Leveraging Next Generation Reasoning for Prognostics and Health Management of the Smart Grid

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ABSTRACT

With the increasing complexity from an evolving Smart Grid, the significance of providing real-time situational awareness and the ability to leverage advanced reasoning and prediction for control and automation will become key differentiators for service providers. Similar techniques are being applied within prognostics and health management (PHM) applications and are providing value by predicting and assuring system reliability, performing real-time detection and diagnosis of failure, and presenting current and predicted system states to users to aid in decision making. With the overlap in application and requirements for advanced software techniques, the smart grid industry is compelled to investigate products and processes applied to PHM across other domains. However, the complexity of grid management, the speed of technology development, the dynamic nature of electric power supply and demand – each of these contribute to the necessity for applying *advanced* reasoning capabilities that provide more flexibility to developers and users. Such advanced capabilities allow for leveraging all available information, enabling accurate predictions of future conditions and availability, and incorporating the necessary knowledge for making high level decisions. Object oriented, model-based reasoning systems have demonstrated value within the PHM community for handling such complexity, and in this paper the authors discuss a pragmatic approach for applying these next generation PHM techniques to the smart grid.

1. INTRODUCTION

Many years of PHM research in the aerospace industry has resulted in the development and validation of various learning algorithms and expert system reasoning platforms for the purposes of monitoring and predicting the health of complex aircraft systems (Ferrel, 1999). Among other things, such PHM systems have demonstrated the ability to detect anomalies from real-time comparisons between measured and expected process values (potentially derived from physics models), recognize and characterize fault signatures, utilize rules and algorithms for isolating root causes, make predictions about future health and remaining useful life, incorporate policy and mission objectives for generating advice, and automate actions according to real-time state assessment for ensuring safety, maximizing availability, and optimizing productivity (Vatchsevanos, Lewis, Roemer, Hess, & Wu, 2006), (Walker, 2010). Recently the application of aerospace PHM techniques has expanded to virtually every other industry where concern of availability and a desire to minimize the costs associated with repair exists (Walker, Kapadia, 2009). Advanced reasoning techniques are especially of value in applications where there is high data dimensionality, an availability of disparate information across subsystems or geographic regions, the need for making predictions based on recognized patterns, and/or the opportunity to optimally reconfigure systems based on well understood cost functions. One such industry where PHM technological advancements are readily applied is that of the so-called energy smart grid.

For smart grid, one of the key objectives is to effect real-time reconfigurations of the electrical grid (generation and distribution) based on the ability to proactively monitor and predict load demand. Additional input for making such decisions might also come from predictions and assessments of infrastructure health, allowing for reconfigurations of the grid based on component failure or anticipated outages. Advanced reasoning systems could also incorporate policy-based rule logic that would guide such reconfigurations based on real-time knowledge of criticality measures, service agreements, or current pricing trends.

Forecasting in smart grid applications is typically performed by applying pattern recognition algorithms over historical usage data, in conjunction with making real-time predictions of availability of conventional and renewable energy sources. Similar pattern recognition techniques are often utilized by advanced reasoning systems for classifying fault signatures or making predictions regarding the onset of failure (Patterson-Hine, Aaseng, Biswas, Narashimhan, & Pattipati, 2007). PHM systems equipped with such advanced reasoning are therefore immediately applicable to the smart grid. Furthermore, anticipating and forecasting demand in such systems can also be utilized to augment predictions of component remaining useful life based on the effects of the anticipated usage.

Often the automated decisions required of smart grid management systems involve the processing of information that is aggregated across many grid components (e.g. meters, switches, and converters) and spans wide geographic areas. These are also characteristics of many large scale enterprise or fleet-wide PHM systems, as the goal of such systems is not just to assess the health of specific assets (vehicles, plants, processes, facilities), but to aggregate such health information into a higher level health assessment of the enterprise (or overall mission capability). Such systems are often architected in a distributed fashion and include supervisory level reasoners for aggregating information and performing high level management functions like generating reports, initiating maintenance actions, automating inventory and management of spares, and producing and presenting executive advisories.

While recent advances stemming from PHM research have successfully been applied for use in the smart grid marketplace, most of the engineered solutions are constrained by a lack of flexibility in the selection and configuration of learning and reasoning algorithms to be employed. Typically the inferences and predictions associated with the smart grid management problem require the application of multiple algorithms and reasoning approaches. However, a review of prominent research demonstrates that many of the smart grid solutions are restricted to single algorithms and characterized by rigid policies (NIST, 2012). Very often an algorithm that is selected or tuned for one application requires tweaking in order to produce similar results in another. It should also be noted that modification and extensibility of such systems typically requires costly reengineering efforts.

One PHM technology that can be used to overcome the limitations of current smart grid management solutions is that of the model-based reasoning platform. Model-based reasoning platforms that support rapid specification of logic through graphical programming languages not only can be used to reduce the cost of developing, testing, and validating software, but they also lend themselves as add-ins for extending existing solutions with limited or constrained flexibility. When such reasoning systems are built on top of goal-oriented expert systems technology, the user is readily able to abstract the management problem to even higher levels. The authors have coined the term "Objective Oriented 3rd Generation Expert Systems" to refer to such advanced model-based reasoning systems.

In the following sections we present some detail regarding the existing challenges presented to the smart grid management system provider, and provide insight as to how Objective Oriented 3rd Generation Expert Systems can be used to overcome those challenges. The implication is that such reasoning systems can be used to enable the full benefits of PHM to smart grid management providers, since the objectives of the smart grid are so inextricably linked to the measured and predicted health of the components, infrastructure, and topology of the grid.

2. CHALLENGES

Smart grids, which use intelligent transmission and distribution networks to deliver electricity, aim at improving the electric system's reliability, security and efficiency through two-way communication of consumption data and dynamic optimization of electric-system operations, maintenance, and planning (Khurana, Hadley, Lu, & Frincke, 2010). The underlying requirements of smart grids indicate a dependency on massive communications between components involving an enormous amount of data. This suggests the inevitability of an increase in fault propagation through the network, and an urgent demand for various technological enhancements that can assist in assessing the health of smart grids. At a high level, the design of smart grid PHM algorithms and products can be categorized into 2 areas: real time analysis and reasoning based prediction.

2.1. Real time analysis

Based on wide area situational awareness, smart grid management systems should be expected to be able to receive and analyze large amounts of real-time data and information from disparate sources. Such systems should also support increased adaptability when facing ever changing conditions. For example, pattern recognition and classification techniques can be effective in re-assignment of grid nodes dynamically and automatically when the load or the availability of renewable energy sources changes (Lu, Tinker, Apon, Hoffman, & Dowdy, 2005). However, with the real-time changes in the grid come changes in the amounts, quality, and availability of data – suggesting that the pattern recognition algorithms and event detection rules themselves be adaptable.

2.2. Reasoning prediction

The power of expert systems allows smart grid system designers to reason over the system process using embedded domain expertise, generic rule based logic, and advanced model-based reasoning even in the presence of incomplete information. This combination of capabilities enables process health and performance prediction involving higher level abstractions of data and information, providing the end users with improved situational awareness and understanding. The ability to transform data and information into knowledge and understanding stems from the expert system's ability to leverage software models of the entire domain – including object associations, relationships, and roles (refer to Figure 1). From the system maintenance side, outage and node/equipment failure propagation can be prevented in advance, if historical event data is available. For energy management, demand from smart appliances and supply from renewable energy sources can be anticipated by investigating the pattern characterization of weather, human activity agenda, etc. Such advanced reasoning capabilities typically involve the incorporation of many business rules which not only need to accommodate ever changing conditions, but also ever changing objectives.

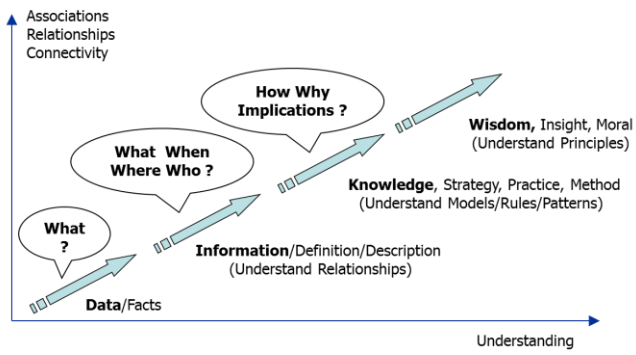

Figure 1. Reasoning – From data to wisdom.

The plethora of choices and the need for a wide variety of approaches presents some dilemmas for the smart grid management provider. Several of these are briefly discussed in the following paragraphs.

Dilemma 1 – Compatibility of multiple 'smart' designs

There are plenty of 'smart' designs appearing in the smart grid market, most of which focus on different objectives. For example, some applications focus on the efficiency, reliability, security and stability of the grid. Others focus more specifically on the energy efficiency, demand response, and load control for residential, commercial and industrial purposes (NIST, Technology, Measurements, and Standards Challenges for the Smart Grid, 2013). Some smart grid designs build up specific scenarios for the grid, which are not compatible with each other in many cases. The uncertainty of each promised scenario is often not clear or is difficult to compare. This general lack of compatibility presents some challenges to the implementer of smart grid PHM solutions, although such apparent incongruity can be successfully addressed with improved architectures equipped with advanced reasoning capabilities.

Dilemma 2 – Changing user objectives

It is also difficult for smart grid management system users/suppliers to define or clarify their objectives at an early design stage. Furthermore, it is typical that requirements and objectives have changed by the end of the development cycle. As in most industries, smart grid suppliers have to adjust their objectives with market requirements and local policies. In many cases their specific designs will need to target specific codes and standards. In other cases, the users/suppliers may have to satisfy multiple codes and standards– all while enduring rapidly changing local policies and grid market conditions. In addition, the grid has to stay open to new emerging grid technologies which introduce new data, requiring potentially new event detection approaches, and resulting in changes to policy and objectives. In general, as the smart grid evolves, users and providers place increasing demands on higher level management capabilities that involve new modeling constructs and policies. Smart grid management providers have to adjust with all of these challenges and opportunities in a short time and can be plagued by technologies that are not sufficiently flexible or extendable.

Dilemma 3 – Requirements for higher level management system interoperability

Another trend occurring across the smart grid landscape is the emergence of new alliances and the requirements for interoperability between management systems. One example is the trend for crossover corporations that combine services between multiple industries. In China, a new corporation has been proposed that combines the telecom industry with the smart grid in order to minimize the service line cost and share end user resources. In another case the convergence of solar, smart grid and healthcare IT in one offering or platform is also raising the attention and funding of the investors (Prabhu, 2013) Modifying or incorporating logic that addresses such interoperability is a challenge for most reasoning system platforms.

Dilemma 4 – Expensive design implementation

To embrace a novel PHM design with the existing grid system, there is much effort required prior to implementation. Design options vary, and with somewhat fluid requirements, implementation time can be excessive. Meanwhile, test requirements for PHM systems can be severe (Vatchsevanos, Lewis, Roemer, Hess & Wu, 2006). According to a typical solution delivery framework (SDF), the original design should be adjusted, tested and verified in the existing system environment. This process is always time consuming and costly. Ideally, the designers of smart grid management systems can make use of tools that allow for minimizing the labor associated with designing, implementing and testing solutions in the presence of such difficulties.

Dilemma 5 – Too much information

Due to the large numbers of components, the dynamic nature of supply and demand, and the increase in digital information being shared across the infrastructure, smart grid reasoning systems produce extremely large numbers of advisories and events. Since the goal of smart grid health management systems is to increase situational awareness, this inundation of alarms and information actually acts to degrade operator situational awareness. But ever increasing data and information is an unavoidable consequence when you consider the advancements being made with smart meters, new sensing technologies, and the proliferation of networked infrastructure components. When you add the requirement of real-time health monitoring of the grid and its components, the situation becomes even worse. The smart grid PHM designer requires tools that will aid in the reduction of alarms and events, principally through filtering, correlation and alarm subsumption.

Dilemma 6 –Advanced PHM out of reach

While the smart grid PHM designer expects to achieve benefits like root cause isolation (through the deployment of fault models), the ability to leverage supervised and unsupervised learning, and meaningful predictions regarding remaining useful life, very often these advanced capabilities remain out of reach. Ideally, the tools available to the smart grid PHM designer would enable higher level management capabilities such as Condition Based Maintenance. For example, advanced PHM systems should support real-time determinations regarding the most appropriate responses to current and predicted conditions. Typical responses might include differentiating between maintain, repair, and replace actions. To simplify decision making involving 'smart' designs and products, and to bring more opportunities for grid service providers, Objective-Oriented 3rd Generation Expert Systems can be utilized. These kinds of systems provide a powerful and reconfigurable environment that can speed up overall design and testing times as well as providing state-of-the-art reasoning capabilities. Objective-Oriented 3rd Generation Expert Systems will be discussed in greater detail in the next section.

3. OBJECTIVE-ORIENTED THIRD GENERATION EXPERT SYSTEMS

Objective-Oriented 3rd Generation Expert Systems are used to create model-based reasoning solutions for interpreting data in real-time. Such systems can also readily leverage knowledge derived from historical data, and apply that knowledge to making better predictions. Model-based reasoning in such advanced reasoning systems can pave the way for a wider use of PHM design in smart grid management platforms by providing the tools needed to address the challenges mentioned in Section 2. In this section we discuss the main advantages of using Objective-Oriented 3rd Generation Expert Systems and how they can be applied to address the problems associated with delivering smart grid management solutions.

3.1. Compatibility

Objective-Oriented 3rd Generation Expert Systems can easily interface to standard supervisory control and data acquisition software (SCADA) and distributed control systems (DCS), making it possible to quickly set up data sources for your application. The software also supports standard databases such as Oracle and SQL server. Standard simulation designs can be captured and validated in graphical software development environment, allowing the instant re-use of pre-existing designs. Whole infrastructures and processes can be modeled and simulated very quickly by using the wealth of reconfigurable graphical tools. These features can be used for operator training, education, process optimization, and also to validate and test a hypothesis.

Re-configurability

Vast libraries of mathematical and statistical functions are available for easy integration in an application. These can be used to analyze large quantities of real-time data such as the data generated by the sensors deployed over a smart grid. The main advantage of using such libraries is that algorithms can be quickly reconfigured or interchanged. Figure 2. shows a typical palette from which functions can be readily selected and used within an application. Most data mining and analysis applications rely on machine-learning algorithms to find patterns in the data and extract the valuable knowledge required for situational awareness. However, testing different machine learning algorithms on the same application can be very complex and time-consuming.

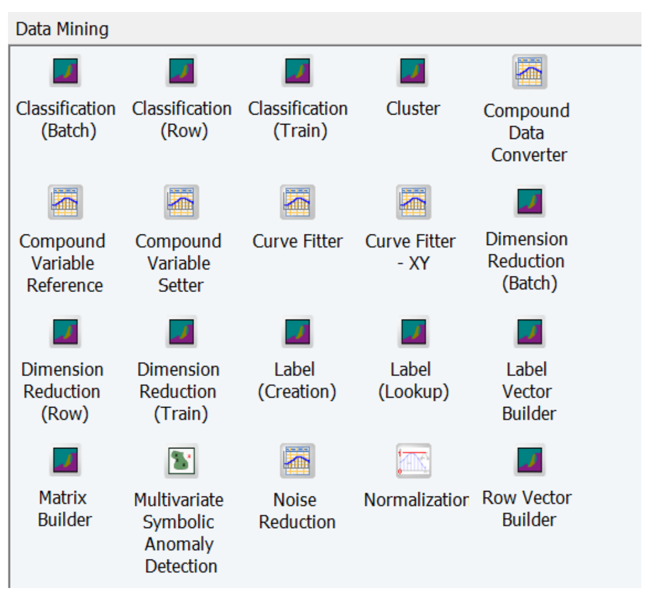

Figure 2. A palette of data mining functions.

With model-based platforms, different algorithms can be easily applied to the same application, making it possible to quickly test different approaches to your solution or to simultaneously apply multiple algorithms to the same problem. The platform can also enable real-time model selection and switching based on system state.

The re-configurability of Objective-Oriented 3rd Generation Expert Systems allows system designers to quickly adapt their software to changes in the technology, the objectives, and policies.

Objective-Oriented Design

One of the important aspects of modern reasoning systems is the ability to be configured based on user-defined objectives. Objective Oriented platforms typically leverage a graphical software development suite with vast auto configuration features that drastically reduce the amount of engineering time required to create or re-configure applications. Creating applications using model-based platforms results in a better cost-benefit ratio than in-house IT development, especially if developing software is not the core expertise or goal of your company.

Advanced Reasoning Capabilities

By adopting model-based reasoning, Objective-Oriented 3rd Generation Expert Systems provide a platform for accurate fault modelling and root cause analysis. Figure 3 shows the implementation of a Bow-Tie rule in one such expert system. Reasoning engines are used to analyze the model and automatically detect anomalies or even predict them ahead of time. These model-based reasoning capabilities can also be used to make automated decisions, for example: Condition-Based Maintenance (CBM) of equipment. CBM determines when maintenance should be carried out on equipment in order to ensure that the whole system keeps running without faults for as long as possible.

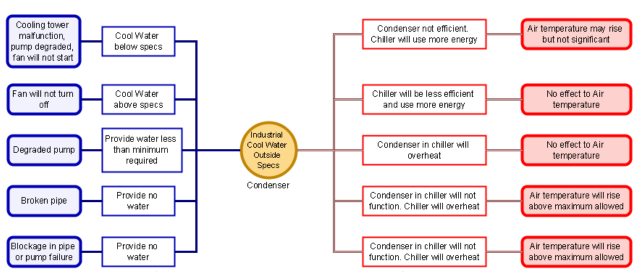

Figure 4. A bow tie rule.

Another added value that Objective-Oriented 3rd Generation Expert Systems can offer is Advanced Alarm Management (AAM). The generation of too many events and alarms in a system can confuse an operator and hinder their situational awareness rather than aiding it. The advanced reasoning mechanisms that are gained by adopting a PHM design allow AAM solutions to actively reduce the quantity of alarms presented to the operator and improve the quality of the alarm messages presented. Figure 6. shows an example of alarm grouping where alarms that provide the same information are grouped together (subsumed) so as to avoid presenting duplicate information to the operator. All of this is done at an advanced level that is often not possible with DCS and SCADA systems.

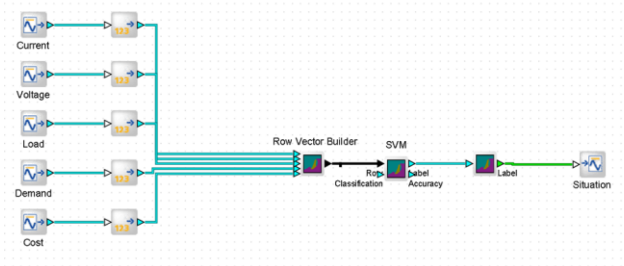

Figure 5. A simple analysis rule using SVM.

In order to provide the advanced reasoning capabilities required for smart grids, Objective-Oriented 3rd Generation Expert Systems should allow the implementation of a combination of rule-based schemes. Rules can be used to make applications react to abnormal situations in real-time. The decision making process can be based on logic, statistics, machine learning, or a combination of these and other algorithms. Figure 5 shows an example of how a Support Vector Machine (SVM) can be used to classify a situation based on readings from a set of data points in a model-based platform. The parameters are read from the data points, arranged into a row vector, and fed into a SVM block that computes what label best classifies the information shown in the input vector. The output is used to set a variable that can then be used in another rule for decision making.

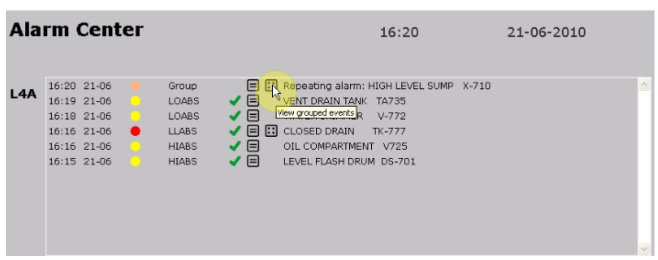

Figure 6. Alarm grouping.

4. CONCLUSION

The benefits and capabilities of PHM systems developed and demonstrated across multiple industries are readily applicable to the health and prognostics management of the electric grid. In addition, most of the algorithmic and reasoning technologies associated with assessing and predicting complex system health are also directly associated with the requirements and objectives of modern day service providers. These objectives include the assessment and prediction of optimal grid configuration in the presence of dynamic conditions associated with recent modernizations. Unification between existing smart grid management solutions and an overall grid PHM capability seems highly appropriate. However, the proliferation of new information and the demand for improved service in the presence of ever changing requirements present significant challenges to the developers of smart grid management systems. One proven solution to these challenges is the incorporation of advanced reasoning capabilities derived from Objective Oriented 3rd Generation Expert Systems. Such systems provide significant benefits to the smart grid management system developer, including rapid deployment; extensibility; scalability; and iterative, incremental development.

REFERENCES

Ferrell, B. L. (1999), JSF Prognostics and Health Management. *Proceedings of IEEE Aerospace Conference*. March 6-13, Big Sky, MO. doi: 10.1109/AERO.1999.793190

Khurana, H., Hadley, M., Lu, N., & Frincke, D. (2010). Smart Grid Security Issues. *IEEE Security and Privacy*.

Lu, B., Tinker, M., Apon, A., Hoffman, D., & Dowdy, L. (2005). Adaptive automatic grid reconfiguration using workload phase identification. *First international conference on e-Science and Grid Computing*.

NIST. (2012). NIST Framework and Roadmap for Smart Grid Interoperability Standards.

NIST. (2013). Technology, Measurements, and Standards Challenges for the Smart Grid.

Patterson-Hine, A., Aaseng, G., Biswas, S., Narashimhan, K., Pattipati, K.(2005). A Review of Diagnostic Techniques for ISHM Applications. *ISHM Forum 2005*, Napa, CA.

Prabhu, R (2013) *Smart Grid Receives $434 Million in VC Funding, $17 billion in M & A transactions recorded* Retrieved from www.engrreview.com/Editorial_pages/2013/02/ER0213_Client-Tech_22.html

Schwabacher, M., & Goebel, K. F. (2007). A survey of artificial intelligence for prognostics. *Proceedings of AAAI Fall Symposium*, November 9–11, Arlington, VA. www.aaai.org/Library/Symposia/Fall/2007/fs07-02-016.php

Vachtsevanos, G., Lewis, F. L., Roemer, M., Hess, A., & Wu, B. (2006). *Intelligent fault diagnosis and prognosis for engineering system*. Hoboken, NJ: John Wiley & Sons, Inc

Walker, M., (2007). Model-based Reasoning Applications for Remote Intelligent Systems Health Management. *Proceedings of ASNE Intelligent Ships Symposium*. May 2007.

Walker, M,, Kapadia, R. (2009). Integrated Design of Online Health and Prognostics Management. *Proceedings of the Annual PHM Society Conference*, San Diego, CA. October 2009.

Walker, M. (2010). Next Generation Prognostics and Health Management for Unmanned Vehicles. *Proceedings of the IEEE Aerospace Conference*, Big Sky Montana, March 2010.

BIOGRAPHIES

Gilbert Cassar Gilbert Cassar received his B.Eng from the University of Malta (2008), his M.Sc. from the University of Surrey (2009), and his Ph.D. from the University of Surrey (2013). He worked as a Research Fellow at the Centre for Communications Systems Research for 1 year and is now an Application Engineer at UReason. His research interests include Internet of Things, Smart Cities,machine learning, and probabilistic graphical models.

Mark G. Walker received his BSEE from Cal Poly University, Pomona (1990), and his MSCompEng from the University of Southern California, Los Angeles, CA (1994), where he specialized in machine intelligence. He has been working in applied artificial intelligence since 1989, and has co-authored four patents in the field. His work with HUMS and PHM began with BFGoodrich Aerospace, Vergennes, VT in 1996. He also spent 6 years as Senior Consulting Engineer for expert system manufacturer Gensym Corporation and 10 years as Lead Engineer, Intelligent Systems for General Atomics, where he led GA in the development of reusable PHM systems applied to the energy industry. He also serves as an ISHM SME for NASA, with active projects at SSC and KSC. He has been with UReason since 2014, where he is employed as Applications Specialist, Reasoning Systems. He resides with his family in Oceanside, California.

Yueting Yang received her BSc in Environmental Engineering diploma in 2011 from Zhejiang University, China and Master degree in Sustainable Energy Technology from the Technological University of Eindhoven (TU/e), the Netherlands in 2013, favored with a scholarship from the TU/e. She graduated on zero energy smart grid in Smart City and intelligent building design and performance optimization in European Project GEOTABS. Currently, she works as a Solution Engineer at UReason, in the field of real-time data interpreting and proactive advisory decision-making system.

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