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Internet-connected DGA Monitoring at MIT's Alcator C-Mod Fusion Facility

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SUMMARY

MIT's Plasma Science Fusion Center (PSFC) operates the world's strongest toroidal magnetic field Tokamak fusion reactor. In March 2016, heavy precipitation resulted in water breaching the main tank of one of the facility's transformer rectifier units, resulting in its complete failure. A Dissolved Gas Analysis (DGA) sensor was installed to monitor moisture and hydrocarbon levels going forward. By connecting the sensor to the Internet via a cellular gateway, the operating team and equipment manufacturer are able to remotely monitor the transformer continually. This paper summarizes this "Internet of Things" solution and the business case for this class of online monitoring. Future steps, regarding machine learning methods and fleet-level management, are briefly discussed.

KEYWORDS

Transformer monitoring, Internet of Things, Condition based maintenance, Dissolved Gas Analysis, Asset Management, Remote monitoring

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1. INTRODUCTION

MIT's Plasma Science Fusion Center is a leading fusion research laboratory, operating Alcator C-Mod, the largest university-run fusion reactor [1]. Power for the reactor is supplied from the grid via an on-site substation and a 225 MVA alternator with a 75-ton flywheel.

In early 2016, one of four transformer rectifier units in the substation failed catastrophically due to moisture incursion in the main tank. A second transformer rectifier had higher than expected moisture in oil during an annual inspection. It was determined that an online DGA and moisture sensor would allow the plant team to closely monitor operating conditions in this transformer and take preventative action as required.

The transformer rectifier units face a unique duty cycle, with highly variable, pulsed loads. The engineering team desired high-resolution (<1 minute) data from the sensors to correlate with the reactor's operating cycle and the associated pulsed loads.

By connecting a Hydran sensor to the Internet via a cellular modem, the team is able to collect, store, and visualize the data from the sensor via a web application. Data is sent once per second. The high data resolution is important, since reactor "shots" last only several seconds. With these higher resolution data, the team can identify correlations between operating conditions and environmental conditions.

2. INSTALLATION & DESCRIPTION OF MONITORING SYSTEM

The system set up was designed to be as simple as possible, consolidating as much of the computational work into a cloud-based web-server. The basic arrangement is outlined in Figure 1.

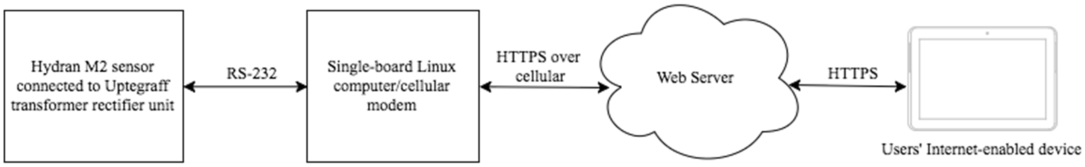

Figure 1 : High-level solution overview

Installation

The transformer rectifier unit was manufactured by Uptegraff, and included two access valves to the main tank. For clearance and better oil circulation, the team integrated the Hydran sensor to the top press filter valve. Installation went smoothly and took approximately two hours.

After the sensor was connected to the transformer rectifier unit, the team connected a single-board Linux computer with a cellular modem directly to the sensor via a serial connection. This was enclosed in a weatherproof box mounted to the side of the transformer rectifier unit input termination cabinet.

Description

The computer polls the sensor once per second using the Modbus RTU protocol, and the resulting data is sent to a designated web server via a cellular network. As an alternative implementation, the sensor could be connected directly to an industrial cellular gateway with a serial interface.

The web platform collecting the data is built on third party infrastructure from Amazon. Data was sent encrypted end-to-end using SSL to secure the HTTP traffic.

The streaming data, various visualizations, and simple analytics (rates of change, averages, etc.) are made available to authorized users through the web application. One advantage of sending raw sensor data to the cloud is that any updates or new analytics can be updated without an on-site visit, and can be distributed across a large fleet easily. Data collected includes a composite gas level (with sensitivity to H_2, CO, C_2H_2, and C_2H_4, measured in ppm), oil temperature (ºC), moisture in oil (ppm), and relative humidity (%).

In summary, the Hydran sensor was attached to the transformer, and then connected to a single-board computer and cellular modem via an RS-232 connection. The data from the sensor is sent via cellular to web servers, where it is parsed and stored. Authorized users can then view the streaming and historical sensor data using a web browser from anywhere with an available Internet connection.

3. ECONOMIC BENEFITS

An effort was made to estimate the value of both the online DGA and the Internet-based implementation. The principle quantifiable benefits of the Internet-based implementation are (1) reductions in unplanned downtime, (2) deferred equipment replacement (enabled by continual monitoring and advanced analytical models), (3) reduced installation time, and (4) diminished installation cost.

We based our economic analysis on the model developed as part of IEEE C57.143-2012[1], with some modifications to the cost-benefit analysis assumptions based on claims data published by Hartford Steam Boiler (HSB)[2], a property insurer. Specifically, the overall transformer failure rate was cut in half, from 1% annually, as specified in the IEEE standard, to 0.5%, based on claims data published by HSB. This implies a 50% reduction in failure probabilities vs. the IEEE published model.[1]

The model results are summarized in Figure 2. Annual savings are rounded to the nearest hundred. The primary benefit of the online DGA monitoring here is a reduction in expected reactor downtime, valued at approximately $31k annually. A secondary benefit is the reduction in expected replacement (alternatively, a deferment in transformer replacement),

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[1] In other respects, the cost-benefit model is identical to that in IEEE C57.143-2012. For more detail on how the model is set up and the assumptions going into it, we recommend readers reference Section 7 of that document.

valued at $1k annually. In aggregate, for the Internet-based implementation, this is approximately 16% of the purchase price of the asset.

Figure 2 : Cost-benefit model summary[2]

	Without Monitoring	**DGA Monitoring**	**Internet-based DGA monitoring**
Failure Probabilities (from IEEE C57.143-2012)			
Failure occuring without advance warning	0.350%	0.140%	0.119%
Failure prevented by early detection of fault	0.150%	0.360%	0.381%
Major failure occuring without advance warning	0.347%	0.139%	0.118%
Catastrophic failure	0.004%	0.001%	0.001%
Additional preventative repair work	0.000%	0.210%	0.242%
Expected Failure Costs			
Major Failure	$ 1,559	$ 624	$ 530
Catastrophic Failure	$ 53	$ 21	$ 18
Preventative Repair Work	$ -	$ 126	$ 145
Total	$ 1,612	$ 771	$ 693
Annualized reduction in failure resolution cost		*$ 841*	*$ 919*
Cost of Reactor Downtime			
Failure occuring without advance warning	0.350%	0.140%	0.119%
Lost facility productivity due to failure	$ 13,150,080	$ 13,150,080	$ 13,150,080
Expected lost productivity due to failure	$ 46,025	$ 18,410	$ 15,649
Annualized reduction in lost productivity		*$ 27,615*	*$ 30,377*
Annual Savings		**$ 28,500**	**$ 31,300**

For generator step up or transmission transformers, additional value from an Internet-based DGA solution includes (1) avoided lost revenue, (2) increased overload capacity, and (3) avoided penalties from contractual power not delivered. These benefits can be quantified using the same model employed here. For example, in the case of a nearby power plant, the estimated savings are $250k per year for a station transformer with a similar system installed, largely due to a reduction in expected lost revenue.

4. RESULTS

Following installation of the sensor and cellular modem, users can access streaming data from the DGA sensor using a web browser. The deployment was successful and sensor data is now streamed to an Amazon-hosted web server: Ten different measurements (including temperature, moisture, and a composite dissolved gas reading) are sent to the web servers once every few seconds, where they are parsed and stored.

Data is preliminary, but alerts have been programmed on absolute levels for each measurement, in addition to rates of change. If the moisture reading, or its rate of change, exceeds the specified threshold, authorized users immediately receive an email indicating the issue.

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[2] The PSFC transformer rectifier unit failure probabilities are likely higher than transformer population averages due to the pulsed duty cycle and long idle times. Additionally, the expected cost of failure could be as high as $20M in a year if the failure overlaps with a sixteen-week experiment campaign. If the failure occurs outside of an experiment campaign and can be remedied before the start of the next experiment campaign, disruptions would be substantially lower.

By tracking measurements at a high resolution, MIT's PSFC has been able to compare temperature, moisture, and dissolved gas measurements to reactor operation. As more data is collected, the team will work to discern relationships between transform rectifier unit operating conditions and environmental variables/reactor activity.

5. FUTURE STEPS

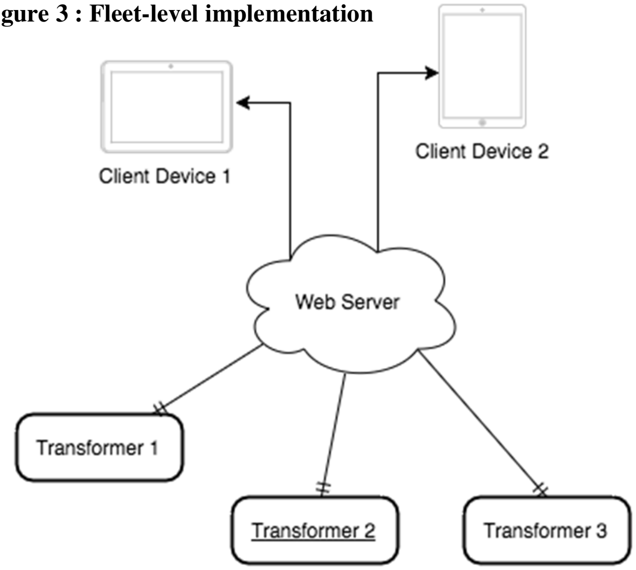
Unlike existing monitoring solutions, a web-based application allows for improvements in analytics, data visualization and application performance, without an on-site visit. Updates in software are pushed to web servers, and the updated application is available to all clients.

In the authors' view, one of the most exciting opportunities for this arrangement is the ability to collect and build models at a fleet level. Because the application is agnostic to DGA sensor vendor (any sensor with digital output is compatible), data from a large population of transformers could be collected and analyzed. This has two primary advantages over existing methods.

First, since the data is available to authorized users, it is simple to get support directly from equipment manufacturers or service companies. The PSFC has qualified electrical engineers on staff, but none have a comparative advantage in detailed interpretation of transformer DGA data. By managing the data in a web application, it is easy for the team to request analysis by a qualified third party, including the transformer manufacturer or a DGA laboratory.

Second, this model provides the opportunity to collect an unprecedented volume and resolution of DGA data. Though transformers might be owned and operated by different entities, the data can be pooled to build models to identify faults. For example, a nearby cogeneration plant is sending data from DGA sensors on their transformers to the same web application. The data from both sites is used to identify outliers in the condition and operation of each individual transformer, but the models might be vastly improved with hundreds or even thousands of transformers monitored concurrently.

Figure 3 : Fleet-level implementation



Additionally, an Internet-based deployment of DGA sensors also has major cost-benefits over existing solutions. For a couple hundred dollars in incremental cost, any DGA sensor can be made to send its data in real-time to a web server. The fixed cost of a fleet-level management system is reduced. In some cost categories (for example, managed IT infrastructure) it is eliminated entirely. This makes online monitoring of distribution or lower cost transformers now economical. It also makes online monitoring feasible for transformers in substations with no existing communication infrastructure, so long as there is a cellular signal available.

Finally, future steps at this project site may include the incorporation of additional equipment or sensors. A web application is capable of handling data from a variety of sources. So long as the communications protocol is well documented, it is a straightforward exercise to incorporate additional equipment (anything with Modbus RTU, ASCII, or DNP3 output, for example, could be integrated). One proposed follow-on project is to apply web-connected current transformers to measure real-time load current. This data could be correlated with increases in oil temperature, dissolved hydrocarbons, or any other captured measurement in real-time. On larger transformers, other measurement points might include cooling fan/pump status, OLTC temperature, and ambient weather conditions.

6. CONCLUSION

Following failure of a rectifier transformer at MIT's fusion reactor laboratory, an Internet-connected DGA sensor was installed to monitor moisture, temperature, and dissolved gas levels in a transformer with elevated moisture readings. The goal was to test the feasibility of an Internet-connected DGA sensor and to automatically monitor the measurements of moisture and dissolved gas in particular.

Based on our model, the Internet-connected DGA sensor will save the MIT PSFC $31k per year over the life of the transformer. These savings are driven primarily by decreased downtime and deferred replacement expenditures. For larger transformers supporting revenue, the savings could be several orders of magnitude greater (principally, by cutting lost revenue).

The deployment has also shown the feasibility of using cellular networks and off-the-shelf cellular hardware to enable DGA remote monitoring. By this method, it costs only a few hundred dollars to provide remote monitoring capabilities. This makes DGA monitoring on lower value transformers economically feasible. By our model, Internet-based online DGA is economical for transformers with a replacement cost in excess of $120k, considering only the value of deferred replacement (that is, ignoring all the benefits of reduced downtime, expanded overload capacity, etc.).

Future applications for Internet-connected DGA sensors are broad, and include fleet-level analytics, comparisons across utilities/operators fleets, and improved analytic methods (using machine learning, for example).

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