Demonstration of HVAC chiller control for power grid frequency regulation

by

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Bachelor of Applied Science in Engineering Science
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Abstract

Secondary frequency regulation is a necessary electric grid ancillary service that balances electric power system supply and demand on short time intervals of seconds to minutes. Commercial HVAC chillers may be well positioned to provide secondary frequency regulation as a demand side resource. Commercial 200 ton (703 kWth) chillers serving two buildings in the Boston area are used to experimentally develop a practical closed-loop controller that modifies chiller power demand to provide secondary frequency regulation. In the first setup, a physical controller is connected directly to the chiller and adjusts power through chilled water setpoint. In the second setup, both the chiller and air handling units are controlled through the BAS. Demonstrations using standard electric system operator test routines show the chiller power response to exceed qualification requirements while providing up to ±25% of chiller nameplate power in secondary frequency regulation capability. The controller is further demonstrated to provide secondary frequency regulation continuously for several hours longer than the standard test routines, during which building cooling load changes significantly. Analysis of results indicate minimum power and variable COP as two factors that could be incorporated into future models to more accurately reflect observed chiller transient behaviour and predict performance. BAS communication delays, ramp rate limits, and compressor cycling are additional factors that can have significant negative impacts on controller performance.

Extrapolation of experiment results to higher-level analysis indicates that chillers can contribute to the secondary frequency regulation requirements at the grid level in aggregate, although potential varies greatly depending on climate and building type. There is more potential in the south, where 21% of secondary frequency regulation requirements might be met with chillers; the contribution of chillers in colder climates is minimal. Short-term power balance to achieve stability is essential for the operation of the modern electrical power system. Providing stability through modified control of existing HVAC chillers in commercial buildings is a technologically feasible alternative to existing solutions and can make a meaningful contribution to the electrical grid.

Thesis Supervisor: Leslie K. Norford
Title: Professor of Building Technology
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1 Introduction

For all of its enormous size, the North American electric power grid is, in fact, a finely tuned machine that must constantly be kept in balance to minimize disturbances for users – the worst case scenario of widespread blackouts can occur within seconds following instability from power imbalances. These issues gain in importance as the grid continues to absorb a wide variety of intermittent generation resources including wind and solar technologies.

1.1 Frequency Regulation on the North American Grid

Grid resources must be controlled to achieve balancing on multiple time scales. Figure 1 shows the continuum of control as defined by the North American Electric Reliability Corporation (NERC). NERC publishes and enforces standards that balancing authorities follow to maintain grid reliability. Balancing authorities are entities that control grid resources, such as power plants, to ensure electricity generation matches consumption and the frequency is maintained (Figure 2). In North America, the power system is nominally maintained at 60Hz; upward deviations indicate an instantaneous excess of power and downward deviations vice-versa. Short-term balancing of power is consequently named “secondary frequency regulation” (FR). To achieve FR, balancing authorities send requests for power adjustment every 2-4 seconds to resources to correct for frequency error; these control signals can be referred to as “regulation signals” (NERC, 2011).

Much of North America operates under regional electricity markets, while the remaining regions operate under vertically integrated utilities (Figure 3). This thesis uses the regional market structure as a reference for discussions regarding grid operation. The regional markets are administered by an independent system operator (ISO) or regional transmission organization, which were established under order of the US Federal Energy Regulatory Commission (FERC) (FERC, 2014). In their jurisdictions, the ISO/RTO is also the balancing authority. For simplicity, the term “system operator” is used to refer to the ISO, RTO, and balancing authority.
Figure 1: NERC power balancing control continuum. Excerpted from (NERC, 2011).
System operators require a certain amount of available FR, measured in ±power, at all hours of the year. This FR requirement is generally related to the expected demand but is also influenced by variability of load and increasingly by the penetration of renewables with variable output. (NERC, 2011) describes how FR adequacy is determined. PJM Interconnection (PJM), which is the largest system operator in North America by capacity, has a peak demand of approximately 155,000 MW and currently requires 700 MW of FR during peak hours (PJM, 2014a, 2014c). System operators procure sufficient FR in the regional market to meet their requirement. Typically, grid resources can offer FR service by bidding their FR capability for specific hours of the day. FR capability is the amount of ±power adjustment a resource has available for FR, after meeting other output requirements. For example, a power plant may be scheduled to provide 300 MW of power between 7AM to 8AM tomorrow in order to meet forecasted demand. However, the maximum capacity of the power plant is 500 MW. In this scenario, the power plant may have a FR capability of ±200 MW between 7AM and 8AM.
Resources that bid FR capability are accepted in order of price until the procured capability is satisfied. The last resource to be accepted sets the FR clearing price for the entire market. Precise market mechanics differ by region and are often revised. In PJM, the accepted resources are compensated based on the FR market clearing prices and FR performance. PJM’s Manual 11 (PJM, 2015) describes its regulation market while (Monitoring Analytics, 2014) provides examples on resource compensation.

Performance reflects the ability of the resource to track the regulation signal and is calculated by comparing measured power response of the resource to the requested response using a weighted set of PJM formulas, which results in a composite performance score between 0 for worst and 1 for best (PJM, 2014a, 2014d). PJM’s performance scoring method will be used throughout this thesis.

The performance score is an average of three components: correlation score, delay score, and precision score; each component can yield 0 to 1. Correlation score is the statistical correlation between the measured FR response, after adjustment by a temporal shift to compensate for a delay, and the regulation signal. The delay is used to calculate the delay score, with less than 10 seconds yielding 1 and greater than 5 minutes yielding 0. The delay is chosen to maximize the sum of the correlation score and delay score. Lastly, the precision score is calculated based on the absolute error between the regulation signal and FR response, with no adjustment for delay. Detailed descriptions of the performance score methodology can be found in (PJM, 2014d).
1.2 Frequency Regulation Using HVAC Chillers

FR has traditionally been provided by centralized power plants at the megawatt level. While these generation resources can provide large amounts of FR from a single site, they incur significant opportunity costs associated with capacity that is not used to generate electricity. Expanding on the previous example, if the 500 MW power plant wishes to provide 200 MW of FR, then it can only be scheduled to generate 300 MW of electricity rather than 500 MW. The power plant owner is forgoing 200 MW worth of electricity payments in exchange for 200 MW of FR payments. At a grid system level, reserving generation capacity for FR results in the need for more total capacity and the subsequent construction of more power plants and transmission lines. Construction and siting of these facilities is capital intensive and can be politically difficult.

Providing FR from demand side resources rather than generation may mitigate some of these technical, economic, and political challenges. Rather than adjust power output like generators, demand resources can adjust power demand at short time intervals to follow an inverse of the regulation signal. For example, a commercial building consuming 400 kW of power can offer to provide 100 kW of FR by tracking the regulation signal to continuously adjust power demand between 300 kW and 500 kW. Figure 4 shows normalized sample regulation signals from PJM; the magnitude of the regulation signal is scaled proportionally to the assigned regulation capability (e.g. 200 MW or 100 kW) for each demand or generation resource.

Demand resources do not incur the same opportunity cost as generation. However, demand resources can be orders of magnitude smaller than central power plants in terms of power usage and must be used in aggregate to provide substantial benefit to the grid. In addition, demand resources must consider whether their primary purpose of electricity usage, such as manufacturing or space comfort, would be compromised by changes in usage to provide FR. Therefore, demand resources that convert electricity into thermal energy may be particularly well-suited for FR. There is often sufficient thermal mass in the process that short-term changes in electricity usage do not adversely affect operational requirements. This thesis focuses specifically on HVAC chillers used in commercial buildings.

HVAC chillers are vapour-compression refrigeration machines that cool water to be circulated throughout a building. The chilled water is then used to cool or dehumidify air to provide comfort in occupant spaces. A schematic of a chiller plant is shown in Figure 5. The primary source of electricity use in chillers is the compressor, which is often a rotating machine driven by an electric motor. Commercial HVAC systems account for approximately 8% of U.S. electricity use (EIA, 2008, 2014). Chillers within commercial HVAC system are often the single largest electrical load and may be suitable candidates to provide FR. Chillers equipped with variable frequency drives (VFDs) can modulate power to track regulation signals and thus provide FR by leveraging a building’s thermal storage capacity through the chilled water system. Due to thermal mass, short-term changes in
cooling output will not affect occupant comfort given that average cooling remains constant over a longer period of time.

Figure 4: Sample PJM regulation signals
1.3 Thesis Objectives and Structure

The research objective of this thesis is to experimentally determine the practicality of using chillers as a FR resource. To do so, a Frequency Regulation Controller (FRC) is developed and demonstrated at two commercial buildings. The first building is an office and laboratory building owned by Fraunhofer CSE, located in Boston, MA. The second building is an MIT dormitory in Cambridge, MA. The FRC is a physical device that can be retrofitted onto existing HVAC systems to continuously adjust chilled water supply setpoint (CHWSP) to modulate chiller power to follow regulation signals. The FRC’s ability to track FR signals is quantified using the PJM performance score (PJM, 2014d). Based on the FRC testing results and project experience, the thesis discusses the potential for broader deployment in other HVAC systems and the possible grid level contributions of chillers providing FR in aggregate.

The remainder of Chapter 1 provides a literature review to support the experimental work explored in this thesis. Chapter 2 describes the FRC setup and development process at Fraunhofer. Chapter 3 analyses the Fraunhofer experimental results, including comparisons to simulation model predictions from existing literature, and some practical considerations such as efficiency and FR capability constraints. Chapter 4 describes the FRC setup and development process at MIT. Chapter 5 analyses the MIT results in comparison to Fraunhofer, and discusses additional practical considerations uncovered by the testing. Discussions include BAS network based implementations, alternative control points, and compressor cycling. Chapter 6 extrapolates the results of the previous chapters to estimate the potential contribution of chillers to FR requirements at a national level.

Material from Chapter 2 can be found in (Su & Norford, 2015a), while material from Chapter 3, 4, and 5 can be found in (Su & Norford, 2015b). The technology disclosed in this thesis is Patent Pending.

1.4 Literature Review

FR poses unique challenges for HVAC systems due to the need for relatively precise control at short time intervals rather than the on/off control on longer intervals used for slower types of demand response. Blum & Norford (2014) and Zhao, Henze, Plamp, & Cushing (2013) both simulated FR performance of commercial VAV HVAC systems using different open-loop control strategies. In contrast, the FRC uses closed-loop control to improve robustness by compensating for uncertain chiller characteristics and real-world disturbances. In both papers, the major sources of FR power response were the chiller and fans, with the relative distribution dependent on strategy. Blum & Norford (2014) modeled four control strategies, and concluded that static pressure adjustment and chilled water temperature adjustment achieved acceptable FR performance and performed relatively well compared to other strategies. Blum & Norford (2014) acknowledged the need for further exploration of chiller dynamics. Zhao et al. (2013) modeled static pressure adjustment and zone temperature adjustment, and identified acceptable performance for both strategies, though zone
temperature adjustment achieved higher PJM performance scores. Zhao et al. (2013) acknowledged the need for experimental work.

Experimental verification is necessary due to the challenges of modeling short-term dynamics of HVAC systems. The transient response of an HVAC system depends on the actions of numerous components for which accurate representation is difficult. The transient power response of a chiller to changing setpoint depends on the details of the chiller’s proprietary internal control algorithm. A successful demonstration of FR using a full sized commercial chiller within an occupied building will definitively show that, at least with some HVAC systems, FR can be provided with chillers.

The majority of experimental work with HVAC transient response has centered around on/off control schemes for residential (Eto et al., 2007; Hammerstrom et al., 2007) and commercial (Kiliccote et al., 2012; Kiliccote, Piette, & Ghatikar, 2009; Kirby, Kueck, Laughner, & Morris, 2008) systems; on/off control is useful for emergency curtailment and types of demand response other than FR (Aghaei & Alizadeh, 2013). Experimental work focused on FR is limited. Hao, Lin, Kowli, Barooah, & Meyn (2013) and Maasoumy, Ortiz, Culler, & Sangiovanni-Vincentelli (2013) developed transient models for HVAC fans based on empirical data to show that large HVAC fans within air handling units can provide FR through direct control of fan speed. Berardino & Nwankpa (2010) investigated the response of a commercial chiller to a step change in CHWSP. While the experiment showed that chiller power does indeed respond to CHWSP, the resolution and quality of data were limited and it remains unclear whether the chiller could provide the continuous modulation necessary for FR.

In terms of system level analysis, Hao, Sanandaji, Poolla, & Vincent (2015) investigates the FR potential of residential thermal loads in California. More comprehensively, Ma et al. (2013) develops a methodology for estimating the ancillary service potential of all demand resources, including FR and commercial cooling as a subset. Olsen et al. (2013) and Hummon et al. (2013), in related work, use similar methods to estimate more generally the potential in the Western Interconnection from all demand response types. These three studies use power system models that include demand response to optimize between different types of demand and generation resources. In contrast, the system level analysis in Chapter 6 considers only FR and uses a simplified representation of the power system. While narrower in scope, Chapter 6 uses newly introduced experimental results to provide a more accurate assessment of FR specifically from chillers.
2 Controller Development at Fraunhofer CSE

The Fraunhofer Center for Sustainable Energy Systems building (Fraunhofer) is a 50,000 ft$^2$ (4645 m$^2$) historic building located in Boston. Fraunhofer completed an extensive retrofit in 2013, including installation of the chiller under analysis, and primarily contains offices with some lab spaces. At the time of testing, four of the seven floors were fully occupied. Controller development at Fraunhofer centers on a physical FRC that is directly wired to the building’s chiller and bypasses the BAS. The majority of experimental data is likewise collected from the chiller, with some auxiliary data and control using the BAS. After completing basic system characterization, the FRC is developed through real-time testing with the chiller in the control loop. The final FRC design is tested with a series of 40 minute standard regulation test signals from PJM and a continuous seven hour test using historical PJM regulation signals.

2.1 Experiment Setup

Fraunhofer is served by a 200 ton (703 kWth) water-cooled centrifugal chiller$^1$ installed in 2013. The chiller has two VFD controlled compressors rated at 60 kW each$^2$. The chilled water system is variable primary flow, with two VFD controlled primary chilled water pumps rated at 7.5 kW each. Local cooling is achieved by a combination of fan coils on the primary chilled water loop and radiant cooling, chilled beams, and displacement ventilation systems on a secondary (higher temperature) loop. Ventilation is provided via a dedicated outdoor air system by a 20,000 CFM (9439 L/s) air handler with a cooling coil rated at 131 tons (461 kWth). A schematic of the chiller plant at Fraunhofer is shown in Figure 5. Natural gas boilers provide HVAC hot water.

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$^1$ Multistack MS0210FC1L4W2H1AA44-134a
$^2$ Danfoss Turbocor TT-400
Figure 5: Fraunhofer cooling plant schematic

The FRC is programmed as a real-time model in SIMULINK with the chiller in the loop; communication with the chiller is through analog input and output ports on the chiller’s onboard Master Control Panel (MCP) (Figure 6). The FRC reads chiller power, chilled water supply temperature (CHWST), and chilled water return temperature (CHWRT), and sends CHWSP. CHWRT is collected for analysis but not used for control, and hence not shown in Figure 6. Various additional data points recorded internally by the MCP and BAS are also used for analysis. Note that chiller power from the MCP is updated on sub-second intervals and is sufficient for the experiment; however, power metering equipment meeting grid system operator requirements is necessary for commercial implementation.
Figure 6: Fraunhofer FRC setup

CHWSP is the chosen control variable because CHWSP adjustment is part of traditional chiller operation and can influence chiller power without modifying unknown proprietary internal software. Presumably, the chiller’s onboard logic considers physical limitations such as compressor surge and choke to meet CHWSP without negative consequences. In contrast, lower level methods such as directly adjusting compressor speed may produce better control (Kim, Norford, & Kirtley, 2014) but also raise practical challenges for implementation on a full-sized chiller in an occupied building.

For experimental purposes, the FRC is supplied with locally stored historical PJM regulation signals and PJM standard test regulation signals; the setup does not include communication with the system operator. PJM issues two types of regulation signals: RegA is a slower moving signal designed for traditional power plants, and RegD is a faster moving signal designed for energy-limited demand resources. RegD ramps up and down more quickly but is also closer to energy neutral over a period of time; on average, the RegD signal is approximately to zero. The 40 minute duration RegA and RegD standard test signals are used to qualify resources; these two test signals are also used here to experimentally evaluate FRC performance.

2.2 System Characterization

Achieving sufficient control over chiller power through CHWSP depends on the chiller’s onboard control logic. While the onboard logic is proprietary, we make several practical observations regarding operational characteristics.

The power characteristics of Fraunhofer’s centrifugal chiller can be divided into three distinct operation regimes based on cooling output control method. The operation regimes are summarized in Figure 7 with approximate power threshold values. Note that chiller behaviour is generally asymmetric between decreasing and increasing power, and overlap between operation regimes is possible.
At high to intermediate power, cooling output is controlled by compressor speed, which is set based on two control loops in series. In the primary control loop, the input is CHWST minus CHWSP and the output is compressor requested power. In the secondary control loop, the input is compressor requested power minus compressor measured power and the output is compressor target speed. Both loops are roughly PI/PID with additional non-linear logic. For example, the secondary control loop is constrained to keep compressor speed within surge and choke limits. Figure 8 illustrates the relationship between CHWST, requested power, and actual power during a CHWSP step change. When the requested power remains above a threshold for a prescribed duration, the second compressor will be added.

Figure 8: Step change in CHWSP
At intermediate to low power, when the compressor speed cannot decrease any further to meet requested power due to the surge limit, cooling output is controlled by modulating the inlet guide vane (IGV) to meet requested power. While IGV operation has minimal effect on efficiency, the power response is slower than for compressor speed operation. In addition, when increasing power the IGV must fully open before compressor speed operation can begin. As a result, when the chiller moves from IGV operation to compressor speed operation, significant power overshoot often occurs due to accumulated integral error resulting in a requested power much higher than the compressor’s measured power.

At the lowest power levels, cooling output is controlled by the load balancing valve (LBV), also known as the hot gas bypass valve. Opening the LBV decreases cooling output but has little impact on power. LBV operation adversely impacts chiller efficiency and should be avoided when providing FR. If the required cooling output is below LBV operation limits for a duration, the compressor shuts off. Alternatively, when increasing power, the LBV must fully close before the IGV will begin to open. Data for IGV position, LBV position, compressor requested power, and compressor speed are recorded internally by the MCP at 5 second intervals.

Ultimately, the goal of the chiller’s onboard controls is to maintain constant CHWST rather than to control power characteristics. With constant cooling load, supply water temperature is typically maintained within ±0.3°F (±0.17°C) of setpoint; however, chiller power is observed to fluctuate in the range of ±5% (±3 kW) of rated power (Figure 9). These fluctuations are due to minute changes in CHWST and are not accurately predictable. Hence, the FRC must not only control chiller power to track the regulation signal, but must also reject disturbances introduced by the fluctuations in baseline power.

![Graph showing temperature and power fluctuations over time](image)

**Figure 9: Short-term baseline power variations**
Step response to CHWSP change is unpredictable when consecutive step changes were made. The CHWST requires several minutes to settle after a step change; the effect of additional step changes during this time depends on the transient relationship between the CHWST, original CHWSP, and new CHWSP. For example, if the CHWST is 45°F (7.2°C), the original CHWSP is 43°F (6.1°C), and the new CHWSP is 44°F (6.7°C), the chiller power may continue to increase despite a step increase in CHWSP.

2.3 Controller Design

The core control loop of the FRC, shown in Figure 6, is a PID Routine with input $e_{\text{PID}} = P_{\text{PID,REF}} - P_{\text{CH,MEAS}}$ and output $u_{\text{PID}}$. To address the issue of unpredictable response from CHWSP step changes, the FRC output is instead pegged to CHWST such that $u_{\text{FRCCH}} = \text{CHWSP} = \text{CHWST} - u_{\text{PID}}$. In other words, the PID Routine specifies a CHWSP relative to the currently measured CHWST. For example, if $u_{\text{PID}} = 1$, the FRC continuously adjusts the CHWSP to remain 1°F (0.56°C) below CHWST based on real-time measurement. The method also avoids the problem of compressor shut-off due to low CHWST, which occurs if CHWST is 2.5°F (1.4°C) lower than CHWSP for more than 300 seconds. By setting $\min u_{\text{PID}} = -2.5$, the FRC ensures that the limit is not exceeded. The minimum CHWSP allowable by the chiller is 38°F (3.3°C) (Figure 10).

There are two additional routines that together allow for regulation signal tracking over many consecutive hours while ensuring that a moving average chilled water supply temperature CHWST$_{\text{avg}}$ remains close to the BAS nominal setpoint CHWSP$\text{NOM}$. The Input Filter Routine modifies the regulation signal to reach energy neutrality over a shorter period of time. The Baseline Routine continuously adjusts the baseline power $P_{\text{CH,BL}}$ based on CHWST$_{\text{avg}}$.

2.3.1 Input Filter Routine

It is desirable to control the maximum difference between CHWST and CHWSP$\text{NOM}$. The difference increases when the regulation signal is above or below zero for an extended period of time, in effect requesting net energy from the chiller. For the purpose of FRC design, the regulation signals can be considered stochastic around zero, resulting in eventual energy neutrality. Energy neutrality tends to be reached more quickly for RegD than RegA.

The Input Filter Routine reduces the time to reach energy neutrality and limit $\max|\text{CHWST} - \text{CHWSP}_{\text{NOM}}|$. The Input Filter Routine subtracts a moving average regulation signal $P_{\text{REG,RAW,avg}}$ from the regulation signal $P_{\text{REG,RAW}}$, effectively creating a high-pass filter to produce $P_{\text{REG,FLT}}$. In other words, if the regulation signal is consistently above or below zero, the Input Filter Routine compensates and the chiller sees a filtered signal that is centered around zero. While the method does not provide a guarantee, the length of the moving average can be decreased to reduce $\max|\text{CHWST} - \text{CHWSP}_{\text{NOM}}|$. The Input Filter Routine moving average is 10 minutes in Figure 12.
The Input Filter Routine deteriorates the performance score because the PID loop is tracking $P_{\text{REGFLT}}$ rather than $P_{\text{REGRAW}}$. However, the impact is small for RegD. More importantly, the Input Filter Routine increases robustness by preventing CHWST from leaving the acceptable range and also complements the Baseline Routine.

2.3.2 Baseline Routine

$P_{\text{CHBL}}$ should be the power the chiller would use if it were not providing FR. Accurately calculating $P_{\text{CHBL}}$ is particularly important for closed-loop control relative to open-loop control because the controller tries to maintain $P_{\text{PID,REF}} = P_{\text{REGFLT}} + P_{\text{CHBL}}$. Even small errors in $P_{\text{CHBL}}$ will cause CHWST$_{\text{avg}}$ to deviate from CHWS$P_{\text{NOM}}$ without bound if uncorrected.

Zhao et al. (2013) and Blum & Norford (2014) assumed that $P_{\text{CHBL}}$ would be available from a building model. Hao et al. (2013) proposed a technique where baseline power for HVAC fans was extracted using a low-pass filter. The building modeling approach may be challenging and excessively time-consuming in practice, particularly considering the aforementioned accuracy needed for closed-loop control. On the other hand, separating regulation response and $P_{\text{CHBL}}$ using filters in the frequency domain necessitates use of open-loop control strategies, where the variable controlled is not power.

We proposed an alternative method, where $P_{\text{CHBL}}$ is interpreted as the power necessary to maintain CHWST$_{\text{avg}} = \text{CHWS}P_{\text{NOM}}$. For instance, if $P_{\text{CHBL}}$ is too low, CHWST would rise over time, even if $P_{\text{REGRAW}}$ is energy neutral. Using this principle, $P_{\text{CHBL}}$ is adjusted by the Baseline Routine using a slow-acting PI control loop whose error input $e_{\text{BL}} = \text{CHWST}_{\text{avg}} - \text{CHWS}P_{\text{NOM}}$, where CHWST$_{\text{avg}}$ is taken over a duration sufficiently long such that CHWST$_{\text{avg}}$ is not affected by the regulation signal. Hence, a shorter moving average duration for the Input Filter Routine allows a shorter moving average duration for the Baseline Routine because energy neutrality is reached more quickly in $P_{\text{REGFLT}}$. If the Baseline Routine moving average is too short, $P_{\text{CHBL}}$ may inadvertently inversely correlate with $P_{\text{REGRAW}}$ and if too long, $P_{\text{CHBL}}$ will not reflect changes in building cooling load. The Baseline Routine is demonstrated in Figure 12, where the Baseline Routine moving average is 30 minutes.

The proposed method relies on the characteristic of the regulation signal to be close to energy neutral over a period of time, but is not otherwise dependent on the regulation signal itself. As a result of the moving average, the proposed baseline method (Figure 12) produces a smoother baseline than actual (Figure 9), and is also somewhat delayed. The actual baseline responds immediately to any CHWST – CHWS$P_{\text{NOM}}$, while the proposed baseline responds based on CHWST$_{\text{avg}}$. From the grid’s perspective, the proposed method can be seen as first smoothing out the baseline and then superimposing a FR response.
2.3.3 PID Routine

The core PID Routine is implemented in a SIMULINK Discrete PID block using the ideal form transfer function.

\[
\frac{u_{\text{PID}}}{x} = K_p \left( 1 + K_i T_s \frac{1}{z-1} + K_D \frac{C_F}{1+C_F T_s z^{-1}} \right)
\]

The proportional gain \(K_p = 0.75\), integral gain \(K_i = 0.01\), derivative gain \(K_D = 0.03\), filter coefficient \(C_F = 5\), and sampling time \(T_s = 0.1\) seconds. The same gains were used for both RegA and RegD tracking, although the derivative gain could be removed for RegA with little impact on performance. The Zeigler-Nichols Ultimate Gain method is used as a starting point for online PID tuning, with suggested gains \(K_p = 1.6\), \(K_i = 0.061\), \(K_D = 4.1\). Some observations are made regarding the relative roles of the gains.

\(K_p\) provides the bulk of the controller response, and has units of °F/kW. The proportional gain was increased without integral and derivative gains until continued oscillations were observed. The final gain is taken to be roughly half that value. The proportional gain can be set aggressively without noticeable detriment to performance, although PID saturation is reached more often.

\(K_i\) is set to a minimal value. The steady state error using only the proportional gain is small relative to the inherent disturbances even while tracking a constant reference power. Hence, a small value for integral gain is acceptable. In addition, it is observed that high values of integral gain caused significant overshoot when chiller power exhibited a delayed response, for instance when transitioning between the IGV and compressor speed operating regimes (Figure 7).

\(K_D\) introduced noticeable improvements to response time and attenuated overshoot caused by the integral gain. The derivative gain is particularly important for tracking the faster RegD signal.

The PID Routine contains additional non-linear logic. Saturation limits are set to limit \(u_{\text{PID}}\) from +3°F (+1.7°C) to -2.5°F (-1.4°C) to avoid tripping on low CHWST. To complement the saturation limit, the clamping anti-windup capability of the SIMULINK PID block is used. The anti-windup is important in preventing overshoot due to delayed response.

Note that the rationale behind the tuning process and the research objectives as a whole is to demonstrate a practical and feasible control design, rather than a theoretically guaranteed “optimal” controller. It is entirely possible that another combination of PID gains or an alternate controller structure could produce superior performance.
2.4 Experiment Results

Figure 9 shows chiller measurements without providing FR over 40 minute interval. Due to partial occupancy, the cooling load is significantly lower than the chiller’s maximum capacity. The chiller’s onboard control logic only activated one of the two compressors throughout all experiments. Constant condenser water flow was maintained at 80°F (26.7°C).

Figure 10 and Figure 11 show chiller measurements while the FRC respectively tracks the RegA and RegD standard test signals with assigned regulation capability AReg = ±15 kW (PJM, 2014a). The PJM performance score is 0.89 for RegA and 0.86 for RegD; in comparison, the qualification threshold is 0.75. Cooling load is increased to accommodate AReg = ±15kW by turning off the air handler energy wheel, turning on the preheating coil, and opening windows. Similar results are observed at AReg = ±5 kW, for which the artificial cooling load increase is not necessary. When tracking the standard test signals, P_{CH, BL} is assumed constant over the 40 minute interval; the Baseline Routine and Input Filter Routine are not used. No appreciable impact on room temperature is observed through BAS monitoring.

Note that perfect tracking of the regulation signal is not necessary for FR service to be valuable to the grid. Table 1 shows the components of the performance score corresponding to Figure 10 and Figure 11. In a qualitative sense, performance requirements are derived from the limitations of the generators that currently provide the majority of FR. Hence, chillers need only outperform generators. Performance comparisons between chillers and other FR resources are made in Chapter 3.2.

Throughout the experiment in Figure 10 and Figure 11, the primary chilled water flow rate is approximately 1/4th of the rated flow and varied by ±5%. The condenser loop is constant flow, although the difference between condenser supply and return varied by ±20%. The total rated power is 15 kW for the primary chilled water pumps and 15 kW for the single cooling tower fan. Potential impacts of variations in pump and cooling tower power on overall FR response is discussed in Chapter 3.4. Only chiller power is presented in these results.

Figure 12 shows chiller measurements over seven hours during which the FRC continuously tracks a historical RegD signal with AReg = ±5 kW. The hourly performance scores range from 0.71 to 0.80 and averages 0.75. Both the Baseline Routine and Input Filter Routine are active and no appreciable impact on room temperature is observed. The cooling load at Fraunhofer is relatively constant over a typical day. In order to emulate a changing cooling load, the temperature of the air on the air handler cooling coil inlet was varied using the air handling unit preheat coil. The cooling coil is rated at 131 tons (461 kWth) and represents a significant load; the relationship between air temperature and baseline chiller power confirms the cooling load impact of the loading strategy. Within experimental error, the average CHWST over seven hours is the same as CHWSP_{NOM} = 44°F (6.67°C). This result demonstrates the effectiveness of the Baseline Routine.

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Table 1: Performance score components for Fraunhofer standard test signal results

<table>
<thead>
<tr>
<th>PJM Test Signal</th>
<th>Correlation Score</th>
<th>Delay Score</th>
<th>Precision Score</th>
<th>PJM Composite Performance Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>RegA, AReg = ±15 kW</td>
<td>0.91</td>
<td>0.99</td>
<td>0.78</td>
<td>0.89</td>
</tr>
<tr>
<td>RegD, AReg = ±15 kW</td>
<td>0.86</td>
<td>0.95</td>
<td>0.76</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Figure 10: FRC performance for the PJM RegA test signal. Performance score was 0.89.

Figure 11: FRC performance for the PJM RegD test signal. Performance score was 0.86.
2.5 Conclusion

A commercial chiller serving the Fraunhofer building in Boston was used to experimentally develop a practical closed-loop FRC that modifies chiller power demand to track regulation signals by adjusting CHWSP relative to CHWST. The design of the FRC was influenced by the existence of distinct chiller operating regimes. The FRC uses a PID control loop with gains determined by online tuning. The FRC also contains Input Filter and Baseline Routines that allow robust tracking of regulation signals over long durations by accounting for changes in building cooling load.

Demonstrations using standard PJM test signals show the chiller power response exceeded market qualification requirements at AReg up to ±15 kW for both RegA and RegD regulation signals while using a single 60 kW compressor. The FRC was further demonstrated to provide FR continuously for several hours while maintaining CHWST_{avg} close to CHWSP_{NOM} even as building cooling load changed significantly.

FR has been successfully demonstrated using Fraunhofer’s systems. However, detailed analysis of results and some considerations for practical deployment remain unexplored. These and other issues are discussed in Chapter 3.
3 Analysis of Fraunhofer CSE Results

Chapter 2 demonstrated that FRC performance with Fraunhofer’s chiller meets system operator requirements for providing FR. Chapter 3 compares results to existing simulation models in the literature and to other FR resources. Furthermore, chiller efficiency considerations, the effect on other HVAC equipment, and limiting factors for FR capability are identified.

3.1 Comparison to Model Results

The FR performance score is similar to (Blum & Norford, 2014)’s simulation results for chilled water supply temperature setpoint (CHWSP) adjustment based on another building. The magnitude of chilled water supply temperature (CHWST) change from a given range of changes in CHWSP was also comparable, suggesting similar cooling system dynamics. The observed time constant in the compressor speed operation regime is 30 sec to 1 min; in comparison, Zhao et al. (2013) simulated first-order chiller models with time constants in the range of 1 min to 10 min. However, first-order chiller models do not account for delays and ramp rate limitations, which can play a significant role in FR performance and are discussed Chapters 5.1 and 5.3 respectively.

The minimum allowable chiller power while providing FR is 33% to 50% of rated power and is higher than assumed by Blum & Norford (2014) and Zhao et al. (2013), which results in lower FR capability than simulated. FR capability is explored further in Chapter 3.5. Also unlike the simulations, experimental results showed small performance score improvements of around 0.05 when increasing AReg from ±5 kW to ±15 kW. The performance improvement is attributed to the relative decrease in the magnitude of disturbances.

3.2 Comparison to Other Regulation Resources

In terms of regulation signal tracking performance, Fraunhofer’s chiller scores lower than batteries but higher than most traditional generators. The average performance score for generators in PJM from January to June 2014 was 0.79 for generators following RegA and 0.91 for generators following RegD; the amount of provided RegA regulation in MW was six times RegD. Storage and demand resources made minimal contributions (Monitoring Analytics, 2015). Battery systems typically score approximately 0.95 and follow RegD (PJM, 2014b). Hao et al. (2013) did not use the PJM scoring method when evaluating air handling unit (AHU) fan FR performance, but results indicate faster and more accurate response than the chiller. This is consistent with observations at
Fraunhofer where AHU fan speed could be controlled directly and fan power responds rapidly. However, providing FR with fans cause different downstream effects than with chillers.

FR with chillers can be compared to storage in terms of equivalent energy storage capacity, where higher energy storage capacity results in higher FR capability. Fraunhofer’s chiller, when operating with a single 60 kW compressor on the 40 minute RegA standard test signal, had an equivalent energy storage capacity of 0.85 kWh when AReg = ±5 kW and 2.3 kWh when AReg = ±15 kW. The standard RegD test signal yielded 0.56 kWh when AReg = ±5 kW and 1.6 kWh when AReg = ±15 kW. Assuming good tracking performance, equivalent energy storage is roughly directly proportional to AReg for a given regulation signal. The equivalent energy storage value is calculated from the measured chiller power $P_{CH,MEAS}$ and the baseline chiller power $P_{CH,BL}$ as shown in Equation 2 and Figure 13.

**Equation 2**

Equivalent Energy Storage Capacity

$$= \max \left( \int_0^T (P_{CH,MEAS} - P_{CH,BL}) \, dt \right) - \min \left( \int_0^T (P_{CH,MEAS} - P_{CH,BL}) \, dt \right)$$

![Diagram](image_url)

*Figure 13: Calculation of equivalent energy storage capacity*
Discharge time at rated power is an energy to power ratio that measures the minimum time required to fully discharge stored energy; the metric is used to quantify the suitability of energy storage technologies for various grid applications (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010; Díaz-González, Sumper, Gomis-Bellmunt, & Villafá́ila-Robles, 2012). A comparable metric can be calculated for chillers by dividing the equivalent energy storage capacity by the maximum FR capability. For Fraunhofer’s chiller, equivalent discharge time at rated power is $2.3 \text{ kWh} / 15 \text{ kW} = 9.2 \text{ min}$. The metric is compared to other storage technologies in Figure 14. 9 minutes is comparable to flywheels, nickel-cadmium batteries, and certain lithium ion batteries.

![Figure 14: Discharge time at rated power for various energy storage technologies, excerpted from (Díaz-González et al., 2012). In comparison, Fraunhofer’s chiller has an equivalent discharge time at rated power of 0.15 hours, with a power rating of 15 kW and energy rating of 2.3 kWh.](image)

The cost for FR using chillers scales less with FR capability than using storage or generation. Economic feasibility is discussed in Chapter 6.3.2. Fundamentally, the source of energy storage is pre-existing, and the main cost drivers come from additional measurement, control, and associated labour requirements. A similar set of measurement and control devices can be used for a range of chiller sizes. However, given the size of commercial chillers, aggregation of multiple buildings is likely required, which results in the operation of an aggregated virtual power plant rather than a single site.
3.3 Chiller Efficiency while Providing FR

The average chiller coefficient of performance (COP) during FR is the same as the steady state COP without FR, indicating that FR does not appreciably affect average chiller efficiency. While the average COP is unaffected, FR causes transient variations in CHWST, lift, and cooling output, which lead to transient variations in COP. It is of interest to explore the contribution of transient COP to power response.

The condenser water supply temperature is maintained at 80°F (26.7°C); hence, increases in CHWST decreases lift and vice versa. As expected, COP typically decreases during upwards regulation and increases during downwards regulation. Figure 15 compares the power response of the Fraunhofer chiller in a hypothetical situation, where power is calculated from the cooling output assuming the COP remains constant at the average value, with the actual measured $P_{CH,MES}$. Up to 50% of the power response can be due to changes in COP rather than actual cooling output. The impact of COP is significant and should be considered for inclusion in models. Only the cooling output variations interact with the thermal storage capacity of the building’s cooling system, but both cooling output and COP variations contribute to FR.

![Figure 15: Impact of variable COP on chiller power response](image)

The finding that average COP remains the same with or without FR is predicated on $CHWST_{avg} = CHWSP_{NOM}$; the relationship is enforced by the Baseline Routine and Input Filter. Maintaining the average COP also relies on a roughly linear relationship between cooling output, lift, and COP. Increasing FR capability, thereby expanding FR operation beyond the linear range, or using a chiller with substantially non-linear relationships, may decrease average COP.
3.4 Induced Power Variations in Ancillary Equipment

Adjustment of chiller power through CHWSP may cause cascading secondary effects resulting in short-term variations, from normal operation, in power use of other HVAC equipment. These variations may distort the FR response when the building is taken as a whole. While only the power of the chiller was measured at Fraunhofer, the potential for power variation in other equipment is qualitatively discussed.

Fraunhofer’s chilled water system is variable primary flow. Hence, decreases in CHWST reduce flow due to closing of the AHU cooling coil and various other valves, and vice-versa. The variations in flow translate into variations in power use of the two 7.5 kW primary chilled water pumps, rated at 400 GPM (24.2 L/s) each. While pump power was not measured, the flow rate variation was approximately ±5% during tracking of the RegD signal with AReg = ±15 kW (Figure 16). The limited flow variation, considered in conjunction with low flow relative to rated flow and low pump rated power relative to the chiller, indicates that pump power variation does not significantly detract from the FR response. However, any variations tend to be in the opposite direction of the desired FR response, offset by some delay. Pumping power variations would not be a concern in constant primary flow systems.

![Image of power variations](image_url)

Figure 16: Impact of FR on chilled water pump and condenser water loop
On the condenser side, the water flow rate is constant, and hence condenser water pump power is constant. However, the cooling tower fans maintain condenser water supply temperature at 80°F (26.7°C) using a single VFD driven motor rated at 15 kW. The fan power can vary with changes in ΔT across the cooling tower. Unfortunately, these measurements are not available; only condenser supply and return temperatures at the chiller are recorded. The ΔT at the chiller condenser varies by ±20% in proportion to changes in chiller power and cooling output with negligible delay (Figure 16). This result is expected because the chiller has minimal thermal storage internally, and hence changes in chiller power and cooling output directly translate into condenser heat rejection. ΔT at the cooling tower may also vary in the range of ±20%, which may lead to sufficient fan power changes to distort the FR response. In contrast with the chilled water pumps, cooling tower fan power will change in the same direction as the desired FR response, with some delay. It is recommended that future experimental work measure the cooling tower power use.

The AHU at Fraunhofer is constant volume, so changes in CHWST do not affect AHU fan power. In variable volume systems, it is possible that CHWST changes airflow rate, but the effect should be minimal because the cooling coil valve attempts to maintain a constant supply air temperature and variable air volume terminal units respond to room temperature rather than supply air temperature, hence creating a thermal buffer.

3.5 FR Capability Constraints

FR capability is the amount of ±power available for FR. At Fraunhofer, the maximum FR capability is ±15 kW. A chiller’s FR capability is ultimately dependent on the specifics of the system under consideration. However, results indicate several generally applicable constraining factors.

FR capability is limited by acceptable deviation of CHWST from the nominal CHWSP without providing FR, CHWSPNOM. Excessive deviation may interfere with proper functioning of devices served by the chilled water and/or cause reduction in occupant comfort. The observed deviations increase with AReg. However, the increase was less than directly proportional to AReg and asymmetrical for upward and downward deviation. For Figure 10 and Figure 11, the maximum / minimum CHWST − CHWSTavg deviation is +3.6°F (-2.0°C) / -3.7°F (-2.1°C) and +2.2°F (-1.2°C) / -2.8°F (-1.6°C) respectively. CHWSTavg is the average CHWST taken over the length of test duration. In theory, the magnitude of temperature deviations depend on how downstream components react to CHWST changes, and on the time for chilled water to flow from chiller outlet to chiller inlet (turnover time). At Fraunhofer, the turnover time, estimated as the time between CHWST change to CHWRT change, was approximately 4 min. The chiller manufacturer recommends turnover time greater than 3 min for chiller control stability. Turnover time is a normalized measure of system volume and thermal storage capacity (Bahnfleth & Peyer, 2004); higher turnover time should result in less temperature deviation.
From experience at Fraunhofer and MIT, short-term CHWST deviations of up to ±5°F (±2.8°C) are acceptable for normal system operation at $CHWSP_{\text{NOM}} = 44°F \ (6.7°C)$, as long as the average CHWST remains close to $CHWSP_{\text{NOM}}$. Fraunhofer’s chiller starts when CHWST is 5°F (2.8°C) warmer than CHWSP, and the start-up cycle itself causes CHWST to overcool up to 5°F (2.8°C) colder than CHWSP. Similar variations are observed at MIT during compressor cycling, discussed in Chapter 5.4. These CHWST variations occur without the FRC and have not been observed to detrimentally affect downstream components in these buildings or occupant comfort. However, these limits may change at different $CHWSP_{\text{NOM}}$. Additionally, specialized buildings with sensitive equipment cooled by the chilled water system may have tighter CHWST tolerances.

CHWSP limits impose another set of constraints on CHWST and consequently FR capability. The minimum CHWSP of the chiller is 38°F (3.3°F) and $u_{\text{FRC}} = CHWSP = CHWST - u_{\text{pid}}$ with $\min u_{\text{pid}} = -2.5°F \ (-1.4°C)$ (Figure 6). Hence, the FRC begins to lose effectiveness when CHWST drops below $38 + 2.5 = 40.5°F \ (4.7°C)$ because control begins to saturate. FR performance is qualitatively observed to deteriorate at Fraunhofer when CHWST drops below 40°F (4.4°C). The maximum CHWSP is 60°F (15.6°C) and is not an active constraint at Fraunhofer.

Aside from CHWST, there are minimum and maximum cooling output limits that also impact FR capability, effectively imposing minimum and maximum $P_{\text{CH,MEAS}}$. The maximum power is the 60 kW rated power of the single compressor, although extended operation close to 60 kW would result in the addition of the second compressor, which did not occur in the experiments. Note that some systems may limit maximum power to below rated power. The minimum $P_{\text{CH,MEAS}}$ for FR is 31 kW, which is approximately the boundary at which the compressor inlet guide vane (IGV) begins to close. It is undesirable to operate in the IGV regime due to deterioration of FR performance from slower power response and the potential for overshoot during regime transition, as discussed in Chapter 2.2, although occasional occurrence is acceptable. However, $P_{\text{CH,MEAS}}$ below 20 kW enters the load balancing valve (LBV) regime, which significantly reduces chiller efficiency and should be completely avoided. At Fraunhofer, the minimum and maximum cooling output limits the FR capability to $\min\{ P_{\text{CH,BL}} - 31, \ 60 - P_{\text{CH,BL}}, 0\}$.

The maximum AReg of ±15 kW for the Fraunhofer chiller is primarily constrained by the minimum and maximum cooling output but is also close to the CHWST constraints.
3.6 Conclusion

Analysis of Fraunhofer results indicates FR performance scores similar to model predictions for another building. However, minimum power and variable COP are two factors that could be incorporated into future models to more accurately reflect observed chiller transient behaviour and predict performance. When compared to other FR resources, Fraunhofer’s chiller scored higher than traditional generators but lower than batteries and HVAC fans. Comparisons should also consider how a chiller’s operational and economic characteristics differ from other FR resources. For future work with water-cooled chillers such as Fraunhofer’s, the power use of the cooling tower should be metered to ascertain impact on overall FR response. In terms of FR capability, the Fraunhofer chiller was constrained by CHWST, CHWSP, and minimum power limits. Maximum AReg was ±15 kW on a single 60 kW compressor.
4 Controller Development at MIT

The MIT building (MIT) used for controller development is a historic dormitory housing 490 students that was renovated in 2011, including installation of the chiller under analysis. Only part of the building is cooled. The goal of the parallel FRC development at MIT is to provide a second set of testing results from another HVAC system and FRC setup that may pose a different set of limitations and characteristics from Fraunhofer. Unlike Fraunhofer, the physical FRC at MIT is wired to BAS field panels rather than directly to the chiller. In addition to control of CHWSP, the MIT FRC also controls the supply air temperature setpoint, SATSP, of the air handling units; this provides an alternative method of influencing chiller power (Figure 17). The fundamental components of the FRC controller design are similar to Fraunhofer’s. The final FRC design was tested with a series of 40 minute standard regulation test signals.

4.1 Experiment Setup

MIT is served by a 200 ton (703 kWth) air-cooled chiller\(^3\) with variable primary flow and three VFD controlled centrifugal compressors rated at 75 kW each\(^4\). The compressors are similar to those at Fraunhofer. Three constant volume dedicated outdoor air system AHUs constitute the majority of the chiller’s load; their cooling coils are rated at 50 tons (176 kWth), 70 tons (246 kWth), and 139 tons (489 kWth).

In some instances, it may not be possible to wire a physical controller directly to the chiller. For example, placement and wiring of the controller may be difficult and expensive in the case of air-cooled rooftop chillers or multiple chillers. At MIT, setpoint commands and chilled water temperature readings are communicated to the FRC through the campus BAS network (Figure 17).

The FRC is wired to the BAS field panel containing sequences for the chiller. The FRC sends CHWSP to the panel via analog signals, which is then communicated to the chiller within the BAS network. The FRC also reads the CHWST and CHWRT measurement points from the BAS chiller field panel, although CHWRT is not used for control. The FRC sends SATSP to the BAS AHU field panel, which is physically located at a different location in the building. A second physical device is wired to the AHU field panel and serves to relay communications from the FRC using an internet connection. This approach is preferred over communicating internally within the BAS network due

\(^3\) SMARDT AA073.3BG6.25V.KM0.001X.V
\(^4\) Danfoss Turbocor TT-300
to BAS network delays. Communication delays are discussed in Chapter 5.1. Minor modifications are made to BAS programming to accommodate the FRC inputs and outputs. A dedicated power meter is installed that is capable of updating power on 100 ms intervals; the power meter is also at a different location in the building and communicates with the FRC via Modbus over a wireless bridge.

Figure 17: MIT FRC setup

### 4.2 Controller Design

The Baseline Routine and Input Filter Routine are identical to the Fraunhofer implementation. The PID Routine is also similar, although with different gains and saturation limits. The proportional gain $K_p = 0.375$, integral gain $K_i = 0.0001$, derivative gain $K_d = 0.03$, filter coefficient $C_f = 0.5$, and sampling time $T_s = 1$ seconds. Saturation limits are set to limit $u_{PID}$ from $+4^\circ F (+2.2^\circ C)$ to $-4^\circ F (-2.2^\circ C)$. The same PID Routine is used to control both the SATSP and CHWSP, although SATSP is not pegged to SAT (Figure 17). The approach accommodates easier adaptation and comparison to Fraunhofer. However, using separate PID Routines may provide better control outcomes.

A formal process of system characterization and PID gain tuning was not completed with the MIT FRC due to limited data available and time constraints. In general, gains are set to achieve the most consistent tracking of the RegA and RegD test signals. Overall, the FRC was set to respond less aggressively due to communication delays in the BAS network and slower response from the chiller. Using the Fraunhofer FRC gains at MIT would result in rapid control saturation. The saturation limits were likewise expanded to allow for more consistent control when the CHWST seen by the FRC may differ from the CHWST seen by the chiller due to communication delays. The threshold for compressor shut-down due to low CHWST relative to CHWSP is unclear. Qualitatively,
increasing the saturation limit did not have a noticeable effect on the instances of compressor cycling for the regulation signals tested. The saturation limits are determined by limits to the AHU SAT after discussions with MIT Facilities and dormitory representatives.

### 4.3 Experiment Results

Results for RegA and RegD test signals with AReg = ±20 kW are presented in Figure 18 and Figure 19; performance scores are 0.74 and 0.56 respectively, which are lower than at Fraunhofer. Additional results are presented in Table 2. Note that both CHWSP adjustment and SATSP adjustment are used at MIT, compared to only CHWSP adjustment at Fraunhofer. SATSP adjustment is discussed specifically in Chapter 5.2.

**Table 2: Summary of MIT experiment results**

<table>
<thead>
<tr>
<th>PJM Test Signal</th>
<th>Control Method</th>
<th>AReg, kW</th>
<th>P_{CHWS}kW</th>
<th>PJM Performance Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>RegA</td>
<td>CHWSP</td>
<td>±15</td>
<td>80</td>
<td>0.81</td>
</tr>
<tr>
<td>RegA</td>
<td>CHWSP &amp; SATSP</td>
<td>±20</td>
<td>70</td>
<td>0.74</td>
</tr>
<tr>
<td>RegA</td>
<td>CHWSP</td>
<td>±20</td>
<td>125</td>
<td>0.63</td>
</tr>
<tr>
<td>RegA</td>
<td>SATSP</td>
<td>±20</td>
<td>125</td>
<td>0.77</td>
</tr>
<tr>
<td>RegA</td>
<td>CHWSP &amp; SATSP</td>
<td>±20</td>
<td>115</td>
<td>0.61</td>
</tr>
<tr>
<td>RegD</td>
<td>CHWSP</td>
<td>±30</td>
<td>80</td>
<td>0.56</td>
</tr>
<tr>
<td>RegD</td>
<td>CHWSP</td>
<td>±20</td>
<td>70</td>
<td>0.45</td>
</tr>
<tr>
<td>RegD</td>
<td>SATSP</td>
<td>±20</td>
<td>70</td>
<td>0.56</td>
</tr>
<tr>
<td>RegD</td>
<td>CHWSP &amp; SATSP</td>
<td>±20</td>
<td>70</td>
<td>0.56</td>
</tr>
</tbody>
</table>

![Figure 18](image.png)

**Figure 18**: MIT FRC performance for the PJM RegA test signal with CHWSP and SATSP control. Performance score was 0.74.
Figure 19: MIT FRC performance for the PJM RegD test signal with CHWSP and SATSP control. Performance score was 0.56.

Figure 20: MIT FRC performance for the PJM RegD test signal with SATSP control only. Performance score was 0.56.
Figure 21: MIT FRC performance for the PJM RegD test signal with CHWSP control only. Performance score was 0.45.

4.4 Conclusion

A FRC was implemented for a commercial chiller serving an MIT dormitory building in Cambridge, with the goal of providing a second set of testing results for comparison. The MIT FRC design differed from Fraunhofer primarily in the use of BAS based communications and control over SATSP in addition to CHWST.

Performance outcomes using the same PJM test signals showed considerably different results. In all cases, the MIT setup had lower performance scores. For RegD, the scores are below the qualification requirements. Chapter 5 discusses potential sources of differences, and how they may affect FRC implementation in other buildings.
5 Analysis of MIT Results

In this chapter, some observations and comparisons are made based on the MIT FRC implementation and on general experience with chillers and HVAC systems. First, the effect of design differences for the MIT FRC are discussed, specifically BAS communication delays and SATSP control. Then, effects stemming from using a different chiller and HVAC system are discussed, specifically ramp rate limitations and multiple compressors.

5.1 Effect of BAS Communication Delays

One major contributor to the lower performance score at MIT is network communication delays. Prior to modifications, the BAS network delay from \( u_{FRC,CHLR} \) sent by FRC to CHWSP received by chiller was 5 min. This is comparable to the 2 min network delays experienced by (Berardino & Nwankpa, 2010). The FRC received updates for chilled water temperatures from the chiller once every 20 min, also through the BAS network. After working with the BAS provider and MIT Facilities to prioritize FRC communication, CHWSP delay was reduced to 40 sec and chilled water temperature updates to once every 30 sec, depending on network conditions. Results shown and performance scores are for the setup after these modifications. Network delays are not the same for all devices connected to a BAS; SATSP adjustment for the two AHUs exhibited negligible network delays under 5 sec.

From experience, communication delays of under 10 sec are preferable for FR operation and delays up to 1 min may be tolerated depending on chiller characteristics. Note that the chiller’s own measurement of CHWST should be used for the FRC, because the FRC requires control over the difference between CHWSP and CHWST seen by the chiller. Often, the BAS will read CHWST from an alternate sensor in the chilled water loop; this alternate value should not be used for the FRC.
5.2 Supply Air Temperature Setpoint Adjustment

The FRC adjusts SATSP on the AHU with the 50 ton (176 kW) cooling coil and the AHU with the 70 ton (246 kW) cooling coil. SATSP adjustments induce changes in AHU cooling coil valve position, which in turn induce changes in primary chilled water flow rate. In the CHWSP control loop, CHWSP was pegged to the measured CHWST to address various critical issues, such as inadvertent compressor shutdown (Chapter 2.3). The same issues do not apply to the cooling coil valve. Thus, measured supply air temperature (SAT) is not required for the SATSP control loop and is not an input to the FRC. Instead, SATSP is simply an offset from SATSP\textsubscript{nom}. As shown in Figure 1, \( u_{\text{FRC,AHU}} = \text{SATSP} - \text{SATSP}_{\text{nom}} - u_{\text{PID}} \). The \( u_{\text{PID}} \) range is \( \pm 4°F \) (\( \pm 2.2°C \)).

MIT FR performance with SATSP adjustment control compared to CHWSP adjustment control and combined control is shown in Figure 20, Figure 21, and Figure 19 respectively for the RegD test wave. MIT’s chiller scores 0.45 under CHWSP control versus 0.56 under SATSP control and 0.56 under combined control (Table 2).

In the VAV HVAC model used by (Blum & Norford, 2014) for open-loop supply air temperature adjustment control, the FR performance was hindered by indirect coupling to chiller power, by fully opened cooling coil valves at high loads, and by the action of VAV terminal units to counteract regulation. In MIT’s constant volume system, the action of VAV terminal units is not applicable. However, lack of control at high load is observed for SATSP adjustment, presumably due to fully opened cooling coil valves. Although cooling coil valve saturation did not occur for the results presented, SATSP combined with CHWSP adjustment is generally advantageous because SATSP adjustment provides a relatively quick initial response prior to valve saturation while CHWSP provides the response afterwards. Optimized coordination between the two methods is not examined here.

Although BAS communication delays are minimal for the AHU, some delay in chiller power response is still observed (Figure 20). The likely cause is indirect coupling between the SATSP and chiller power due to slow valve modulation and internal chiller response to flow variation. While cooling coil valve actuators typically have a running time of less than 2 min, valve movement might be significantly slower due to settings within the BAS for the valve control loop.

In general, when attempting to change chiller power through flow variations such as SATSP adjustment, one should be conscious of flow rate change limits. For example, Fraunhofer’s chiller specifies a maximum flow rate change of 10% per minute. Typical recommended values range from 2% to 30% per minute (Bahnfleth & Peyer, 2004). Also, depending on downstream components, SATSP adjustment may have more direct impact on occupied space temperature than CHWSP adjustment. At MIT, there is no reheat at the terminal units, hence changes in SAT are felt directly. On the other hand, MIT’s AHUs only serve corridors and public spaces, where precise control of temperature is less crucial.
5.3 Chiller Ramp Rate Limitations

Unlike Fraunhofer, MIT’s chiller included parameters in the onboard control logic that constrain the ramp rate of internal PID loops. The default value is 3-5% per minute. Accordingly, Fraunhofer’s chiller has a maximum observed ramp rate of 44 kW/min while MIT’s chiller has a maximum observed ramp rate of 8 kW/min. Note that observed ramp rates are approximate, as it can be difficult to distinguish between transient fluctuations in power versus ramps that can be maintained.

In comparison, the maximum 10 sec ramp rate for the RegD test wave is 1.5 kW/min and maximum 30 sec ramp rate is 0.85 kW/min for each kW of AReg. Lower ramp rates for the chiller may be acceptable, but deteriorates performance. Ramp rate is a limiting factor at MIT for both FR performance and capability. While the ramp rate limit and other internal parameters are adjustable in the field, they are kept at their default values as commissioned for the experiments. Changing the chiller’s ramp rate limit parameter, under the guidance of the manufacturer, may be a first step to improving FR performance.

5.4 Multiple Compressors and Cycling

Compressors may continuously cycle even when cooling load is constant, as observed at low cooling output for the single compressor at Fraunhofer. For the multiple compressors at MIT, cycling is observed at both low and intermediate cooling output. Continuous cycling of compressors poses a number of implications for FR operation.

At MIT, cycling is a limiting factor for FR capability. AReg greater than ±20 kW tends to trigger the adding and dropping of compressors. Once cycling begins, regulation signal tracking is lost and continued setpoint adjustments by the FRC causes cycling to continue resulting in increasingly unstable CHWST. FR control should not be implemented for chillers that often cycle because regulation performance is significantly decreased and day-ahead bidding of FR capability is difficult. No cycling occurred in any of the test signal results (Table 2).

Predicting the thresholds for cycling is difficult. The thresholds are primarily dependent on cooling output, but are also affected by other factors such as chiller internal parameters and cooling system characteristics. During normal operation without the FR for two days with similar cooling requirements, one day may exhibit continuous cycling while the other day may not (Figure 22). These results indicate that observation of actual operation in addition to design information is required to determine whether a particular system is suitable for FR. The maximum starts per compressor per hour recommended by the manufacturer is 10 for Fraunhofer and 4 for MIT.
Figure 22: MIT chiller power and water temperatures during normal operation without FR. Compressor cycling occurs in Sample 1 but not Sample 2.

Cycling may be ameliorated through adjustment of internal parameters. With MIT’s chiller, compressor add and drop is triggered when compressor speed or difference between CHWST and CHWSP surpass certain thresholds for a duration of time. These internal parameters are field adjustable and should be set appropriately as part of the normal commissioning process so that cycling does not occur at intermediate loads. However, evidence suggests proper adjustment does not always happen or system characteristics change over time (Figure 22). Also, further changes to internal parameters to expand FR range may decrease chiller efficiency. Cycling parameters are set so that all compressors operate close to peak efficiency as much as possible. For example, compressors are added before existing compressors reach maximum because efficiency drops at high speeds.

The fact that chillers in some existing buildings often cycle provides some reassurance regarding the impact of FR on the chiller and HVAC system. Careful monitoring and parameter adjustments will be made to chillers used for FR to prevent cycling, potentially improving chiller lifetime by coincidence. Also, CHWST can fluctuate up to ±5°F (±2.8°C) throughout the day due to cycling (Figure 22), which is greater than the fluctuations that would be induced by FR, yet still do not produce noticeable deficiencies in occupant comfort.
5.5 Conclusion

A second set of tests was conducted at MIT with a chiller comparable to Fraunhofer’s. The MIT FRC controlled the chiller and two AHUs through the campus BAS system whereas the Fraunhofer setup controlled only the chiller and connected directly to the chiller itself. Control of the AHUs allowed SATSP adjustment, which can be used in conjunction with CHWSP adjustment to improve FR performance. While control through the BAS network can be easier to set up, communication delays can be significant enough to make FR impractical. Communication delays contributed to lower performance scores at MIT compared to Fraunhofer. In terms of FR capability, the MIT chiller was constrained by ramp rate limits and compressor cycling. Maximum AReg was ±20 kW for a chiller with three 75 kW compressors. Field adjustments to chiller internal parameters under manufacturer guidance can likely alleviate ramp rate and cycling constraints.

The flexibility and adaptability of the FRC concept has been demonstrated in Chapters 2 to 5 and key considerations for FR using chillers have been identified. Chapter 6 conducts a high-level analysis to extrapolate the results of the previous chapters to estimate the potential contribution of chillers to FR requirements in aggregate at a national level.
6 Aggregated Frequency Regulation Potential

The previous chapters investigated the FR potential of chillers at the level of an individual building, using experiments at specific operating conditions. The goal of Chapter 6 is to expand analysis to the entire US commercial building stock in order to determine how the widespread use of commercial HVAC chillers for FR may contribute to meeting the FR requirements of the US grid, in aggregate. The two key effects investigated are the variation of FR potential with building cooling load and the variation of FR requirements with overall grid demand. The methodology combines experimental results from the previous chapters with energy models and a top-down approach from survey data.

Chapter 6 goes beyond calculating a single number for the entire country. FR potential is quantitatively analyzed for different climate zones and building types. In addition, economic feasibility, manufacturer comments, and the possible use of other types of cooling equipment for FR are discussed.

6.1 Methodology

The methodology combines experimental results from the previous chapters with EnergyPlus models and data from CBECS (EIA, 2003) and California CEUS (California Energy Commission, 2002). The three main outputs of the analysis are: Annual FR, annual electricity consumption, and coincident FR supplied. Outputs are calculated for each CBECS 2003 climate zone (Figure 23) (EIA, 2015a).

6.1.1 Annual FR

Annual FR is the amount of FR, measured in kWh or MWh, that is available over a year. For example, if a chiller can provide ±50 kW of FR for all 8760 hours in a year, then the chiller’s annual FR is 438 MWh. Annual FR is calculated by using an EnergyPlus simulation for specific building types to generate a climate zone specific load duration curve (LDC) for the number of hours in a year a chiller spends at each partial load condition. The DOE commercial reference models for new construction large office and large hospital are used (DOE, 2015) for the representative cities of Minneapolis, Chicago, Baltimore, Atlanta, and Houston for climate zones 1 to 5 respectively. The LDC is normalized to rated chiller power (Figure 24 and Figure 25).
Figure 23: CBECs 2003 climate zones
Figure 24: Chiller power load duration curves for large office by climate zone
Figure 25: Chiller power load duration curves for large hospital by climate zone
The annual FR per kW of installed chiller capacity can be calculated from the LDC for each building type. The relationship between chiller power and FR capability is discussed in Chapter 3.5; this analysis uses those general principles in addition to the experimental results from Chapter 2.4 and Chapter 4.4.

For each compressor, it is assumed that the FR capability is 20% of rated power, with a minimum power of 50% and a maximum power of 100%.

**Equation 3**  
Single Compressor FR Capability  
\[
= \min\{ \text{Rated Power} - \text{Compressor Power} , \\
\text{Compressor Power} - \text{Rated Power} \times 0.5 , \\
\text{Rated Power} \times 0.2 \}
\]

However, most buildings will have more than one compressor. It is assumed that compressors are sequenced to stage on/off to maintain as much power in each operating compressor as possible without exceeding 80%. For example, a chiller with five compressors is assumed to sequence four 100 kW compressors to operate at 75 kW each rather than three 100 kW compressors to operate at 100 kW each. It is further assumed that compressors stage similarly regardless of their distribution between different chillers. For example, four compressors on a single chiller will produce the same staging sequence as two chillers with two compressors each. When the sequence is considered for all compressors, the resulting FR capability as a function of the total rated power of all compressors is shown in Figure 26.

The analysis does not separate buildings by number of compressors. Instead, a single relationship between compressor power and FR capability is used for all buildings, shown in Figure 26 and Equation 4. Whereas Equation 3 represents the FR capability of a single compressor, Equation 4 represents the FR capability of an entire building with multiple compressors. The building FR capability is 25% of the total power of all compressors at a given hour and is limited by a maximum 100% of rated power and a minimum of 25%.

**Equation 4**  
Building FR Capability  
\[
= \min\{ \text{Rated Power} - \text{Chiller Power} , \\
\text{Chiller Power} - \text{Rated Power} \times 0.25 , \\
\text{Chiller Power} \times 0.25 \}
\]
Figure 26: Chiller FR capability vs. chiller power
The annual FR per MW of installed chiller capacity for each building type is shown in Table 3.

Table 3: Annual FR per MW of installed chiller capacity

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual FR, Office Type (MWh/MW)</td>
<td>219</td>
<td>216</td>
<td>313</td>
<td>483</td>
<td>512</td>
</tr>
<tr>
<td>Annual FR, Hospital Type (MWh/MW)</td>
<td>1065</td>
<td>1171</td>
<td>1532</td>
<td>1474</td>
<td>1276</td>
</tr>
</tbody>
</table>

The next step is to determine the installed chiller capacity for each building type in each climate zone. The purpose of modeling different building types is to account for differences in LDC. Inpatient hospitals have distinct LDCs due to 24/7 occupancy (Figure 25); the annual chiller electricity used by inpatient hospitals for each climate zone is determined from CBECs microdata (EIA, 2003) and summarized in Table 4. The LDC from the large hospital DOE reference model and CBECs inpatient hospital chiller electricity consumption are used to calculate the installed chiller capacity (Table 5). All chiller electricity use not from hospitals is assumed to be in buildings that are only occupied during working hours, which are all analyzed together under the “Office Type” LDC, using the large office DOE reference model. The same procedure is used to determine the installed chiller capacity in Office Type buildings (Table 5).

Table 4: Chiller electricity energy use percentages by building type

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Electricity Use, Office Type</td>
<td>86%</td>
<td>85%</td>
<td>92%</td>
<td>81%</td>
<td>85%</td>
</tr>
<tr>
<td>Annual Electricity Use, Hospital Type</td>
<td>14%</td>
<td>15%</td>
<td>8%</td>
<td>19%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 5: VFD chiller installed capacity

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed Capacity, Office Type (MW)</td>
<td>696</td>
<td>1584</td>
<td>1348</td>
<td>1672</td>
<td>1501</td>
</tr>
<tr>
<td>Installed Capacity, Hospital Type (MW)</td>
<td>25</td>
<td>60</td>
<td>31</td>
<td>120</td>
<td>111</td>
</tr>
<tr>
<td>Installed Capacity, Total (MW)</td>
<td>721</td>
<td>1644</td>
<td>1379</td>
<td>1792</td>
<td>1612</td>
</tr>
</tbody>
</table>

Note that the installed chiller capacity is only for VFD driven chillers, even though CBECs does not distinguish between VFD and non-VFD chillers. Instead, the California CEUS microdata was used. CEUS indicated that 30% of installed chillers are VFD driven and the ratio varies minimally with building type. The 0.3 factor was applied across the board. The estimate is likely low because the CEUS survey was based on 2002, and VFDs have become more prevalent since. One final factor of 1.22, the ratio of total commercial floor space, was applied to chiller installed capacity to adjust 2003 CBECs data to 2012.

Annual FR is the product of the per MW values in Table 3 and the MW of installed capacity in Table 5. Results are summarized in Table 6.
6.1.2 Annual Electricity Use
Annual electricity consumption is necessary to assess annual FR (TWh) and annual FR requirement (TWh). FR requirement is estimated as 1% of electricity demand at all times and therefore annual FR requirement is also 1% of annual electricity consumption. In practice, determining FR requirement is a complex issue and different system operators have their own methods, and the requirement values are frequently adjusted (KEMA, 2011; PJM, 2014a).

The CBECs climate zones do not correspond to state boundaries. Therefore, it is necessary to break electricity consumption into finer granularity, even though only state level electricity consumption data is available (EIA, 2015b). Annual electricity consumption for each county was calculated as the product of the state consumption and the portion of state population in the county (U.S. Census Bureau, 2013). Electricity consumption for the climate zone is the sum of all counties within the zone.

Results are shown in Table 6.

6.1.3 Coincident FR Supplied
FR requirement varies proportionally to the hourly grid demand, while FR capability varies depending on chiller power use. The two profiles will be dissimilar to a certain extent. The coincident FR supplied is a comparison of FR capability versus FR requirement on hour-by-hour intervals, totalled over a year. For hours where FR capability exceeds FR requirement, 100% of the required FR could be supplied by chillers. It is further assumed the market will prioritize FR from chillers over other resources.

Hourly FR requirement is 1% of demand. Demand is calculated for climate zones 1, 3, and 5 by using the 2014 demand profile of ERCOT, PJM, and MISO respectively. The demand profile is scaled such that the total electricity consumption over a year matches the values calculated previously for the climate zone. Climate zones 2 and 4 are excluded from this part of the analysis due to difficulty in establishing an overall demand profile based on the geography. Figure 27 shows the normalized daily maximum and minimum demand for each climate zone, plotted on daily intervals.

Hourly FR capability is calculated from hourly chiller power using Equation 4. Hourly chiller power is obtained from the large office and large hospital DOE commercial reference models and scaled to match the installed chiller capacity for Office Type and Hospital Type buildings in Table 5. Similarly to the LDC calculations, 2014 actual meteorological year data is used. The FR capability over a year is plotted on daily intervals in Figure 28. FR capability for a typical summer day is shown in Figure 29.

The ratio of FR capability to FR requirement is shown in Figure 30 and the coincident FR supplied is summarized in Table 6.
Figure 27: Daily maximum and minimum electricity demand in 2014
Figure 28: Daily maximum and minimum VFD chiller FR capability in 2014
6.2 Results

The aggregated frequency regulation potential of chillers is highly dependent on climate. The annual FR per unit of installed capacity varies by twofold from climate zone 1 to climate zone 5 for Office Type buildings, due to the shape of the LDC (Figure 24). Chillers in colder climates spend more hours at rated or minimum capacity, where they cannot provide FR. As expected, the climate effect is much less for Hospital Type buildings, which are dominated by internal loads rather than external loads (Figure 25). The aggregated installed chiller capacity is much higher for Office Type versus Hospital Type buildings (Table 5) and higher relative to total electricity use in hotter climates versus colder climates (Table 6). Overall, the climate dependence means that chillers might be able to provide 21% of the annual FR requirement in Texas and only 2% in Minnesota (Table 6).

Table 6: Summary of VFD chiller FR potential estimates

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual FR (TWh)</td>
<td>0.18</td>
<td>0.41</td>
<td>0.47</td>
<td>0.98</td>
<td>0.91</td>
</tr>
<tr>
<td>Annual Electricity Use (TWh)</td>
<td>904</td>
<td>714</td>
<td>782</td>
<td>837</td>
<td>431</td>
</tr>
<tr>
<td>Annual FR / Annual Electricity Use</td>
<td>0.02%</td>
<td>0.06%</td>
<td>0.06%</td>
<td>0.12%</td>
<td>0.21%</td>
</tr>
<tr>
<td>Coincident FR Supplied</td>
<td>2%</td>
<td>6%</td>
<td>6%</td>
<td>12%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Analysis at finer time intervals indicates that chillers mostly provide FR during the day, when the majority of commercial buildings are operating. In hotter climates and near design days, the FR capability dips in the midday as chiller power nears maximum and flexibility is reduced (Figure 29). While Hospital Type buildings operate at night, their contribution is minimal in this scenario of total adoption; hence, the minimum FR capability for each day is near zero (Figure 30). In reality, hospitals may be one of the first building types to adopt FR due to favourable economics, to be discussed in Chapter 6.3.2.

As expected from climate effects, chillers in hotter climate zones can provide FR more consistently and for a larger portion of the year, as shown in Figure 30. However, dips in FR capability still occur on weekends and less predictably on unusually hot or cold days. Actual variations in FR capability may be less extreme due to greater diversity in chiller load profiles than accounted for in this study with only two building types. Note that maximum FR capability never exceeded the FR requirement for climate zones 1, 3, and 5. As a result, the coincidence calculation did not reduce the estimate from annual values in zones 1, 3, and 5. The same is assumed in climates zone 2 and 4, such that the coincident FR supplied in zone 2 and 4 is simply the annual chiller FR divided by the annual FR requirement, as shown in Table 6. Summing up the columns in Table 6, the estimated FR potential of commercial building VFD driven chillers in the continental US is 8% of required.
Figure 29: FR requirement and capability for a typical summer day with VFD chillers
Figure 30: Percentage of FR requirement that can be supplied by chillers in 2014

Certain parallels can be drawn between the methods used in this section and those in (Ma et al., 2013), (Olsen et al., 2013), and (Hummon et al., 2013). Specifically, the relationship between chiller power and FR capability in Equation 4 is similar to the concept of “sheddability” described in (Olsen et al., 2013). Also, the fraction of VFD driven chillers determined from CEUS could be indicative of “controllability” (Olsen et al., 2013). The parallels indicate that the results of this section may be used within the existing larger scope framework.

6.3 Discussion

6.3.1 On/Off Control Strategy

Thus far, this thesis has assumed chiller power is controlled through the continuous modulation of VFD driven compressors. The method has the advantage of not cycling compressors but is limited both in terms of modulation range and availability of VFD driven chillers. In this section, the no cycling assumption is temporarily relaxed so the potential of turning chillers on/off in aggregate to provide FR can be discussed.

Each installed MW of chiller capacity can provide a maximum of ±0.5 MW of FR capability when subjected to on/off control. However, there may not be sufficient equivalent energy storage to prevent adverse impact on occupant comfort. Using Equation 2, the equivalent energy storage (MWh) required to provide 0.5 MW of FR is calculated by taking samples using a sliding 1-hour
window over historical PJM RegD signals. The resulting distribution is shown in Figure 31. If the chiller can supply 0.2 MWh of energy storage per installed MW, the chiller should be able to satisfy almost all hours when providing 0.5 MW of FR. When 1 MW of installed capacity is turned off for one hour while the baseline cooling load is 100%, then 1 MWh of equivalent energy storage is supplied. Using the same reasoning, 0.2 MWh of energy storage will be akin to turning off 1 MW of capacity for 12 minutes on a full-load day. 12 minutes of chiller shut-down while under 100% cooling load is conveniently taken as the acceptability threshold to have no adverse impact on building operation. It is further assumed that the building operation impact is the same for a 24 minute shut-down with 50% cooling load, resulting in the same energy storage.

![Figure 31: Equivalent energy required to provide 0.5 MW of PJM RegD FR](image)

Optimal control of on/off aggregated demand resources is not trivial and is beyond the scope of this thesis. Hao et al. (2015) provides a residential perspective. For this simplified analysis, it is assumed that individual chillers run at either maximum or off, such that the aggregate chiller power use in indistinguishable from Figure 24 and Figure 25. Furthermore, it is assumed that units which are on can be turned off at any time and vice-versa. The equivalent energy storage capacity is assumed to be symmetrical, such that a building with zero cooling load can run its chiller at 100% power for 12 minutes. The result is the hourly aggregated FR capability shown in Equation 5, where all values are aggregated amounts.
Equation 5
Aggregated FR Capability

\[ \text{Rated Power} - \text{Chiller Power}, \]
\[ \text{Chiller Power}, \]
\[ \text{(Rated Power \times 0.5)} \]

Substituting Equation 5 for Equation 4 and following through the remainder of the analysis used previously for VFD driven chillers, the FR potential is found to be significantly higher. This is both due to an approximately threefold increase in available installed chiller capacity and a twofold to threefold increase in annual FR capability per MW of installed capacity. The results are summarized in Table 7. Note that the coincident FR supplied is lower than the ratio of annual FR to annual FR requirement due to oversupply during some hours (Figure 33). Coincident FR supplied for climate zones 2 and 4 are interpolated. The total estimated FR potential for all climate zones is 41% of required.

The amount of cycling necessary under on/off control is estimated by the number of times the FR signal crosses through the ±0.1 and ±0.9 bands. For example, the signal in Figure 34 crosses through the bands 16 times and 1 time, respectively. It is assumed that crossing through the ±0.1 band necessitates some chillers to turn on or off, while crossing through the ±0.9 band necessitates most chillers to turn on or off. The principle is applied to historical PJM RegD signals to obtain a distribution of cycling intervals (Figure 35). Of course, various optimization methods may be applied to distribute cycling among chillers as evenly as possible; these estimate serve as upper and lower bounds. Cycling can be reduced proportionally by reducing the FR capability.

Compressor cycling causes reduced efficiency and reduction in compressor lifetime, discussed further in Chapter 6.3.4. The effect is difficult to quantify. Hence, while the on/off control method is presented here for comparison, there are other obstacles to practical implementation.

Table 7: Summary of on/off chiller FR potential estimates. Values in italics are interpolated.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual FR, Office Type (MWh/MW)</td>
<td>580</td>
<td>609</td>
<td>939</td>
<td>1096</td>
<td>1333</td>
</tr>
<tr>
<td>Annual FR, Hospital Type (MWh/MW)</td>
<td>2187</td>
<td>2442</td>
<td>2814</td>
<td>2564</td>
<td>2143</td>
</tr>
<tr>
<td>Installed Capacity, Office Type (MW)</td>
<td>2320</td>
<td>5280</td>
<td>4493</td>
<td>5573</td>
<td>5003</td>
</tr>
<tr>
<td>Installed Capacity, Hospital Type (MW)</td>
<td>83</td>
<td>200</td>
<td>103</td>
<td>400</td>
<td>370</td>
</tr>
<tr>
<td>Annual FR (TWh)</td>
<td>1.53</td>
<td>3.70</td>
<td>4.51</td>
<td>7.13</td>
<td>7.46</td>
</tr>
<tr>
<td>Annual Electricity Use (TWh)</td>
<td>904</td>
<td>714</td>
<td>782</td>
<td>837</td>
<td>431</td>
</tr>
<tr>
<td>Annual FR / Annual Electricity Use</td>
<td>0.17%</td>
<td>0.52%</td>
<td>0.58%</td>
<td>0.85%</td>
<td>1.73%</td>
</tr>
<tr>
<td>Coincident FR Supplied</td>
<td>17%</td>
<td>45%</td>
<td>42%</td>
<td>48%</td>
<td>72%</td>
</tr>
</tbody>
</table>
Figure 32: Daily maximum and minimum on/off chiller FR capability in 2014
Figure 33: FR requirement and capability for a typical summer day with on/off chillers
Figure 34: ±10% and ±90% band crossings illustrated with RegD signal

Figure 35: Distribution of chiller cycling time
6.3.2 Economic Feasibility

The economic feasibility of using chillers for FR depends on climate, size and type of building, and system operator jurisdiction. Due to the limited amount of FR provided by commercial chillers relative to industrial facilities or power plants and the challenges of standardized implementation, FR with chillers is not a universally economical proposition.

Table 8 calculates annual revenue in a scenario where all FR provided is accepted with the price-taker assumption, and annual FR is calculated using the method in Chapter 6.1.1 and a typical meteorological year (TMY). The regulation market structure results in prices that are constantly varying. The market mechanics vary by jurisdiction and are beyond the scope of this section. For example, PJM requires symmetric FR in ±MW while ERCOT allows separate upward and downward FR. The estimated FR price used for this analysis is an average price. For PJM, the estimated FR price is based on the average price in 2013 and 2014 then further adjusted by the increase in compensation for resources following the RegD signal (Monitoring Analytics, 2015), which the chiller is assumed to do. For ERCOT, the estimated FR price is the sum of the average upward and downward FR prices (Potomac Economics, 2014).

Table 8: FR revenue estimates for various building types and locations, based on typical meteorological year (TMY) data

<table>
<thead>
<tr>
<th>Location</th>
<th>Building Type</th>
<th>Chiller Rated Power</th>
<th>Annual FR</th>
<th>Estimated FR Price</th>
<th>Annual Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore – PJM</td>
<td>Medium Office</td>
<td>110 kW</td>
<td>24 MWh</td>
<td>$77/MWh</td>
<td>$1850</td>
</tr>
<tr>
<td>Baltimore – PJM</td>
<td>Large Office</td>
<td>475 kW</td>
<td>149 MWh</td>
<td>$77/MWh</td>
<td>$11470</td>
</tr>
<tr>
<td>Baltimore – PJM</td>
<td>Hospital</td>
<td>310 kW</td>
<td>450 MWh</td>
<td>$77/MWh</td>
<td>$34650</td>
</tr>
<tr>
<td>Houston – ERCOT</td>
<td>Medium Office</td>
<td>110 kW</td>
<td>55 MWh</td>
<td>$14/MWh</td>
<td>$770</td>
</tr>
<tr>
<td>Houston – ERCOT</td>
<td>Large Office</td>
<td>490 kW</td>
<td>324 MWh</td>
<td>$14/MWh</td>
<td>$4540</td>
</tr>
<tr>
<td>Houston – ERCOT</td>
<td>Hospital</td>
<td>330 kW</td>
<td>507 MWh</td>
<td>$14/MWh</td>
<td>$7100</td>
</tr>
</tbody>
</table>

While revenues increase significantly with building size and hours of operation (e.g. hospitals), costs may not. Based on experience from the project, the marginal upfront cost per site for the Nth commercial implementation could be approximately $2000 for power metering including installation, $500 for the controller including installation, and $2500 for engineering work. The total upfront cost could be about $5000 or potentially more for sites with multiple chillers requiring separate metering or more advanced BAS control integration. Economies of scale could be difficult due to the uniqueness of commercial building systems.

Considering the upfront costs alone, most sites could achieve payback in a few years. However, operating costs may be significant for FR. An operator must submit day-ahead bids into the regulation market, which would also entail forecasting of FR capability. The operator must also accommodate maintenance or other unexpected situations for each site. These considerations reduce the number of sites a single operator can manage. If a single operator manages on average 30 sites, the annual operating cost could be about $3000, which is a significant portion of revenue.
From an economic perspective, some of the estimated chiller FR potential in small to medium buildings and colder climates may not be feasible. However, it should be noted that the use of chillers as opposed to other HVAC cooling equipment is itself biased towards larger buildings.

6.3.3 Application of FRC for Other HVAC Equipment

As part of the initial exploration for this project, a Variable Refrigerant Flow (VRF) system was tested for its potential to provide FR. The VRF consists of a single 8 ton outdoor unit\(^5\), 3 refrigerant-to-water heat exchangers\(^6\), and 1 refrigerant-to-air cassette\(^7\). The setup was used to produce chiller water using the heat exchangers and to provide airside local heating and cooling using the cassette. The power behaviour of the outdoor unit’s VFD driven compressor is observed relative to air temperature, water temperature, and air and water setpoints.

Despite the VFD driven compressor, the outdoor unit cannot be maintained at partial power. The VFD runs at close to maximum speed so long as any setpoints are not met, and shuts off immediately upon meeting all setpoints. In other words, it is possible to trip the compressor from maximum speed in steady state with a single degree adjustment in setpoint. Similar behaviour is observed at various heating or cooling load levels. The reason for the cycling behaviour on a VFD compressor is likely due to proprietary internal control sequences, to which the author does not have access.

While the estimate for chiller FR potential only accounted for chillers within commercial buildings, central chiller plants may be a particularly economical option for FR due to their size. The major North American chiller manufacturers use centrifugal machines for the largest sizes above 1000 tons, although VFDs are less commonly used due to cost for larger drives. Central chiller plants run on industrial SCADA systems, which are unlikely to have the same delay issues as some BAS networks. However, setpoints might be manually controlled by full-time operators as opposed to automated, and any inadvertent shutdowns will be more serious than for a single commercial building. In discussions with MIT Central Utility Plant staff, cyber-security was raised as a key concern for any kind of automated external control. Chiller plant operation may also be coordinated with local cogeneration, adding to control complexity.

It should be noted that the same types of chillers in commercial buildings are also used in large multi-unit residential buildings. These buildings have varied occupancy schedules and may provide more consistent FR throughout the day as opposed to only during working hours.

\(^5\) Mitsubishi City Multi PURY-P96TJMU-A  
\(^6\) Mitsubishi City Multi PWY-P36NMU-E-AU  
\(^7\) Mitsubishi City Multi PLFY-P36NBMU-ER2
6.3.4 Manufacturer Comments
Throughout the project, the author conversed informally with various chiller, compressor, and building controls manufacturers regarding issues relevant to development of the FRC and demand response in general. Some of the feedback is anonymously documented in this section. Many of the opinions were collected at the 2015 AHR Expo in Chicago.

A prominent issue that is best addressed by manufacturers is the potential impact of FR on compressor longevity. Multiple chiller/compressor manufacturers agreed that the variation of compressor speed using a VFD will not impact compressor longevity. However, it was noted that cycling compressors will negatively impact longevity, even with a VFD. Additionally, some manufacturers raised the potential issue of oil return in compressors due to constantly varying speed and refrigerant flow, particularly for “less compact units”. This issue excludes compressors that are oil free (i.e. magnetic bearings). Also, some VFD driven centrifugal chillers do not use inlet guide vanes, which potentially increases modulation range and FR capability.

The potential use of residential HVAC for FR has recently gained interest. The question of compressor cycling was also posed to manufacturers of residential unitary and split systems, which typically are not VFD driven. Opinions on the issue varied. One manufacturer considered cycling durations longer than the built-in timeouts, which are typically around 6 minutes, to be acceptable. Another opined that if cycling were increased from the typical 5 to 6 times an hour to 10 or 15 times an hour, compressor lifetime could be halved, and that there is no limit at which the compressor is not negatively affected.

BAS communication delay is another issue encountered in FRC development. One of the large controls manufacturers considered a 15 second delay, dependent on the specific configuration, to be typical for new systems. Another considered a 1 second delay to be “extremely decent”, and noted that BAS systems are not intended for response at such short intervals. Demand response using the BAS is usually done on a case-by-case basis, although manufacturers noted the use of routines that optimally shed load in response to emergency curtailment or more generally to reduce demand.

Lastly, equipment manufacturers are increasingly interested in the aggregation of their machines, for potential demand or energy management applications. At least one manufacturer has launched a public initiative (Daikin, 2015).
6.4 Conclusion

The aggregated FR potential for chillers varies greatly depending on climate and building type. There is most potential in the south, where 21% of grid FR requirements might be met with chillers on average over a year, with chiller providing near 100% of FR in certain hours. The grid in these regions can expect fairly consistent FR capability from chillers during working hours in the cooling season. The contribution of chillers to the grid FR requirements is minimal in colder climates, where chiller power use is lower relative to other demand and each unit of installed capacity provides less FR over a year.

From an economic perspective, PJM and southern states are most likely to see adoption of chillers for FR, the former due to high compensation and the latter due to favourable climate. While using an on/off control strategy can provide FR in aggregate with non-VFD driven chillers, most manufacturers agree that such operation will negatively impact compressor longevity. Given the relatively low compensation for providing FR compared to overall chiller energy use and machine cost, negative impacts on longevity and efficiency must be avoided.
7 Conclusion

FR is a necessary grid ancillary service that HVAC chillers may be well positioned to provide as a demand side resource. Commercial chillers serving the Fraunhofer building in Boston and a dormitory building at MIT were used to experimentally develop a practical closed-loop FRC that modifies chiller power demand to track regulation signals. Both FRCs used a PID control loop with Input Filter and Baseline Routines that allow robust tracking of regulation signals over long durations by accounting for changes in building cooling load.

The Fraunhofer FRC was connected directly to the chiller and controlled chiller power by adjusting CHWSP relative to CHWST. Demonstrations using standard PJM test signals show that the chiller power response exceeded market qualification requirements at AReg up to ±15 kW for both RegA and RegD regulation signals while using a single 60 kW compressor. The Fraunhofer FRC was further demonstrated to provide FR continuously for several hours while maintaining CHWST_{avg} close to CHWSP_{NOM} even as building cooling load changed significantly.

Analysis of Fraunhofer results indicates FR performance scores similar to model predictions for another building. However, minimum power and variable COP are two factors that could be incorporated into future models to more accurately reflect observed chiller transient behaviour and predict performance. When compared to other FR resources, Fraunhofer’s chiller scored higher than traditional generators but lower than batteries and HVAC fans. In terms of FR capability, the Fraunhofer chiller was constrained by CHWST, CHWSP, and minimum power limits.

The MIT FRC design differed from Fraunhofer primarily in the use of BAS based communications and control over two AHUs in addition to the chiller. Maximum AReg was ±20 kW on a chiller with three 75 kW compressors, although performance using the same PJM test signals showed considerably different results. In all cases, the MIT setup had lower performance scores.

BAS communication delays were the main contributor to lower performance scores at MIT. While control through the BAS network can be easier to set up, communication delays can be significant enough to make FR impractical. However, control of the AHUs allowed SATSP adjustment, which can be used in conjunction with CHWSP adjustment on the chiller to improve FR performance. In terms of FR capability, the MIT chiller was constrained by ramp rate limits and compressor cycling.
Overall, the flexibility and adaptability of the FRC concept to different sites has been demonstrated and key considerations for FR using chillers have been identified. Extrapolation of the results to higher level analysis indicates that chillers can contribute to the FR requirements at the grid level in aggregate, although potential varies greatly depending on climate and building type. There is most potential in the south, where 21% of grid FR requirements might be met with chillers on average over a year, with chiller providing near 100% of FR in certain hours. The grid in these regions can expect fairly consistent FR capability from chillers during working hours in the cooling season. The contribution of chillers to the grid FR requirements is minimal in colder climates, where chiller power use is lower relative to other demand and each unit of installed capacity provides less FR over a year. From an economic perspective, PJM and southern states are most likely to see adoption of chillers for FR, the former due to high compensation and the latter due to favourable climate.

Short-term power balance to achieve stability is essential for the operation of the modern electrical power system. Providing stability through modified control of existing HVAC chillers in commercial buildings is a technologically feasible alternative to existing solutions and can make a meaningful contribution to the electrical grid.
### List of Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU</td>
<td>Air handling unit</td>
</tr>
<tr>
<td>AReg</td>
<td>PJM assigned regulation capability</td>
</tr>
<tr>
<td>BAS</td>
<td>Building automation system</td>
</tr>
<tr>
<td>CHWSP</td>
<td>Chilled water supply temperature setpoint</td>
</tr>
<tr>
<td>CHWSP(_{\text{NOM}})</td>
<td>Nominal chilled water supply temperature setpoint without FR</td>
</tr>
<tr>
<td>CHWST</td>
<td>Chilled water supply temperature</td>
</tr>
<tr>
<td>CHWST(_{\text{avg}})</td>
<td>Moving average chilled water supply temperature</td>
</tr>
<tr>
<td>CHWRT</td>
<td>Chilled water return temperature</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of performance</td>
</tr>
<tr>
<td>e(_{\text{BL}})</td>
<td>Baseline Routine error input</td>
</tr>
<tr>
<td>e(_{\text{PID}})</td>
<td>PID Routine error input</td>
</tr>
<tr>
<td>FR</td>
<td>Secondary frequency regulation</td>
</tr>
<tr>
<td>FRC</td>
<td>Frequency Regulation Controller</td>
</tr>
<tr>
<td>IGV</td>
<td>Compressor inlet guide vane</td>
</tr>
<tr>
<td>K(_{D})</td>
<td>PID derivative gain</td>
</tr>
<tr>
<td>K(_{I})</td>
<td>PID integral gain</td>
</tr>
<tr>
<td>K(_{P})</td>
<td>PID proportional gain</td>
</tr>
<tr>
<td>kW(_{th})</td>
<td>Thermal kilowatts</td>
</tr>
<tr>
<td>LBV</td>
<td>Compressor load balancing valve (hot gas bypass valve)</td>
</tr>
<tr>
<td>MCP</td>
<td>Chiller onboard Master Control Panel</td>
</tr>
<tr>
<td>P(_{\text{CH,BL}})</td>
<td>Chiller baseline power</td>
</tr>
<tr>
<td>P(_{\text{CH,MEAS}})</td>
<td>Measured chiller power</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>$P_{PID,REF}$</td>
<td>PID Routine power reference input</td>
</tr>
<tr>
<td>$P_{REG,RAW}$</td>
<td>Raw regulation signal</td>
</tr>
<tr>
<td>$P_{REG,RAW,avg}$</td>
<td>Moving average of raw regulation signal</td>
</tr>
<tr>
<td>$P_{REG,FLT}$</td>
<td>Filtered regulation signal</td>
</tr>
<tr>
<td>RegA</td>
<td>PJM RegA regulation signal</td>
</tr>
<tr>
<td>RegD</td>
<td>PJM RegD regulation signal</td>
</tr>
<tr>
<td>SAT</td>
<td>Supply air temperature</td>
</tr>
<tr>
<td>SATSP</td>
<td>Supply air temperature setpoint</td>
</tr>
<tr>
<td>SATSP$_{NOM}$</td>
<td>Nominal chilled water supply temperature setpoint without FR</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable frequency drive</td>
</tr>
<tr>
<td>$u_{FRC,AHU}$</td>
<td>Frequency Regulation Controller output to air handling unit</td>
</tr>
<tr>
<td>$u_{FRC,CH}$</td>
<td>Frequency Regulation Controller output to chiller</td>
</tr>
<tr>
<td>$u_{PID}$</td>
<td>PID Routine output</td>
</tr>
</tbody>
</table>
References


KEMA. (2011). To determine the effectiveness of the AGC in controlling fast and conventional resources in the PJM frequency regulation market.


Appendix: SIMULINK Models
Fraunhofer FRC
CHWST

Baseline

SptBAS

Buffer

Mean

Transpose

BaselineCalc On-Off

Ground

Add

Baseline

StartingBaseline

Gain

AccumulatedError

ControllerErrorInput

K Ts

\( z-1 \)

\( \frac{1}{3600} \)

Discrete-Time Integrator

\( \frac{1}{3600} \)

Gain

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ControllerOutput

PID(z)

Gain

PID Controller

U = U/z

Detect Change

Saturation

Time Scope

Manual Switch

ControllerOutput

num(z)

z^2 - 2z + 1

Discrete Transfer Fcn

Error Input

Zero Crossing

Reset

C:\Users\Leo\Documents\MIT\Research\Fraunhofer FRC Record Copy\FraunChillerController.slx

printed 30-Apr-2015 21:52
Custom Ref Power

PJM-RegA-TestWave.mat
From File

PJM-RegD-TestWave.mat
From File

AGC
From Workspace

Buffer
Mean
Transpose
Subtract

Test-HistoricalSignal

NormalizedSignal

NormalizedFilteredSignal
function [Y, M, D, H, MN, S] = SysTime()
    coder.extrinsic('now');
    coder.extrinsic('datevec');
    
    Y = 0;
    M = 0;
    D = 0;
    H = 0;
    MN = 0;
    S = 0;

    [Y, M, D, H, MN, S] = datevec(now);
end
ControlSignal
ReferencePower
MeasuredPower
PID(z)
Discrete PID Controller (2DOF)
Scope
ControlSignal
1
HitToReset
Constant
Constant1

MaseehChillerController/PIDRoutine

C:\Users\Leo\Documents\MIT\Research\MIT FRC Record Copy\Main Controller - Server\MATLAB\MaseehChillerController.slx

printed 30-Apr-2015 21:58
function [Y, M, D, H, MN, S] = SysTime()
    coder.extrinsic('now');
    coder.extrinsic('datevec');
    Y = 0;
    M = 0;
    D = 0;
    H = 0;
    MN = 0;
    S = 0;
    [Y, M, D, H, MN, S] = datevec(now);
end
Unresolved Link

Analog Output (Single Sample)

Interpreted MATLAB Fcn

Interpreted MATLAB Function

Ground

Display