Practical Applications of Digital Twins:

Digital Solutions for Integrating GTCC Plants as Critical Support for Renewable Energy Production

Daryl MASSEY, Scott CLOYD, Lisa BATSCH-SMITH
Mitsubishi Hitachi Power Systems (United States)

Koji IMAKITA, Kazuyuki MISAWA
Mitsubishi Hitachi Power Systems (Japan)

Abstract

Power plant digitalization is a key solution to the changes taking place in competitive power markets around the world. It is especially vital when considering the increasing penetration of renewable generation. In the last few years, many gas turbine combined cycle (GTCC) plants have moved from continuous operation to daily start/stop operation with fewer numbers of operating hours per year. This shift places the units that were on an original trajectory to become the backbone of grid production into a role that is more analogous to support staff to the expanding renewable production market.

Mitsubishi Hitachi Power Systems (MHPS) has been working very closely with major power generators to develop and demonstrate data-driven digital flexibility upgrades that assist these plants to operate in a more adaptable and economically viable way in today's dynamic market, while maintaining the standards of reliability and availability expected from traditionally base-loaded turbine generators.

This paper will present some of the achievements and future strategies of MHPS to ensure that GTCC facilities will achieve this level of grid support by enhancing their role as grid citizens supporting the reliability and stability of the power market, while working to maximize the power plant owners' and operators' traditional key concerns of reliability, efficiency, flexibility, and profitability.

I. Introduction

The U.S. power grid has been touted by many as the largest and most reliable machine ever crafted, with complex physical and digital components that work seamlessly together to provide continuous power to residential and commercial customers. The efficiency with which this machine runs is obvious in that these customers have come to view the consistency and reliability of power that is delivered as a natural part of daily life, rather than the achievement that it truly is. With the energy supplied to the U.S. grid being more than 4 trillion kWh as of 2017, it would seem a logical deduction that the change of any single generation entity within this machine would have little impact on the overall operation of the interconnected grid. However, since the penetration of the renewables into this system has so rapidly been embraced by so many geographical areas of the grid, the management of each individual generator now requires evaluation to ensure that they are a good citizen to support the shortcomings of their closest generation neighbors.

Building on 20 years of experience with human and software-based analysis of big data sets, including sensor and control system data, MHPS has developed and validated, in cooperation with its User Community, a broad range of data-driven digital upgrades that can be applied to meet specific user needs. Many of these have been demonstrated in both 50 Hz and 60 Hz GTCC plants and have been shown to provide benefits in the areas of:

- Flexible Operation
- Rapid Load Response
- Diagnostics and Predictive Analytics
- Fleet RAM Improvement

Armed with the fleet-wide data from the MHPS Remote Monitoring Centers (RMC) and User feedback, and leveraging engineering expertise, MHPS partnered with the Users of their equipment to develop pilot programs that created digital solutions for real-world challenges. The joint efforts focused on important issues such as the varying demands of grid support and the multi-faceted evolution of competitive wholesale power markets. These programs ultimately led to the creation of the MHPS-TOMONI™ Suite of Digital Solutions. Tomoni is a Japanese word meaning "together with" and embodies MHPS' approach to the digitalization of power plants by working closely with the owners and operators of those plants. The MHPS-TOMONI applications are targeted to provide digital solutions that combine the MHPS technical expertise and User experience with seamless automation for the benefit of the customer.

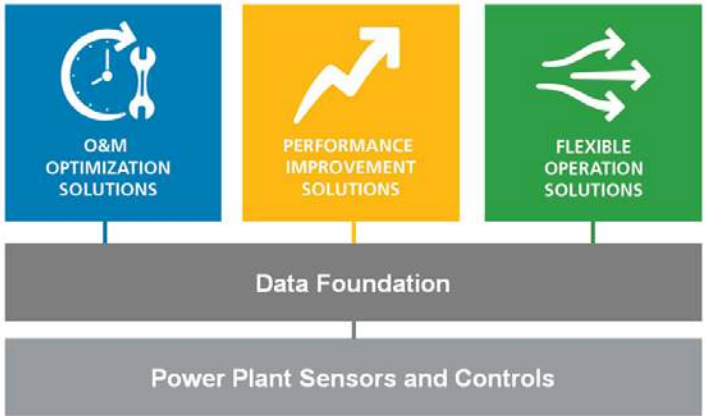

Figure 1: Development Paths of MHPS-TOMONI Digital Solutions

The key to providing solutions for the existing generators contributing to the grid is to ensure that an accurate model of the current unit operation is created in order to optimize a solution that addresses the maximum number of areas needing improvement, while properly identifying and minimizing the number of operational limitations the new solution would also create. The MHPS RMC in Orlando, Florida utilizes the OSIsoft PI System™ software, which is the data infrastructure most commonly used in the power industry for collecting and managing plant process and operational data. MHPS has been using the PI System™ in RMC applications for over a decade and, in 2016, entered into an alliance agreement with OSIsoft to make its software an integral part of many MHPS-TOMONI™ Digital Solutions. The large amount of cross-fleet, operational data is collected not only for immediate operational support but for utilization as a model-development base for visualizing the state of the GT under all actual operating conditions.

Figure 2: MHPS-TOMONI RMC Facilities

Three specific case studies of MHPS-TOMONI applications that have been implemented will be discussed that describe the technical and economic analyses that defined these digital upgrades and the process by which they were verified. The first was implemented at a major US investor-owned utility and substantially improved the starting reliability and flame health monitoring. The second was implemented at another major North American investor-owned utility and substantially improved the emissions profile of a large GTCC power block while increasing stable load turndown and improving part load efficiency. The third was implemented at another large US investor-owned utility and provided increased turndown for better grid support and peak power capability at times of high system demand.

II. Digital (Software-Based) Flame Detection

The traditional method of detecting ignition involves the use of physical flame scanning instrumentation. Although these instruments have a long tradition of reliably detecting the presence of flame to allow for safe acceleration of the GT, they also have sometimes experienced misdetection of a successful ignition, especially as the plant ages. The impact of a start-up trip due to a failed detection of a successful ignition has always had a large effect on operators, in the financial guise of parts-life impact and opportunity cost due to lost generation hours. The cost varies substantially among plants, but can easily exceed $100K per failed start. In addition, in today's market, not synchronizing when expected has an increasing impact on the balance between supply and demand, as the unit being dispatched was to possibly support the predicted unavailability or load reduction of a local renewable generating facility. A single generating unit's unavailability usually does not result in any localized failure for the power consumers, due to the planning for these occurrences that goes into the overall organization by the dispatchers. However, the power that has been allocated as spinning reserve for these unfortunate occasions may reside in a physical location that stresses a congested transmission line and the result is, therefore, sub optimal.

Utilizing data that was gathered by the RMC, engineers were able to develop models based on multi-factor, multi-unit conditions to identify the states that are produced only when there is the presence of a healthy flame within the GT. Beyond ignition, the data that was collected from multiple units under multiple conditions, including but was not limited to:

- Ambient temperature
- Fuel temperature

- Real-time rotational speed
- Rate of change of variables within the system over time

The objective during operation is to both maintain a view of whether the system is in a healthy combustion state and to allow for continued operation and rapidly detect the condition that indicates a loss of flame during GT operation in order to safely shutdown the system.

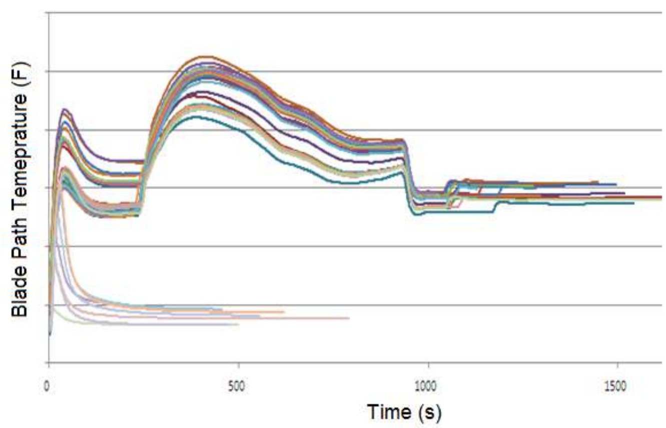

Figure 3: Trends of temperatures during the acceleration profile of multiple units for state identification

The Digital Flame Detection application was developed by analysing the operation of units monitored by the RMC to evaluate a multi-variable state definition that defines a condition that can only be satisfied by the presence of flame within the GT. The final profile that was developed utilizing the operational data as the developmental and confirmation models was further verified by live testing at MHPS' heavily instrumented, commercial power plant in Takasago, Japan, named T-Point. T-Point was built in 1997 to help validate new products in a real, grid-connected power plant that dispatches power to Kansai Electric Power Company. The operational testing allowed for further validation of appropriate set-points during non-deterministic events, such as grid synchronization.

The modification was rapidly adopted and is now the mode for flame monitoring on an increasing percentage of the MHPS fleet. The number of start-up trips attributed to mis-diagnosed flame detection on the overall monitored fleet has been reduced by 80% over the past several years as digital flame detection was introduced. This includes all fleet units monitored by the MHPS Americas RMC, both with the original flame detection instrumentation and the upgraded software detection. This, however, is only one benefit of the modification, as the flame health is continuously monitored through acceleration, synchronization, loaded operation, de-synchronization and shutdown.

III. Improved Frequency Correction Support

The allure of the renewable energy generation products is firmly grounded in the fact that the energy that is utilized to generate the electrical energy for consumption is naturally available and a renewable resource. The downside to that is that the resource is not always available, nor does the availability of that resource always conform to the consumer demand profile. But, due to the efficiency and environmental advantages of the renewables, there is a desire to have them producing whenever their resource does become available. This results in peaks and troughs of renewable energy on an intermittent and irregular level. Bringing these generating units on and off the grid impacts the local, and sometimes more general, frequency at which power is delivered by the grid. Maintaining the frequency within an acceptable band is critical for the health of the generation, transmission and distribution and final end-use equipment and systems.

The growth in the percentage of renewable generation increases the possibility of larger frequency deviations during normal daily production. As a result, many operators are seeking, in order to meet the requirements being requested by their local RTO/ISOs, the ability to respond in a controlled and repeatable manner to these large disturbances in order to assist with stabilization.

To meet increasingly broad customer needs, model systems, utilizing traditional model techniques from theoretical descriptions, coupled with corrections and optimizations generated by the operational data collected by the RMC, were developed and simulations performed to ensure that combustion stability would be maintained during conditions of large frequency deviations from nominal. Once the designs were finalized, live testing was

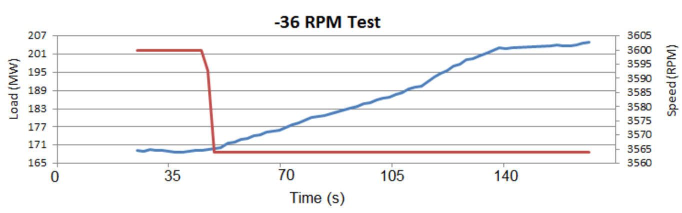

Figure 4: Online testing of units to confirm system stability during off-nominal frequency events as large as 1% deviation.

performed on operational GTs in the US market (running speed at 3600 RPM) with injected deviations of +/-36RPM (1% nominal speed) speed deviations. Testing was performed to ensure that the entire power block would be able to remain online and available for grid support for an indefinite period of time and to provide appropriate load adjustments without the need for AGC setpoint adjustment.

This control upgrade is available to for MHPS units and provides features that meet or exceed the most stringent grid support requirements. The live testing to guarantee the responsiveness and support for the local grid was important to ensure that guarantees made can be backed up by actual response, combustion stability and indefinite time of response. Reports following testing from the local ISO after testing evaluation concluded that the results met the local requirements and exceeded the generating company's expectations.

IV. Broader Operational Range for Increased Operational Flexibility

Per the 2017 U.S. Energy Information Administration summary of utility-scale power production facilities, natural gas is responsible for the majority of the electricity generation by source, having overtaken coal. However, the amount of electricity generated by renewables, although it totals half as much as that of natural gas alone, is now rapidly approaching the amount produced by nuclear power generation and expected to surpass that mark in 2018. With the power generation landscape changing in this way, the need for the natural gas unit to increase the flexible areas of operation to support the ebb and flow of the renewable production has never been greater. For GT operation, the limits of the operation are bounded by two physical factors. The bottom limit is limited by the combustion emission limits set forth in the site permit while the upper limit is determined by the maximum temperature to which the physical components may be exposed. Increasing the span of MW production that these physical limits encompass is a driving goal for development currently to support the new power generation profile of the U.S. grid.

In order to advance this goal, MHPS has implemented several approaches to increase the operational range of the GTCC and has made them available in an upgrade called Flex-Pack.

One approach that assists with the low load operational limit proactively places the Inlet Guide Vanes (IGVs) of the gas turbine based on the mode of operation using a real-time model of the GT state. This predictive placement with feedback optimization results in a rapid response to a modelled target firing temperature. This philosophy minimizes the probability of any large imbalances in the fuel to air ratio (F/A) that would lead to emission or combustion pressure fluctuation (CPF) activity within the combustors.

This model-based predictive positioning is coupled with the use of Compressor Discharge Air Recirculation (CDAR). This is a system that recirculates air from the compressor that has been heated by the compression process back into the compressor flow path. This process assists with reducing the available oxygen during low load operation to work in concert with the predictive IGV placement. The combination of the two systems allows for the unit to achieve a lower power output while still maintaining the lower emission limit, which is usually limited by the Carbon Monoxide (CO) emission permit levels

The Flex Pack concept assists operators with the upper operational limit, as well, by providing peak firing options to increase the upper limit of the power production range. This operator-selected option allows for the unit to experience higher firing temperatures for increased power output. This operation time is accounted for in the calculation of parts-life due to the additional stress that these temperatures produce. But, the additional, on-demand power that this option makes available allows for both the possibility of increased revenue for the operator in the event that power prices become exceptionally high, when additional capacity payments are available or when an unanticipated demand for additional power justifies the additional supply.

This multi-faceted solution was implemented at a large GTCC US facility. The combination of the automation, modelling, and auxiliary systems working in unison resulted in an additional 18% increase in the operational range that each individual GT was able to achieve post-commissioning, as opposed to pre-installation testing values.

V. Looking to the Future for Grid and Operator Support

The effect of the grid support actions by a power block is frequently viewed from the grid perspective as a unified effect. The requirements of the grid do not dictate the method used to produce the support required, however. Therefore, internal modelling and control, coupled with machine-learning and AI inference utilized so that the optimal response from each individual component may be achieved, while still meeting the requirements of the grid is an interesting approach now being evaluated. Providing grid support via rapid load changes and lower-efficiency, low-load operation can negatively impact the profitability of the individual GTCC facility. Therefore, designing cooperative strategies with the plant owner and operator to include additional optimal revenue opportunities in the response profile is an owner/operator focused approach for future development.

Evaluating conditions that are not currently considered in traditional control such as:

- What percentage of the current local grid is this unit producing?
- What is the physical distance to the condition that is responsible for this needed action?
- What is the current efficiency of each element within the GTCC block in order to optimize response financially?

will pave the way for developing new technologies and control strategies, through both traditional control and machine-learning based solutions, to optimize the support of the grid by the GTCC plants, while maximizing the profitability for the owner/operators as their plants are providing this support.

III. Conclusion

While there is growth and development in the renewable generation sector that surpasses the expectations of a decade ago, the flexibility and efficiency of GTCC generating facilities maintains them in a position as the natural support staff for reliability, availability, and responsiveness that the U.S. grid and grids in many other countries require at this time. Continued development in the control strategies and options to make these facilities more flexible not only improves the efficiency and profitability of GTCC plants, but will at the same time increase the performance of the overall power supply structure.

Providing this support allows for the amazing machine that has become known as the U.S. power grid to maintain the quality and availability of the energy supplied to its commercial and residential customers to continue and even improve further as the demand for this resource grows over the next decade and beyond.

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