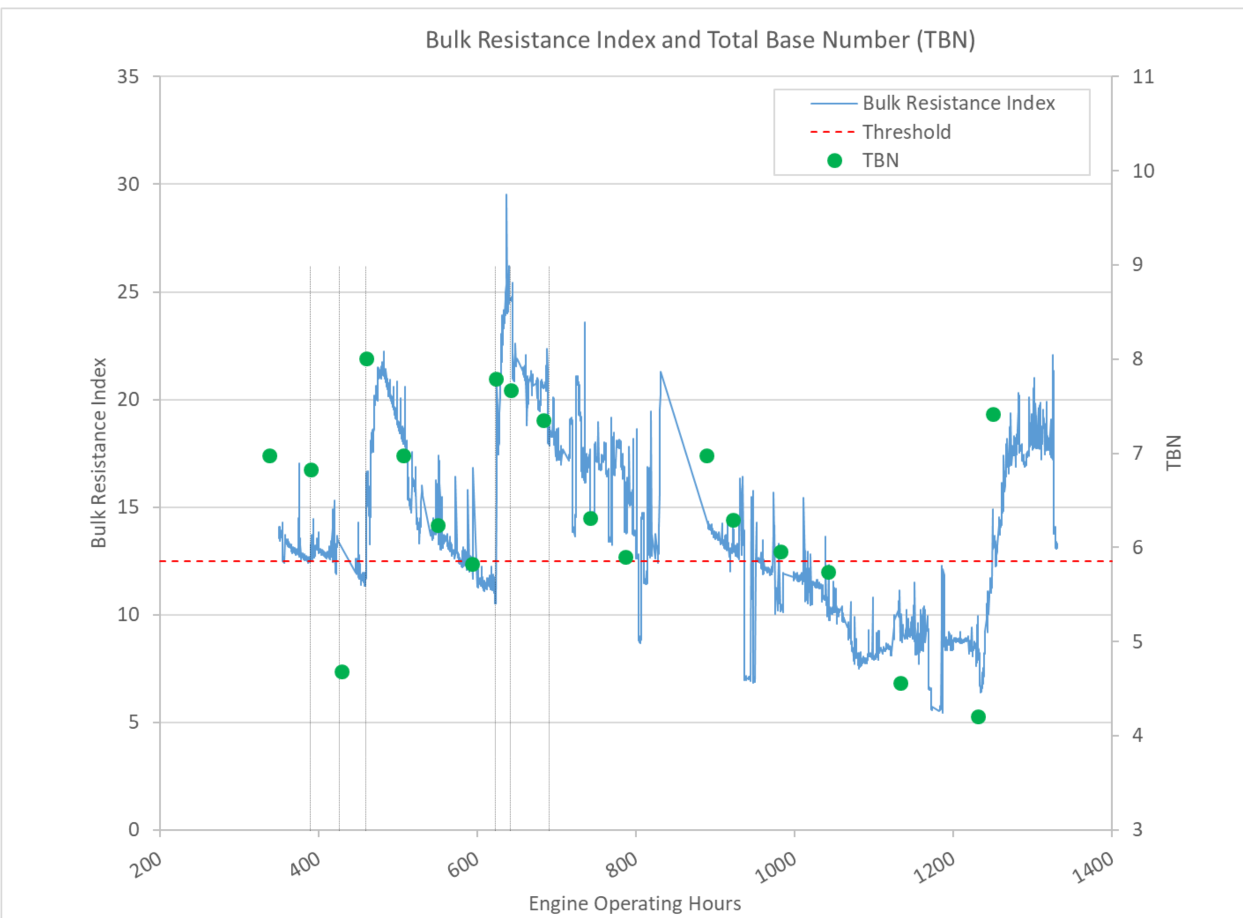

Figure 11: Bulk Resistance Endurance Results

In most applications, an oil quality sensor alone cannot replace a high quality, lab-based oil sampling protocol since it cannot provide all the same level of detailed analysis. Instead, an online EIS-type oil quality sensor can help reduce the amount and frequency of lab sampling that is needed, while affording protection against both normal and abnormal degradation modes. Lab sampling can be conducted as needed, when needed, based on the measured condition of the oil and not based on calendar or operating time. Thus, converting the costly lab sampling from time-based periodic maintenance to condition based maintenance. Implementing a holistic oil condition monitoring program that combines both all the time online oil quality sensing with an as needed focused lab oil sampling program has the potential to provide the ultimate cost benefit by avoiding unnecessary samples for the assets that are nominal, which is majority, while providing coverage to the few assets that may be operating abnormally.

Conclusion

Online fluid sensing technologies, such as the Trident QW3100, stand to make a big impact in operators' reliability programs. Utilizing this advanced sensing technology has proven to lead to higher uptime through lubrication health tracking and event detection, enabling informed timely preventative maintenance. This leads to lower maintenance cost as operators are able to reduce failures and take corrective action earlier. Connecting online fluid data to condition triggered lab testing allows for deeper diagnostics into failure modes, allowing for fluid quality to be tracked in one location for faster and better decision making.

New in-line, real-time fluid quality sensing technology utilizing EIS are just now starting to reveal all the ways they can help improve reliability programs and reduce operational cost. As these sensors are used more and more, new case studies and value drivers will be developed to improve reliability programs. Beyond detecting fault conditions and optimizing drain intervals, more improvements to reliability can be developed by optimizing top-offs, bleed-and-feed, advanced filtration, additive replenishments systems, etc. These early case studies are driving adoption at a significant rate by changing the way best-in-class oil reliability programs operate and make decisions.