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Development and Application of a Digital Twin for Chiller Plant Performance Assessment

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DEVELOPMENT AND APPLICATION OF A DIGITAL TWIN FOR CHILLER PLANT PERFORMANCE ASSESSMENT

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ABSTRACT

As the complexity of industrial equipment continues to increase, the management of the individual machines and integrated operations becomes difficult without computer tools. The availability of streaming data from manufacturing floors, plant operations, and deployed fleets can be overwhelming to analyze, although it provides opportunities to improve performance. The use of dedicated monitoring systems in the plant and field to troubleshoot machinery can be integrated within a product lifecycle management (PLM) architecture to offer greater features. PLM offers virtual processes and software tools for the design, analysis, monitoring, and support of engineering systems and products. Within this paradigm, a digital twin can estimate system behavior based on the assembled physical models and the operating data for preventive maintenance efforts. PLM software can store computer-aided-design, computer-aided-engineering, advanced manufacturing, and data in cloud form for remote access. Integrating physical and performance data into a single database provides flexibility and adaptability while allowing distant commanding and health monitoring of dynamic systems.

The recent attention on global warming, and the minimization of energy consumption can be partially addressed by examining those economic sectors that use large quantities of electric power. Across the United States, heating, ventilation, and air conditioning (HVAC) systems use a collective $14 Billion of resources to control the temperature of commercial and residential spaces. A typical commercial HVAC system consists of a chiller plant, water pumps for fluid circulation, multiple heat exchangers, and forced air blowers. In this research project, a digital twin is created for a single compressor chilled water-based HVAC system using a multi-disciplinary CAE software package. The system level models are assembled to describe a 1400 ton chiller located in the East-side chiller plant on the Clemson University (Clemson, SC) campus. The dynamic models that estimate the fluid pressures, temperatures, and flow rates, as well as the electrical and mechanical power consumption, are validated against the operating data streamed through the OptiCX System.

To demonstrate the capabilities of this digital twin tool in a preventive maintenance mode, various degradations are virtually investigated in the chiller plant's components. The mechanical pump efficiency, electric pump motor friction, pipe blockage, air flow rate sensor, and the expansion valve opening were degraded by 3% to 5%, which impacted component behavior and system performance. The analysis of these predicted plant signals helped to establish preventive maintenance thresholds on these components, which should promote improved plant reliability. A digital twin provides additional flexibility than stand-alone monitoring technologies due to the capability of simulating customized scenarios for analyzing failure-prone conditions and overall equipment effectiveness (OEE). The PLM-based digital twin offers a design and prognostic platform for HVAC systems.

DEDICATION

I want to dedicate this thesis to my parents Mr. Gajanan Moreshwar Kale and Mrs. Surekha Gajanan Kale, who always encouraged me to fulfill my goals. I could not have received all of these opportunities without their constant support and love.

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First, I would like to thank Dr. John Wagner for serving as my research advisor. I appreciate his working style, caring and supportive manner, and patience with students. He encouraged me to take external courses in the PLM (Product Lifecycle Management) Center Laboratory that helped me obtain my Summer 2021 internship with Amazon in Seattle, Washington.

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I want to extend my gratitude to Matthew Holbrooks and Brian Kauer of the Clemson University Facilities Team. Mr. Holbrooks approved our idea of creating a twin for the East side chiller plant and supported it with related engineering materials. Also, he answered my questions about heat exchangers related to the chiller plant. Lastly, thanks to Optimum Energy (OptiCX) and Johnson Control Metasys (external vendors to University Facilities) for access to their software.

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NOMENCLATURE

$\dot{A}$	Mass flow rate of air (kg/s)
AC	Alternate current
AHU	Air handling unit
BOM	Bill of material
BTU	British thermal unit
CAD	Computer-aided-design
CAE	Computer-aided-engineering
CNC	Computer numeric control
COP	Coefficient of performance
Cp	Specific heat (kJ/kg·K)
DC	Direct current
DHL	Dalsey, Hillblom and Lynn
DT	Digital twin
E	Pump power
ERP	Enterprise resource planning
H_c	Refrigerant enthalpy post compressor (kJ/kg)
H_e	Refrigerant enthalpy post evaporator (kJ/kg)
HVAC	Heat, ventilation, and air-conditioning
IoT	Internet of things
$\dot{m}$	Mass flow rate (kg/sec)
N	Pump speed

NASA	National Aeronautics and Space Administration
NPD	New product development
P	Pressure (kPa)
P_c	Pressure across condenser (kPa)
P_e	Pressure across evaporator (kPa)
PLM	Product lifecycle management
PM	Preventive maintenance
PR	Purchase requisition
$\dot{Q}$	Heat flow rate (kW)
$\dot{R}$	Refrigerant mass flow rate (kg/s)
T	Temperature (°C)
T_{co}	Temperature post compressor (°C)
T_e	Temperature across evaporator (°C)
T_{pc}	Temperature post condenser (°C)
TC	Tonnage capacity (Ton)
ΔT	Temperature difference (K)
UPS	United Parcel Service
USPS	United States Postal Service
VCR	Vapor compression refrigeration
VFD	Variable frequency drive
$\dot{W}$	Chilled water mass flow rate (kg/s)
↓	Decrease

↑	Increase
~	No change

CHAPTER ONE

INTRODUCTION

This chapter provides insight into Product Lifecycle Management (PLM), Digital Twin (DT), heating, ventilation, and air-conditioning (HVAC) systems, and refrigeration cycle concepts. The applications of PLM and DT tools will be reviewed in multiple industrial and business sectors with a specific focus on the HVAC/ energy category.

1.1 Product Lifecycle Management

Product lifecycle management (PLM) is a strategy to manage a product, process, business, etc., from concept to end of life of an entity. It enables an organization and their employees to handle processes and datasets [1]. PLM solutions quickly and efficiently adapt to changing business needs, resulting in significant improvement across operations and organizational relationships [2]. This strategy can help maintain equivalent pace in physical and virtual processes, thus providing real-time tracking of the manufacturing processes and field deployments. A multi-CAD environment in the PLM toolset can provide accelerated product development by converting various engineering drawing formats into a universal database. PLM tools are advantageous as they offer enhanced capabilities for analysis and quick impact reviews to troubleshoot problems at the early stage of product development. At present, many manufacturing and service industries have started the implementation of PLM to assess and improve the utilization of their production lines and customer support.

PLM tools can be employed in a range of businesses such as e-commerce, supply chain, and logistics industries such as DHL, UPS, and USPS, etc. E-commerce industries consist of many milestones when delivering a purchased good or unit, from the vendor to the customer's destination. These milestones include different locations like vendor destinations, sorting facilities, warehouses, and final delivery stations. Coordinating the virtual logistics and physical operation of shipping parcels is a critical task to perform on a large scale. PLM tools can accomplish these tasks and others more efficiently by enabling information access at each level of product or process development along with the troubleshooting capabilities. Supply chain represents a growing application area for PLM strategy due to its complexity, exponential growth, and current failure on a global stage [3]. Decentralized information in various independent software packages associated with vendors can be unified into a single PLM tool that decreases the amount of distributed data to be processed and serves as a monotonous procedure for different vendors to receive or send raw materials [4]. Fig. 1.1 shows the presence of PLM tools at multiple stages involved in the supply chain, outsourcing, and logistics industry [5]. This tool can help reduce non-value added activities in any sector, hence reducing the cycle time [6].

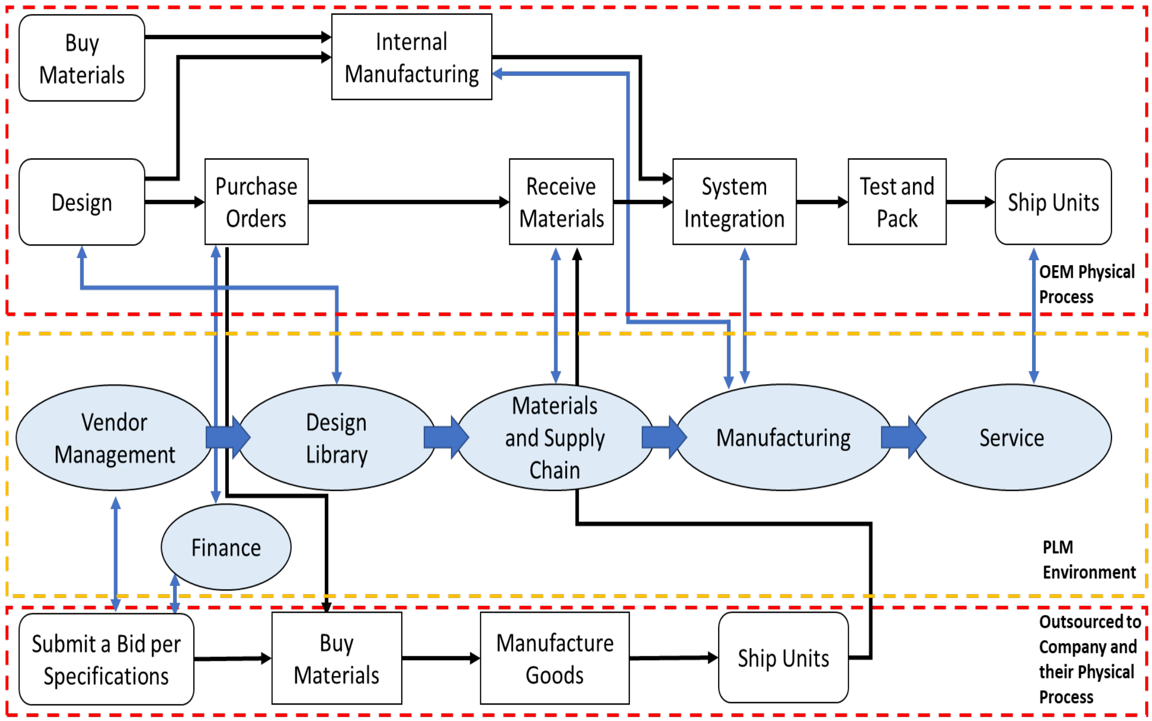


Figure 1.1: Components in PLM – supply chain, outsourcing, and logistics.

Enterprise resources planning (ERP), security of the critical database, and associated documentation remain tedious tasks across various industries – specifically for the plant utility departments responsible for equipment operation and maintenance activities. PLM tools can store and handle maintenance reports, audit reports, multiple applicable drawings, and equipment manuals through the cloud server. Also, individual permissions can be set for associates and employees to control the data access within the tool. PLM tools can seamlessly handle ERP activities such as generating purchase requisitions (PR), sending the request for bid to multiple vendors, material management, and creating the bill of material (BOM). A holistic software package is favorable as it provides flexibility by enabling remote control of the database and serves as a single-point solution.

1.2 Digital Twin

A digital twin comprises of design and engineering data of any product or a machine in a virtual form. The digital twin technology thread can be tracked back to the space program. NASA's (National Aeronautics and Space Administration) Apollo project in the 1960's pioneered the twin's idea when two exact apollo vehicles were developed to simulate the similar conditions experienced in outer space [7] [8]. This physical twin concepts extends into the digital twin to virtually simulate multiple conditions and effects for product development. A brief timeline beginning with the twin concept to the current presence of digital twin tools can be viewed in Fig. 1.2. Today's virtual twin can take input from available historical data and synthesize the design, engineering, and operational tasks to fully examine the operating scenarios. This technology enables rapid risk assessment from remote locations with the use of cloud storage for on-field data and Internet of Things (IoT) based environments.

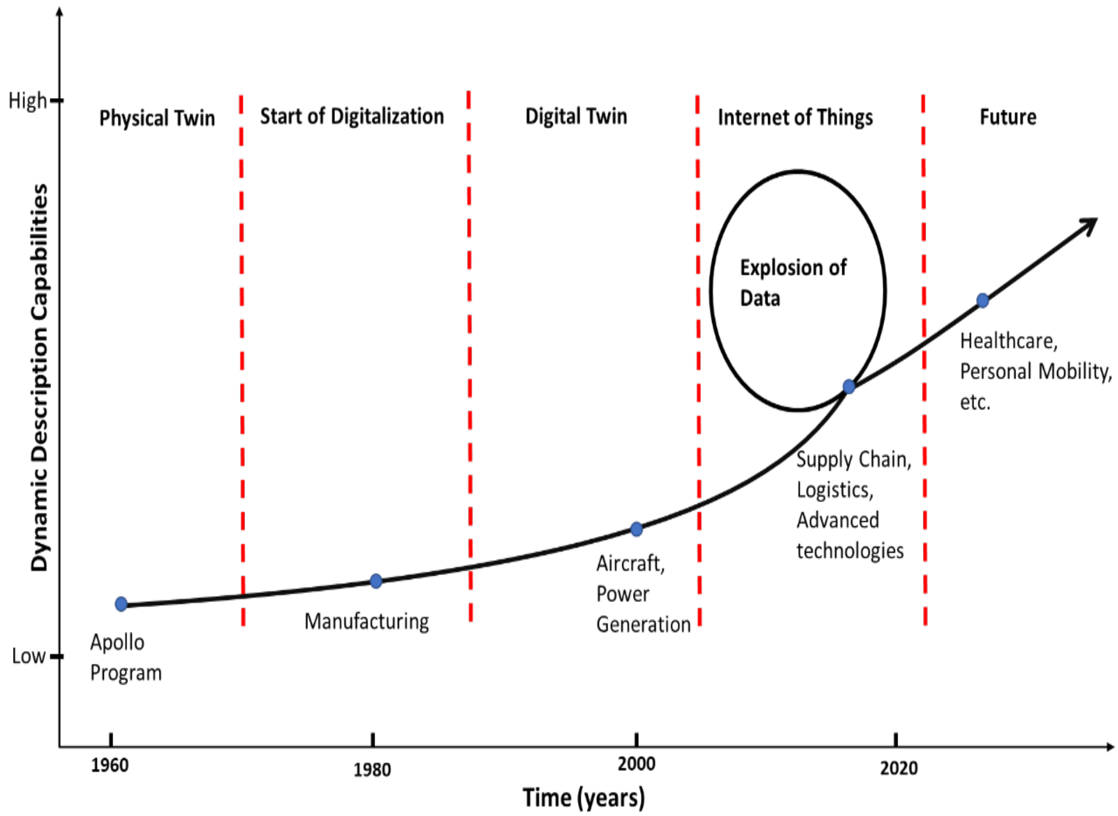


Figure 1.2: Historical development from pioneering twin concept to advanced applications using digital twin technology.

A number of industries such as aerospace, healthcare, advanced manufacturing, robotics, and energy recognize the digital twin as an important asset to improve the overall life cycle of equipment [9] [10]. In aerospace, integrated models and model-based simulations engineering can be applied for mission adaption studies and help monitor mechanical, electrical, and other structural systems for the lifecycle [11] [12] [13]. A hospital digital twin allows for the real-time tracking of patient processes and evaluation of "what if" scenarios during emergencies [14]. The utility sector generates electric power and provides water, gas, etc., used throughout society and can benefit from digital twins for health monitoring and maintenance practices. An assortment of large electromechanical and thermodynamic equipment in HVAC systems provide thermal comfort to building occupants. The continuous operation of these components can gradually deteriorate the performance, which increases the probability of abrupt shut-down. This research explores the application of digital twin tools in the HVAC industry, and specifically, in a chiller plant.

1.3 HVAC Systems

Heating, ventilation, and air-conditioning (HVAC) systems control the air temperature, mass airflow, and humidity within a confined space to maintain specified comfort levels. Ton of refrigeration (Ton) represents the capacity of any HVAC system, although other recognized units are BTUs and kWs. Systems can range from simple household air-conditioning devices of 0.8 tons (9,600 BTU/hr., 2.8 kW) to commercial more than 1400-ton chillers (16,800,000 BTU/hr., 4923.6 kW). The efficiency of any HVAC system is measured by its coefficient of performance (COP) that is the ratio of refrigeration effect to the energy input [15]. If the chiller is providing 2500 kW of refrigeration by consuming 957 kW of energy, then its COP is 2.57. Primary and secondary pumps in the chiller plant circulate chilled water and condenser water. The heat absorbed by the condenser water is rejected to the atmosphere using the cooling tower and associated fans. Fig. 1.3, and Fig. 1.4 show the chiller plant and the cooling tower structure at Clemson University located behind the Fluor Daniel Engineering Innovation Building. Also, a steam (or hot water) loop is present to warm the air (and water) temperature as needed. In a commercial complex or campus, multiple chillers are typically operated on a partial load of the total refrigeration capacity. Even if one chiller stops its operation, the other can take the heat load to provide the required buildings/ facilities cooling. Water-cooled chillers are most favorable due to their higher efficiency and longer life [16] [17].

Figure 1.3: Cooling towers behind Fluor Daniel Engineering Innovation Building at Clemson University

Figure 1.4: Chiller plant behind Fluor Daniel Engineering Innovation Building connected to cooling towers at Clemson University

A refrigerant is a two-phase fluid that flows through the chiller to extract the evaporator's heat and reject it in the condenser. Most common refrigerants are Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), and Hydrofluorocarbons (HFCs). While selecting the refrigerant for the chiller system, it is necessary to consider the application, toxicity, flammability, and critical temperature [18]. Also, the working principle of a compressor can be another selection criteria as some fluids are suitable for centrifugal and others for reciprocating compressors. Refrigerant contains gases that may harm the environment; R12 and R22 in CFCs and HCFCs significantly contribute to the depletion of the ozone layer, whereas R410A and R134 in HFCs are safer to use [19]. Hence, the environmental impact factor should be considered before selecting a refrigerant.

A chiller operates on a regular vapor compression refrigeration (VCR) cycle that comprises processes like mechanical compression, condensation, expansion, and extracting heat in the evaporator. A water-cooled chiller includes the compressor, condenser, expansion valve, and evaporator. Other than the primary components, the intercooler is present post-compressor to lower the temperature of the refrigerant. Compression can occur in multiple stages in larger systems. An accumulator is used to separate the liquid from the two-phase refrigerant, and it ensures to transport only vapor form in the compressor. The thermal expansion valve regulates the refrigerant supply to the evaporator and flashes it to a lower temperature and pressure. The selection of the chiller depends on the tonnage capacity required. Improved chillers include advanced control systems to regulate the refrigerant flow, operate the compressor, and help prevent failures.

The energy demand to produce comfortable conditions for individuals and meet requirements in manufacturing processes has been exponentially increasing over the years. The operation and service of HVAC systems in the USA costs around $14 billion annually [20]. In addition to designing better performing HVAC systems, maintaining existing systems in real optimum conditions is mandatory. the related resources can be strategically determined using advanced technologies. The PLM, digital twin technology will enable engineers to monitor complex HVAC plants efficiently and complete "what if" operating scenarios. Successful plant monitoring will lead to preventive maintenance initiatives that reduce the associated cost with major shut-down-related activities.

1.4 Organization of the Thesis

This research aims to present implementing PLM, digital twin tools in commercial HVAC systems, for health monitoring. Chapter 1 briefly introduces PLM, virtual twin concepts, and its application in multiple interdisciplinary areas. It also gives brief information about types of HVAC systems used for household and commercial purposes. It highlights the fundamental concepts of the refrigeration cycle required to understand digital twin tools' application in the HVAC or energy industry. Moreover, it gives information about refrigerants and their impact on the environment.

Chapter 2 provides insights into PLM and the digital twin in HVAC and energy industries. Also, a case study of a campus situated commercial chiller plant is presented with the specifications and operations. A single-chiller water-cooled HVAC system is developed and simulated in Simcenter Amesim^{TM}. Through the modeling and simulation, the numerical results are analyzed to show the model's outcomes.

Chapter 3 introduces the digital twin philosophy in the operation and maintenance field. The applications and advantages of virtual twins are showcased by comparison of maintenance forecasting approaches, prognosis, and diagnosis. The single-chiller HVAC plant model was investigated to determine the operating threshold in five degraded scenarios. Ideal conditions were varied by 3% and 5% to study the abnormal performance. This demonstrated the twin's capability of simulating customized scenarios and identifying performance degradations in equipment.

Chapter 4 summarizes the final remarks and findings of the simulations done post-creation of the digital twin. The future scope of developing three-dimensional real-time virtual plant models is briefly elaborated by listing potential advancements and tools to create the real twin of the chiller plant.

The appendices give essential information about the technical data used to create the digital twin model. Section A and B include on-field system data obtained from OptiCX (by Optimum Energy) for the east side chiller plant, and the chiller plant CAE model parameters, respectively. Section C describes the chiller plant architecture using multiple libraries used and an approach to assemble select configurations used in the HVAC system. Section D provides east side chiller plant related facts and information. Lastly, Section E presents the reference models from the help manual used to develop the model in Simcenter Amesim^{TM}.

CHAPTER TWO

DEVELOPMENT OF A CHILLER PLANT DIGITAL TWIN WITH APPLICATIONS TO BUILDING COOLING SYSTEMS

The heating and cooling of commercial buildings throughout the year represent an energy-intensive task with continual maintenance requirements. Chilled water can be circulated through an evaporator using a pump to cool and dehumidify the building air. The condenser in the fluid loop interacts with a secondary refrigerant loop to remove the heat, which is rejected to the ambient surroundings. To ensure proper chiller plant and HVAC system design, a digital twin can be created which virtually describes the performance of the integrated system components. In this paper, a digital twin has been created for a university chiller plant that features three loops for the refrigerant, chilled water, and building HVAC to demonstrate the utility of considering various operating scenarios and the impact of overall performance. A three-hour portion of a 24-hour operating cycle with occupant thermal loading will be considered. Representative numerical results show the variations in temperatures, pressures, and chilled water based on the indoor space heat load.

2.1 Introduction

Product Lifecycle Management (PLM) provides the engineering tools and strategies to create a virtual digital twin (DT). PLM is both a holistic process and set of software tools that can manage a product or system from concept to design to prototype to manufacture [21]. The use of rigorous processes is crucial for standardization and efficiency [22]. Across an enterprise, all staff members can work in unison for enhanced workforce performance and product design. A variety of PLM software packages exist for both engineering and business activities. PLM is a practical approach to check the feasibility and scalability of the product or system. It supports real-time simulations of G-code [23] display the tool cutting pathway and final CNC machine product. This function enables pre-assessing a newly designed product for additive manufacturing [24] to reduce operational costs associated with prototyping [25]. Once created, field deployment and servicing can be tracked and data-mined using PLM tools. It captures system-level data throughout its service life and eventual disposal [26]. The detailed operation of a product lifecycle can involve several steps, as displayed in Fig. 2.1.

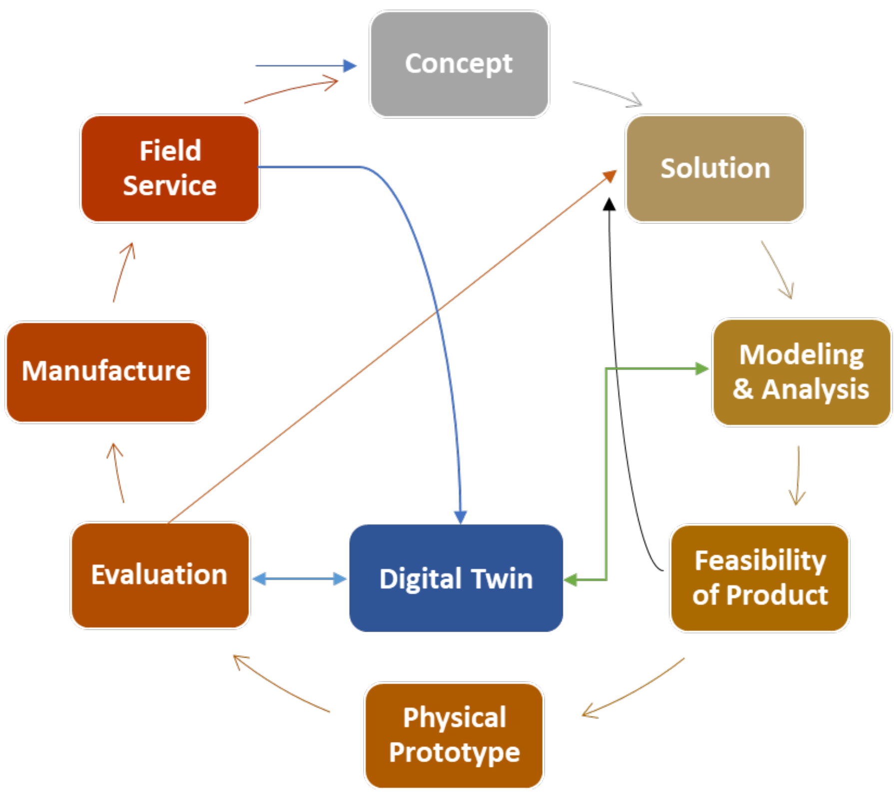


Figure 2.1: Elements in the PLM sphere that support product design, manufacture, and deployment.

PLM can support the design and digital manufacturing processes by storing and managing extensive design and engineering data. When designing a new product, the previous pathway was to build and change the product as needed. Now, computer-aided design (CAD) tools containing design data for a new product enable showcasing virtual effects of the modifications in the early stages of the product development. Virtual designs from CAD tools and engineering analysis data from computer-aided engineering (CAE) tools can lead to a digital twin that showcases different scenarios using a multiphysics platform through simulations. These DTs may also help monitor the system's performance and forecast the likelihood of a system failure. As the sensor data and operating inputs are obtained and supplied through the cloud, it can be supplied to the model and estimates generated for future operation. As the cloud hosted models and data are readily available, users can control, modify, or roll out required changes from remote locations. The adaptability and flexibility of PLM software facilitate its industry-wide acceptance.

HVAC systems are an integral part of a residential, retail, commercial, or workplace building for maintaining human comfort temperature and humidity levels under weather changes and facility demands. Commercial HVAC systems include a central plant (chillers, heat pumps,) chilled water distribution systems, and air distribution systems [27]. These systems are responsible for 10-20% of total energy consumption in building operations [28]. Initial capital investment and operational costs depend upon the tonnage capacity of the chiller plant. Based on the usage, a two-chiller 1400-ton HVAC system can have sizable expenses for its continuous operation and regular equipment maintenance [29]. The chiller compressor has the highest energy consumption in the plant, followed by primary pumps, secondary pumps, and cooling tower fans. Monitoring the HVAC system components using virtual tools like a digital twin is necessary for overall equipment effectiveness and evaluation of operation scenarios.

The research objective is to demonstrate the capability of a digital twin tool and analyze the results to validate chiller plant operations. A case study of the east side chiller plant at Clemson University will be presented. Section 2 introduces the digital twin concept. The chiller plant architecture is discussed in Section 3. Section 4 contains a case study of a university chiller plant. The paper concludes with the final remarks with the future objectives in Section 5.

2.2 Digital Twin Concept

A digital twin (DT) offers a virtual replica of any product, process, or physical system [30]. To create one, subsystem models are assembled with equivalent geometrical and engineering parameters of a physical machine [31]. As DT combines the CAD, analytical, other model, and functional architectural information from PLM software [32], they may be applied in advanced manufacturing, HVAC/ Energy, healthcare, and e-commerce, as shown in Fig. 2.2. When considering a new step in a process flow, DTs can simulate customized configurations to check the feasibility of the alternative procedure and efficacy. In the automotive sector, ongoing efforts to create a digital twin can enable in-advance alerts to customers for periodic vehicle maintenance based on the historical analysis of operating data. In HVAC systems, users can simulate plant operation to ensure optimum performance.

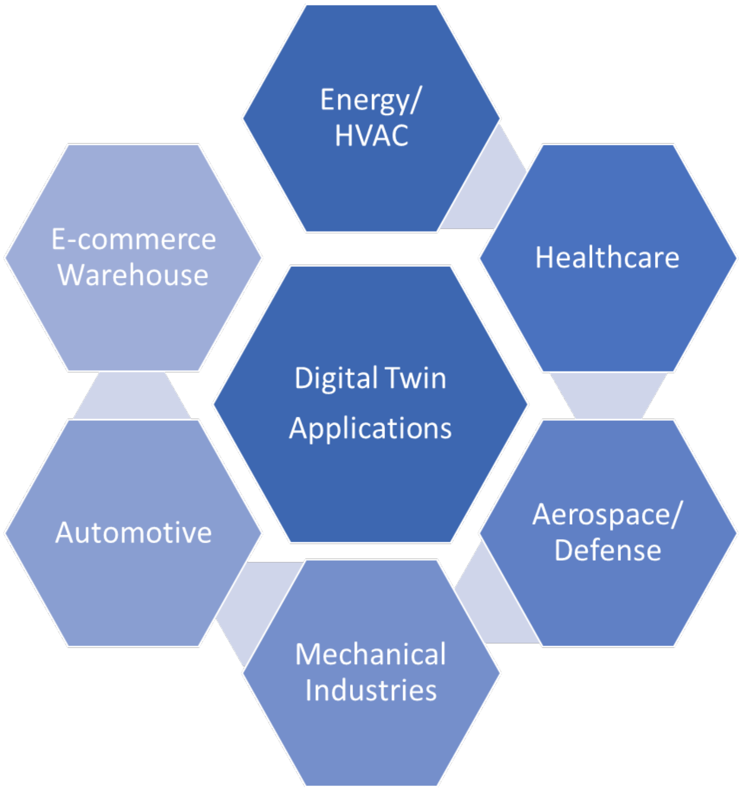


Figure 2.2: Applications of digital twin technology across various business sectors.

In the Industry 4.0 era, the digital twin provides flexibility when designing a new product or evaluating the performance of an existing product. There are three types of digital twins –

1. Product,
2. Production, and
3. Performance.

Fig. 2.3 shows a process and application of product and production digital twin. Employing digital twins in the industry can eliminate the iterative process of testing sample products in new product development (NPD). Performance twins can map the live system data and help in the health monitoring of the system. To ensure optimum performance and check for failure modes, DTs can simulate scenarios based on different parameters supplied. A Real-time internet stream of the field data can enhance the usability of DTs by providing a real-time internet stream of the field data from the physical system.

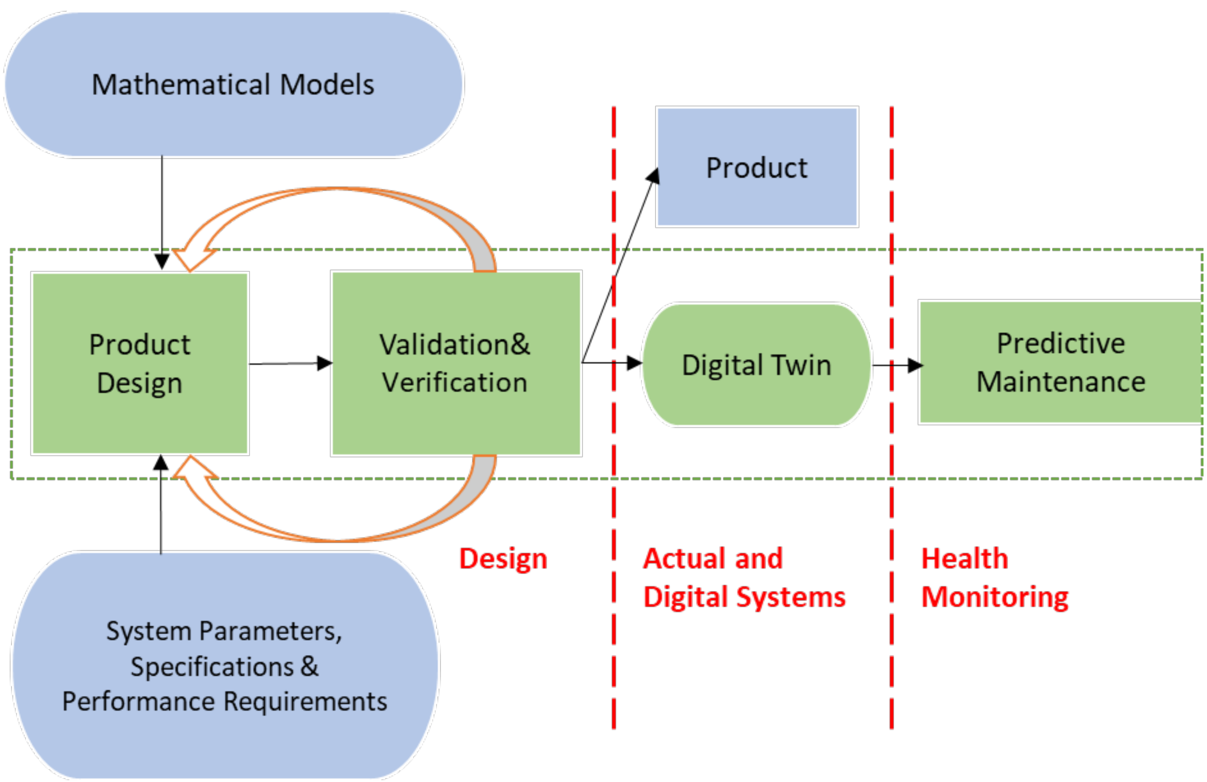


Figure 2.3: Configuration of a digital twin to support predictive maintenance.

Implementation of constructive methodology leads to the creation of a successful performance DT. The most straightforward approach in creating one is to select a specific component from a complex system. The assembled models can be validated using available field data and operating engineering/ science principles.

DT offers flexibility by simulating required physical processes and testing procedures on a virtual model when evaluating new product feasibility. It is easier when considering several iterations of the product designs or re-designs and their manufacturing feasibilities. Post provision of different inputs to the system, DTs help in obtaining maintenance estimates through simulation. Performance DTs are helpful for health monitoring that leads to the recommendation and scheduling of predictive maintenance of the plant or system.

2.3 Chiller Plant Architecture

The chiller plant is a centralized facility system that provides cooling for multiple classrooms, residential halls, and office buildings on the given campus. Chiller plants may be broadly classified based on the condenser type – water-cooled, air-cooled, and evaporative [33]. Among them, the most efficient water-cooled chiller plants are used worldwide for commercial applications. Water-cooled chiller plants typically consist of four loops –

(1) Building Side (HVAC) Air Loop,

(2) Chilled Water Loop,

(3) Chiller Loop, and

(4) Condenser Water Loop

as shown in Fig. 2.4. A typical water-cooled chiller plant includes water pumps, compressors, condensers, expansion valve and evaporators, and cooling tower. Electric motors with variable frequency drives (VFD) power the rotary equipment (compressors, water pumps, blowers) to better match speed with load for energy saving. In practice, more than one chiller is often installed and operational in the plant.

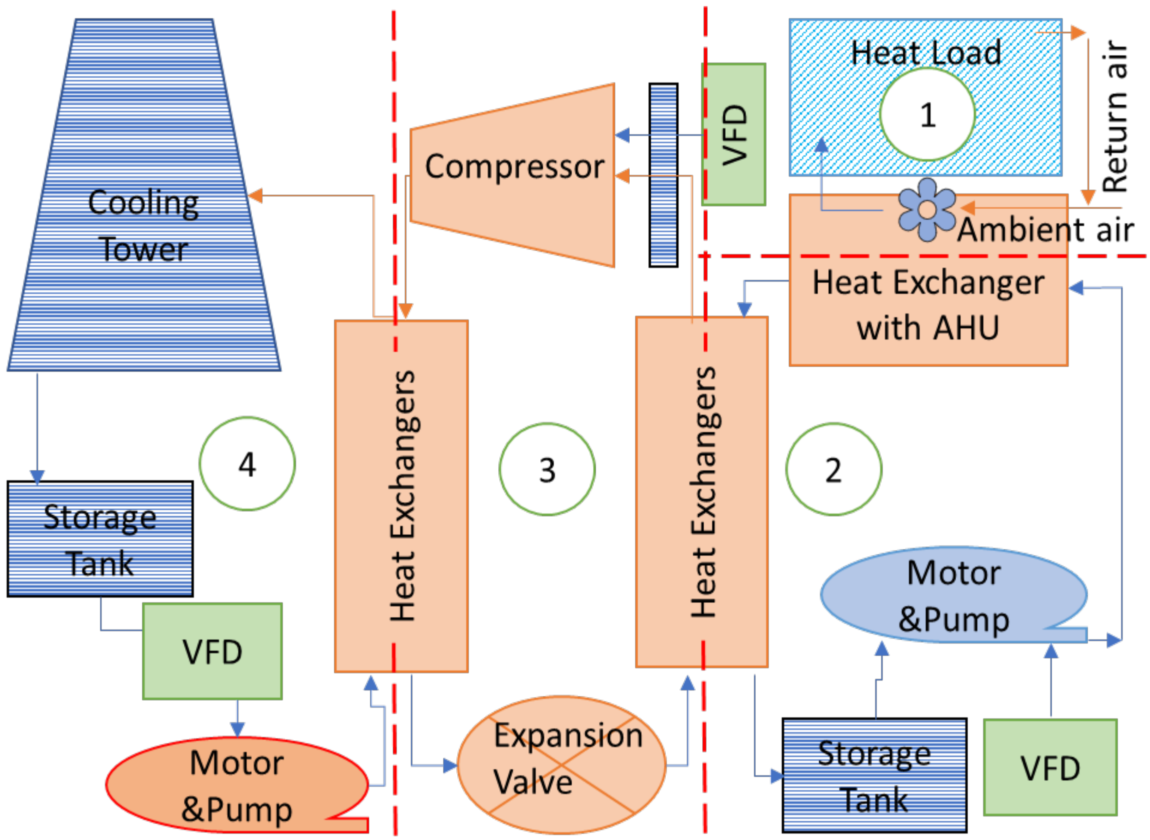


Figure 2.4: High level layout of the water-cooled chiller plant.

The basis of most refrigeration systems used for building cooling is the vapor compression refrigeration (VCR) cycle. These systems consist of four main components: compressor (electric motor driven), condenser, expansion valve, and evaporator. The liquid refrigerant is used as a flow medium and circulated in the system. Refrigerant (low pressure, low temperature) absorbs heat in the evaporator, and then travels as a gas to the compressor. After mechanical compression, the refrigerant in vapor form (high pressure, high temperature) rejects heat to the condenser. Post condenser, the refrigerant flashes in the expansion valve and is supplied to the evaporator in the liquid form, as a cold, low pressure liquid. Hence, the refrigeration process may be called the two-phase. Fig. 2.5 presents the pressure-enthalpy chart for an ideal VCR cycle. According to the application requirements and environmental impact, other refrigerants (e.g., R123, R414) are available for use in these cooling systems.

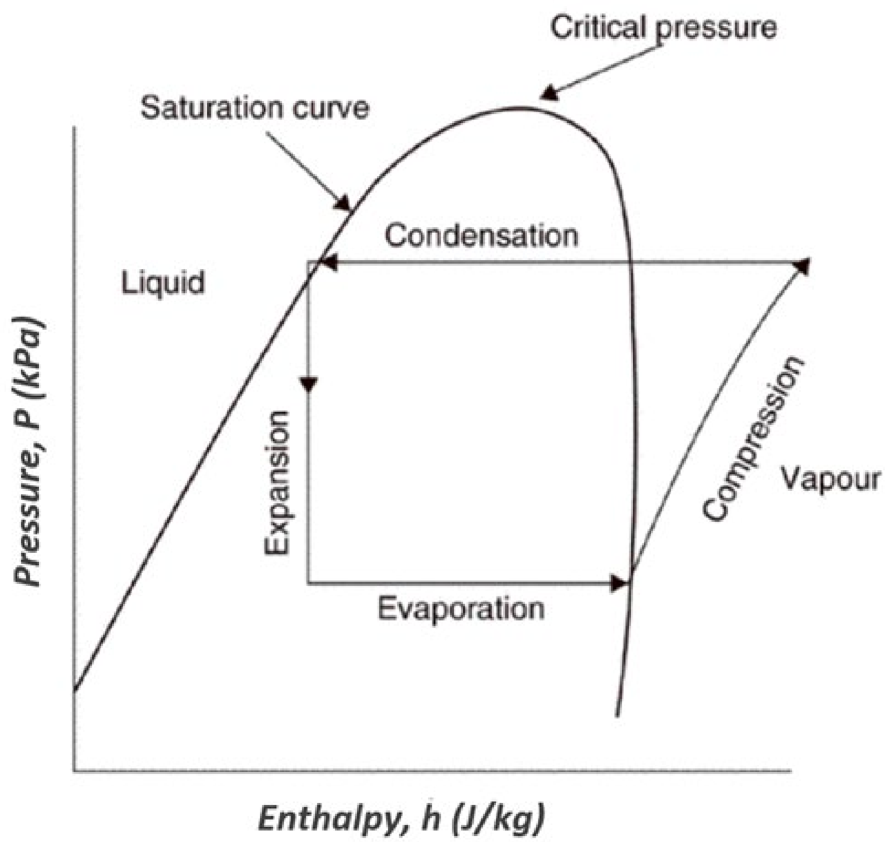


Figure 2.5: Vapor compression refrigeration (VCR) cycle - pressure - enthalpy diagram [34].

The heat extracted in the evaporator of the chiller provides a performance benchmark for heat removal $\dot{Q} = \dot{m}Cp\Delta T$ and the tonnage capacity of the chiller, $TC =$

$0.2843\dot{Q}$ [35]. The four cycles in the water-cooled chiller plant are interdependent and operate continually. Incoming ambient air rejects heat to the chilled water loop through the air handling unit (AHU) in Loop 1. For this study, approximately 15% of return air (from the building) is re-supplied to the AHU and provided to the building post mixing with fresh ambient air. Post that, a blower circulates this cooled air in the building. In Loop 2, chilled water rejects the heat gained from the AHU to the tube/shell evaporator of the chiller loop. The refrigerant in the chiller loop (Loop 3) discharges heat in the tube/shell condenser to the condenser water. Condenser water (Loop 4) gains heat from the refrigerant and ultimately rejects to the atmosphere with the help of a cooling tower and associated fans or other heat sink.

2.4 Case Study: Clemson University East Side Chiller Plant

Clemson University has three campus water-cooled chiller plants to accommodate the overall HVAC demands. Among those, the east side chiller plant has two chillers with a capacity of 1400 tons each. Two 200 HP, 4-pole centrifugal pumps circulate chilled water to the buildings on the given campus loop (Loop 2). Two 100 HP, 4-pole centrifugal water pumps transport condenser water to the cooling towers (Loop 4). The cooling towers have two 50 HP, 4-pole fans that help to exert the heat gained by the condenser water and reject to the ambient air. In some instances, a temperature sink, such as cold lake water, can be applied to remove this condenser heat. VFD units are attached to the electrical motors to regulate their speed according to the demand. VFDs help in optimizing the power consumption of the compressors, pumps, and fans. Clemson University Facilities controls all of the operation and maintenance activities related to the campus plants. Fig. 2.6 shows the user interface of the OptiCX platform (by Optimum Energy) that monitors the system-level data and notifies about oddities or errors for the plant. Johnson Control Metasys monitors the building side air data associated with the HVAC system.

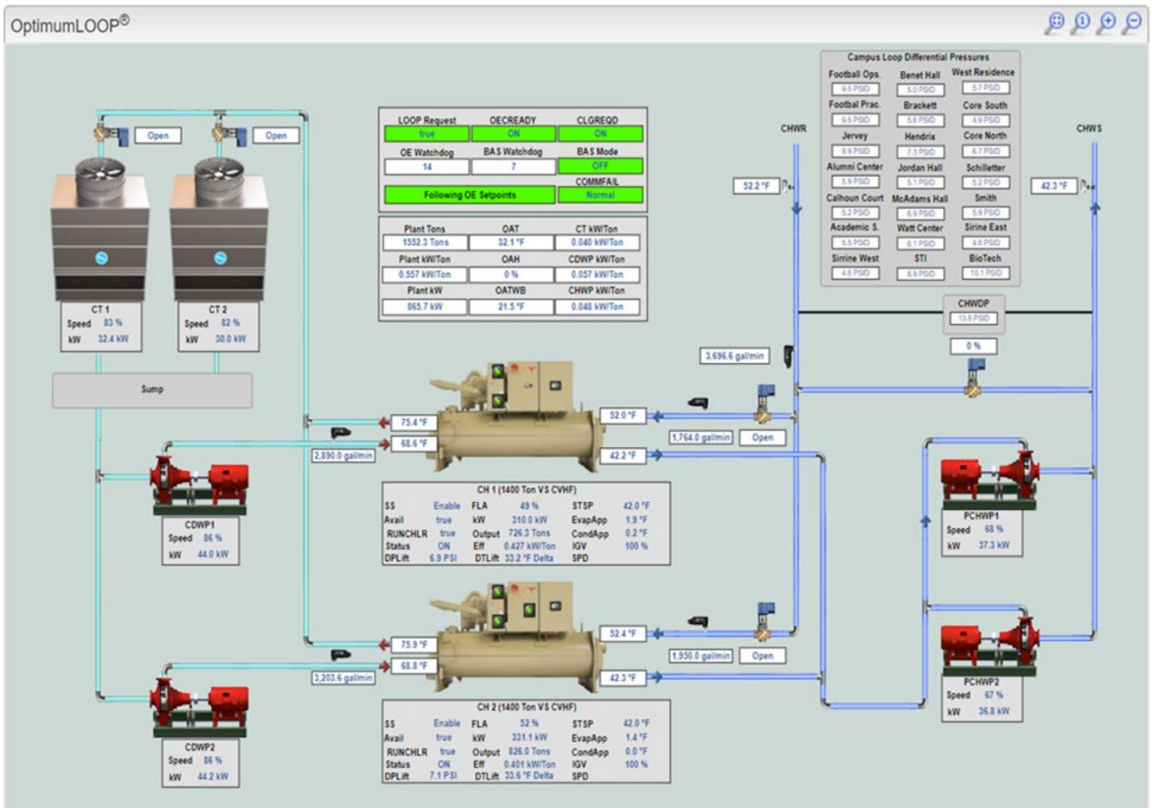


Figure 2.6: East side chiller plant use OptiCX monitoring interface.

For the case study, a water-cooled chiller plant with a single chiller is created and simulated for 24 hours on a typical summer day. The variable ambient temperature is given with a low of 16.8°C and a high of 32.5°C. The target temperature and relative humidity as per the human comfort level is 22°C and 40%, respectively [36]. A variable heat load is given per the day conditions with the highest heat load of 19.58 kW, including a constant equipment heat load of 2.2 kW. The paper includes a systematic study of three loops, i.e., chiller loop, chilled water loop, and building side HVAC loop. A constant temperature heat sink is assumed for the condenser water loop as it is an open loop that interacts with the atmosphere.

2.4.1 Digital Twin Configuration

Simcenter Amesim^{TM} is a multiphysics simulation tool developed by Siemens that can be applied to create a performance digital twin. It includes various libraries that users can directly import to construct a virtual model of any physical system. The water-cooled chiller plant model primarily uses thermal, pneumatic, thermo-hydraulic, hydraulic, two-phase, refrigeration, electric, and control signal libraries. A one-dimensional plant model is assembled and configured according to desired parameters using the libraries. Among the libraries, specific components are combined to develop the interconnected plant loops. This tool can be integrated with other CAD and CAE software to create a real virtual reality (VR) DT. Real-time sensor data (captured from operational machines) enables a successful health monitoring of any system with the help of this software. Simcenter AmesimTM can help in system-level health monitoring and optimization and thus serves as an industry-leading software tool for digital twin.

The building side HVAC Loop (Loop 1) is a combination of components from the thermal and signal-control library. The signal-control library consists of various types of staged signals, transmitters, receivers, and control circuit components like PID control. The ambient atmosphere component supplies the temperature and location data. A constant signal provides the pressure and relative humidity. A variable staged signal provides the dynamic heat load to the room of 600 m^3 volume. The return loop re-supplies the return air

(15% of total air) to the AHU for recirculation. The control circuit uses a PI control with back-calculation and tracking for optimum control. A control signal (D) supplies the targeted temperature to the positive input node, and signal T gives the feedback temperature to the negative node of the PI controller. The controller then delivers a variable frequency between 30Hz to 60Hz using signal C, which ultimately regulates the rotary speed of the centrifugal pump used in Loop 2.

As shown in Fig. 2.7, the chilled water loop (Loop 2) consists of a centrifugal pump with VFD and heat exchangers. Components from the electric, signal-control, and mechanical libraries form the VFD. The 3-phase induction motor and voltage sources are imported from the electric library. The induction motor is a 4-pole motor that delivers rotary speeds up to 1800 RPM at 60 Hz. Depending on the PI controller's output signal, the rotary speed can vary between 900 to 1800 RPM to obtain the desired chilled water flow rate. Additionally, the butterfly valve with a control signal helps to adjust the flow rate, if needed. Signal transmitters and receivers from the control signal library give corrected input to the motor. Sensors provided before and after the heat exchanger monitor the water temperature and pressure.

Components from the two-phase library formulate the chiller loop (Loop 3.) A simplified VFD circuit drives the induction motor that drives the compressor. A 1:3.5 ratio gearbox attached to the motor delivers the required speed to the compressor to circulate the refrigerant R134a. The condenser cools the refrigerant down by rejecting heat to the condenser water (Loop 4.) Post expansion valve, as the temperature further lowers, R134a changes to the liquid form. The refrigerant flows through the evaporator tubes and absorbs the heat from chilled water (Loop 2), and becomes a vapor. Sensors monitor the refrigerant condition (temperature, pressure) at each stage.

For the condenser water loop (Loop 4,) a heat sink with a constant temperature of 18°C is assumed to extract the heat from the refrigerant and supply it to the atmosphere. The condenser water loop serves as an open loop in the chiller plant.

The graphical data presented below is taken with the help of sensors attached to the repspective loops. The sensors, denoted by P, T, Q can be seen in the Figure 2.7 give pressure, temperature, flow rate data. For the compressor speed data, mechanical power sensor (P) is utilized. Some more details of these sensor components can be seen in Appendix C of this document.

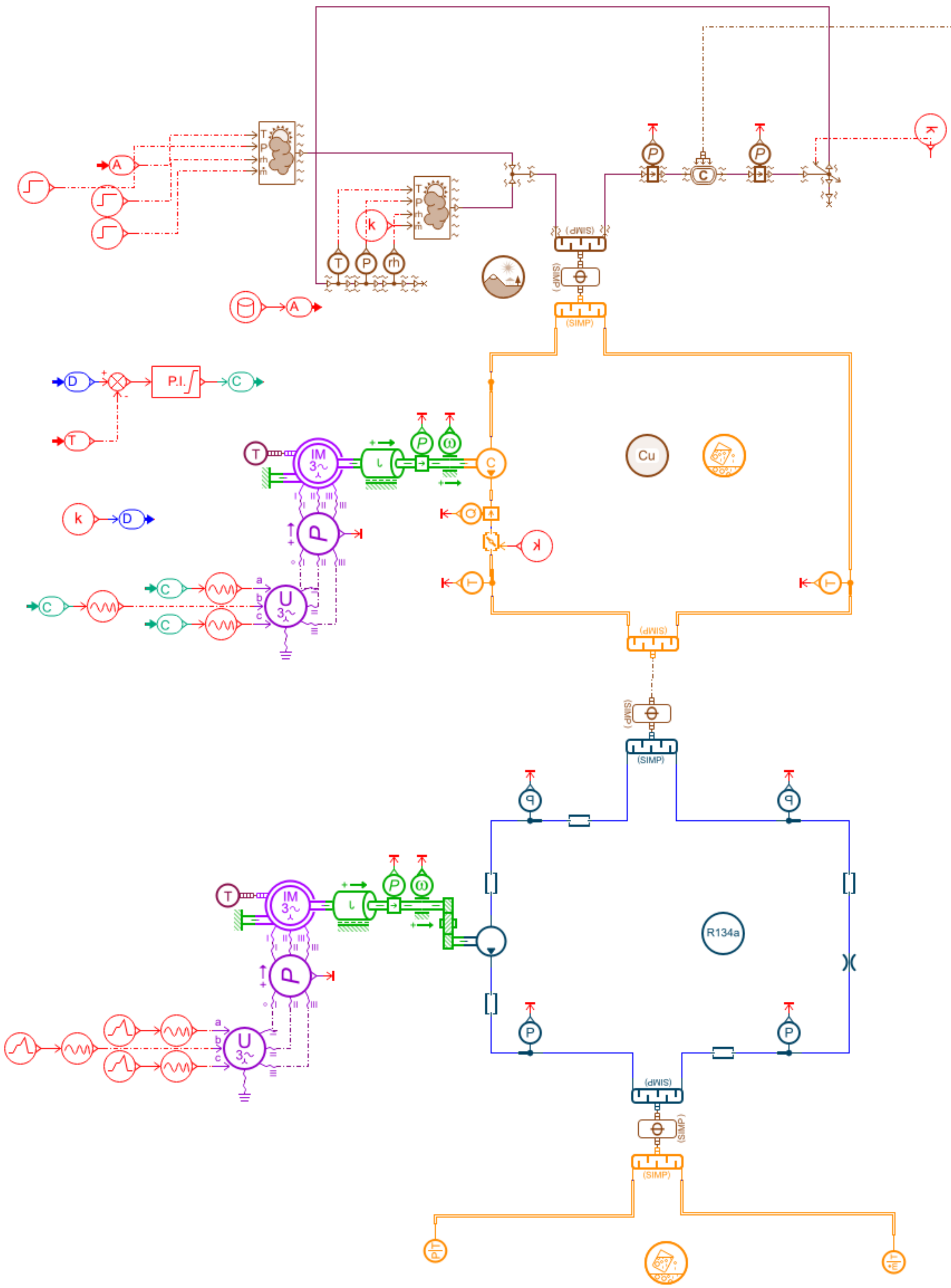


Figure 2.7: CAE model of the chiller plant with Loop 1-3 and heat sink for Loop 4.

2.4.2 Numerical Results

The computer study considered the HVAC system operation over a 24-hour time period. In this paper, the results of the morning cycle, 08:00 to 11:00 hrs., will be presented with a transient heat load applied at 10:00-10:30 hrs which could be attributed to a large group of individuals entering the classroom space. For the chiller (Loop 3), the pressure range on the condenser and evaporator exit was 741.96 to 755.08 kPa, and 26.98 to 119.81 kPa, as shown in Fig. 2.8. Across the evaporator, the fluid temperature experienced a variation between -7.49 °C and -20.77 °C while absorbing heat. Post compression, the refrigerant was supplied to the condenser at a maximum temperature of 43.09 °C. After rejecting heat across the condenser, the temperature reduced to 33.75 °C; the ambient temperature was 25 °C. Then, it flashed in the expansion valve, reducing the temperature further down to -20.77 °C, entering the evaporator in the liquid phase. A sudden drop post 10:00 hrs. was observed in pressure and temperature readings as the dynamic heat load increases to 19.58 kW.

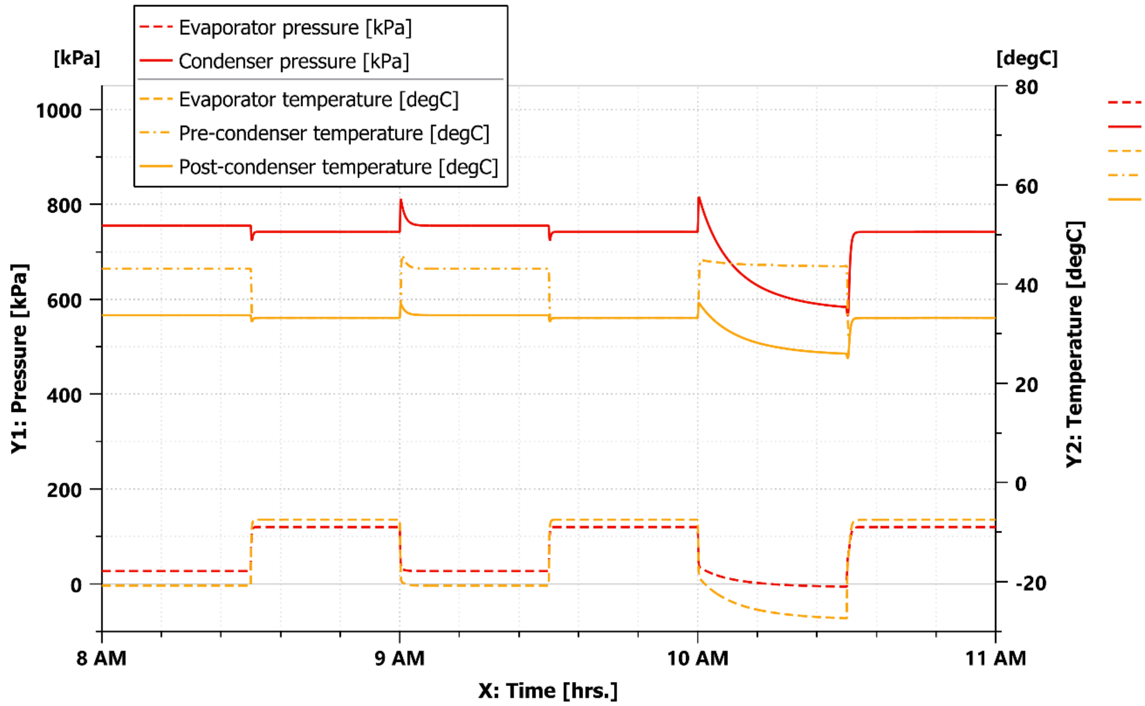
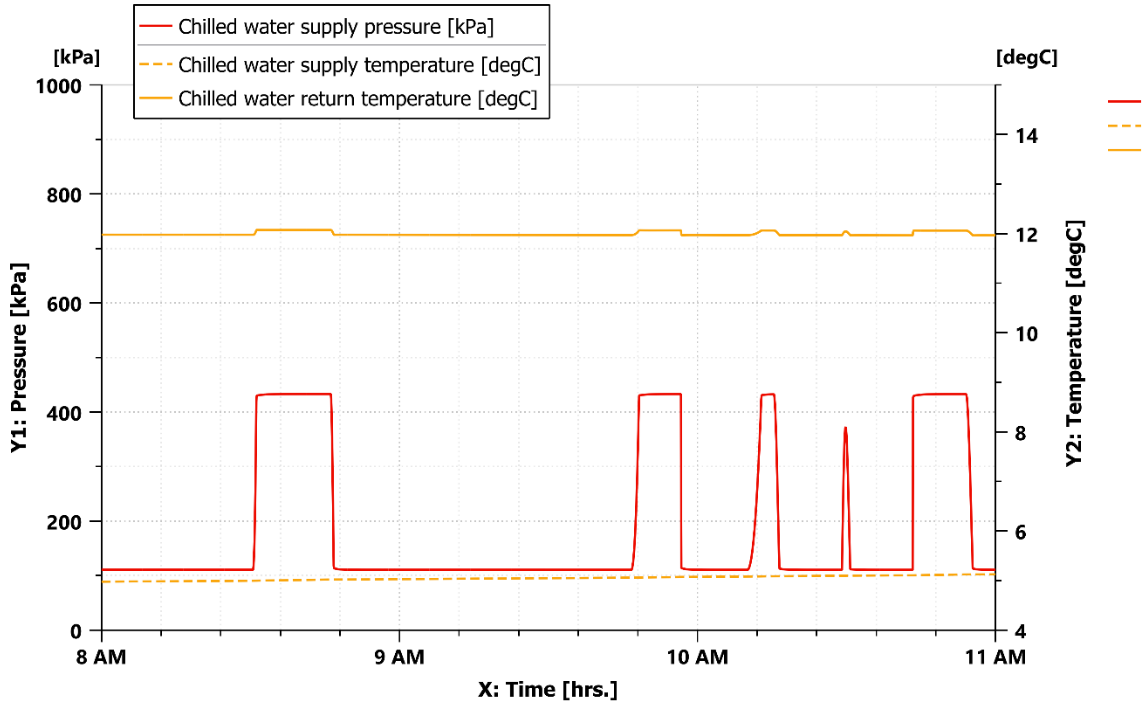


Figure 2.8: Normal operation of the chiller loop with refrigerant R134a (Loop 3) over a three hours time period – pressure and temperature.

Fig. 2.9 (a) shows the pressure and temperature of the chilled water loop (Loop 2). The pump circulated water at a maximum of 424.52 kPa, and post rejecting heat to the chiller loop, it cooled down to 4.44 °C. At the maximum capacity, the chilled water flow rate was 0.18 m^3/s at 1759 RPM, as shown in Fig. 2.9 (b). Depending on the heat load, as the room temperature increases or decreases, the PI controller adjusts the pump's output frequency, ultimately controlling the chilled water flow rate. A constant variation can be seen from 10:00 to 11:00 hrs. as the heat load frequently varied in that period. The estimated centrifugal pump speed and water flow rate closely match the actual flow rate value provided by the OptiCX on-field sensor data in the Clemson University chiller plant. Also, the tonnage capacity of this modeled chiller, at the maximum flow rate, was 1493.83 Ton.



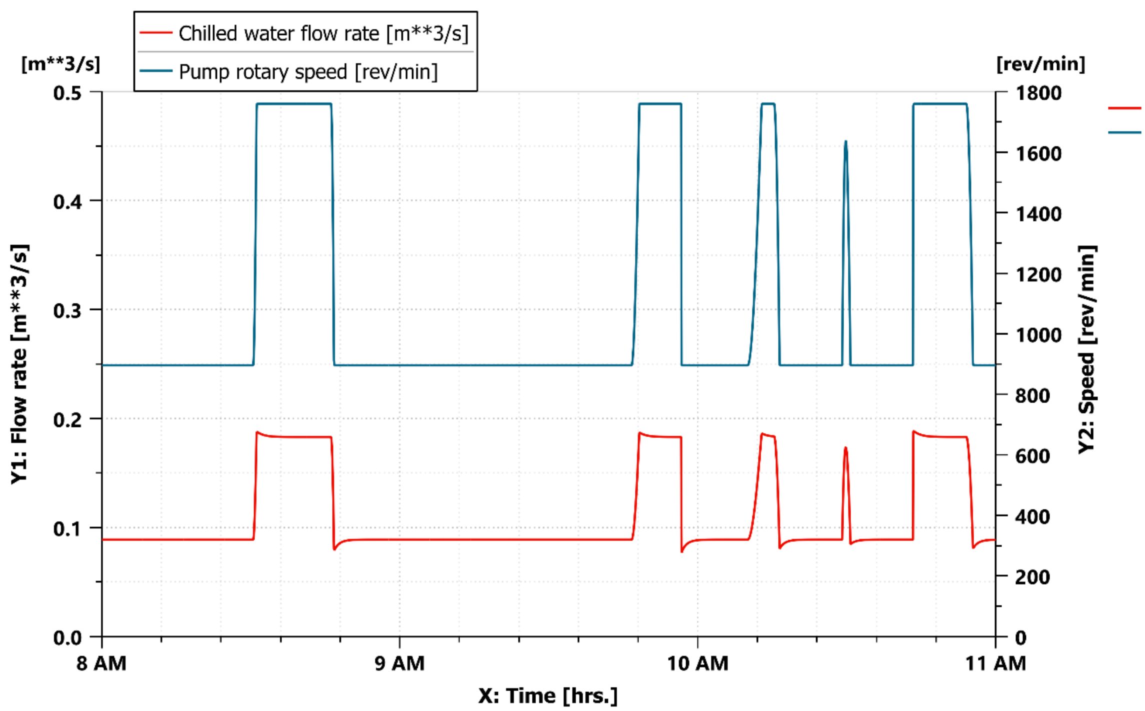


Figure 2.9: Normal operation over three hours monitoring time period for chilled water in Loop 2 – (a) pressure and temperature, and (b) centrifugal pump flow rate and speed.

The room heat load and temperature variations in the building side HVAC loop (Loop 1) can be viewed in Fig. 2.10. The temperature varied from 21.8 °C to 23.05 °C depending on the heat load that ranged from 4.56 kW to 19.58 kW during the morning hours. The relative humidity varies between 30% to 40%. The temperature set point was 20 °C with a disturbance of 30% due to the applied thermal load.

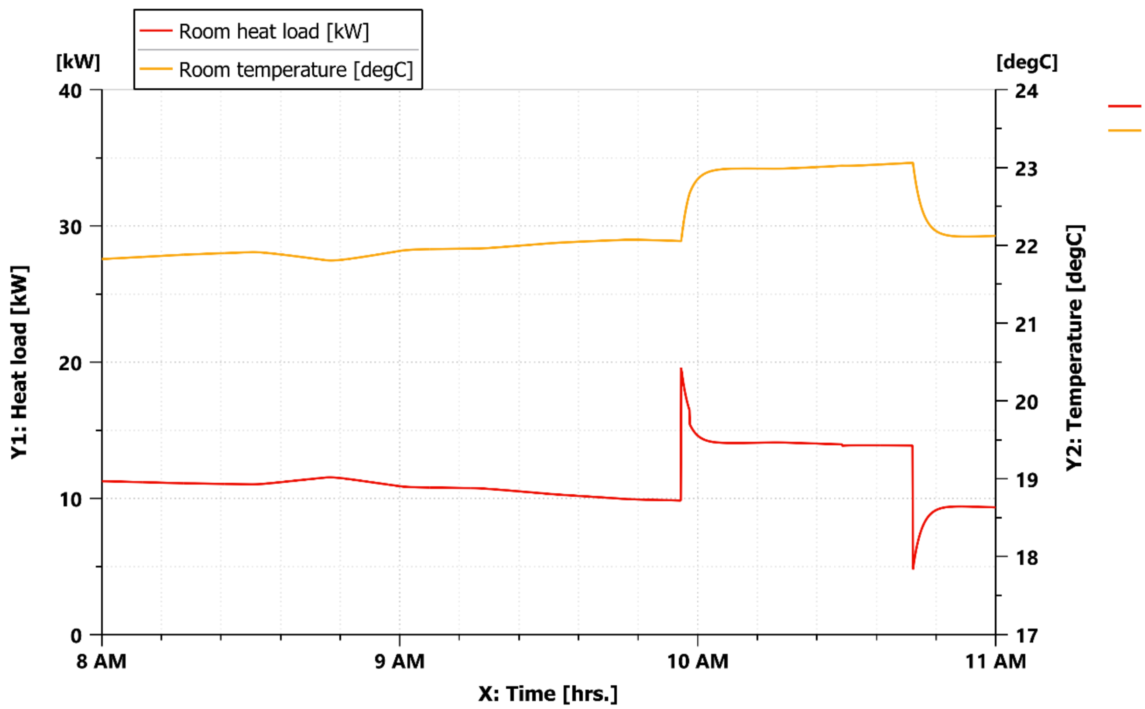


Figure 2.10: Normal operation for HVAC building room (Loop 1) over a three hours time period – heat load and room temperature

2.5 Summary

A digital twin model has been created for a university chiller plant with building HVAC system. Operational data for the east side plant was applied to validate the computer tool. The numerical results offered a good approximation. The chiller loop (Loop 3) in the model has fulfilled all the basic principles of a refrigeration cycle. The chilled water loop (Loop 2) shows convincing results for the pressure and temperature of the water. Classical control for varying the frequency and the flow rate based on heat load demand was successful. Dynamic room temperature variation matches the heat load variation in the building side air loop (Loop 1). Future objectives include creating a complex layout, as shown in OptiCX, with two chillers and associated VFDs in the loops and coupling system health monitoring.

CHAPTER THREE

MAINTENANCE FORECASTING OF A CHILLER PLANT USING DIGITAL TWIN

The availability of a digital twin for a physical product or process can be used in design studies, field support, and failure analysis. The consideration of different operating scenarios with degraded components in the digital twin enables the exploration of prognostics and diagnostics settings in a controlled virtual environment. In this paper, a digital twin of a single chiller HVAC system with variable frequency drives, fans, and pumps has been created to evaluate performance degradations of specific components. A 1493-ton chiller plant with a chilled water loop and heat exchangers provides building comfort. Small degradations of 3% to 5% are virtually introduced into system components to observe their impact and to help establish monitoring thresholds. A case study considers five anomalies in the electric motors, chilled water line, sensors, and expansion valve with estimated performance deterioration revealed. The impact on the system was 3.75% to 15.84%, with recommendations to set operating limits on the thresholds in the preventive maintenance method.

3.1 Introduction

A digital twin, an improvement of PLM tools, is a dynamic digital representation of a physical process or system in a virtual form [37]. The virtual twin model comprises the operational equipment, the virtual object, and the flow of sensor data among the functional and virtual models [38]. A digital twin can predict the machine's status without physically interrupting the operation through simulations [39]. Also, the virtual twin can be modified to reflect the changes in the replaced parts with different capacities. Aerospace and automobile industries actively use the digital twin concept for health monitoring and maintenance purposes [40] [41]. Digital twin generates data that is helpful for future operation and maintenance conditions [42]. When combined with the stored historical data in cloud form, the model can train several graduate associates and engineers to examine a specific historical scenario through simulations.

The digital twin strategy is advantageous in the preventive maintenance of operational components in HVAC systems. Fig. 3.1 shows the interactions of chiller plant components with the digital twin to estimate performance and forecast maintenance schedules. The feedback sensor data and operational conditions provide parameters to the chiller plant components to get the desired output. Users can supply similar parameters to the virtual plant model to validate its performance with the physical plant. Moreover, digital twin tools can estimate the performance and effectiveness of the equipment when provided with specific scenarios. Also, they help analyze the sensor data provided by the physical system and report if any error is detected based on simulation from digital twin tools. Post identification of deviation in simulations, employing reverse engineering tactics to detect the failure of individual components will lead to successful scheduling of predictive maintenance.

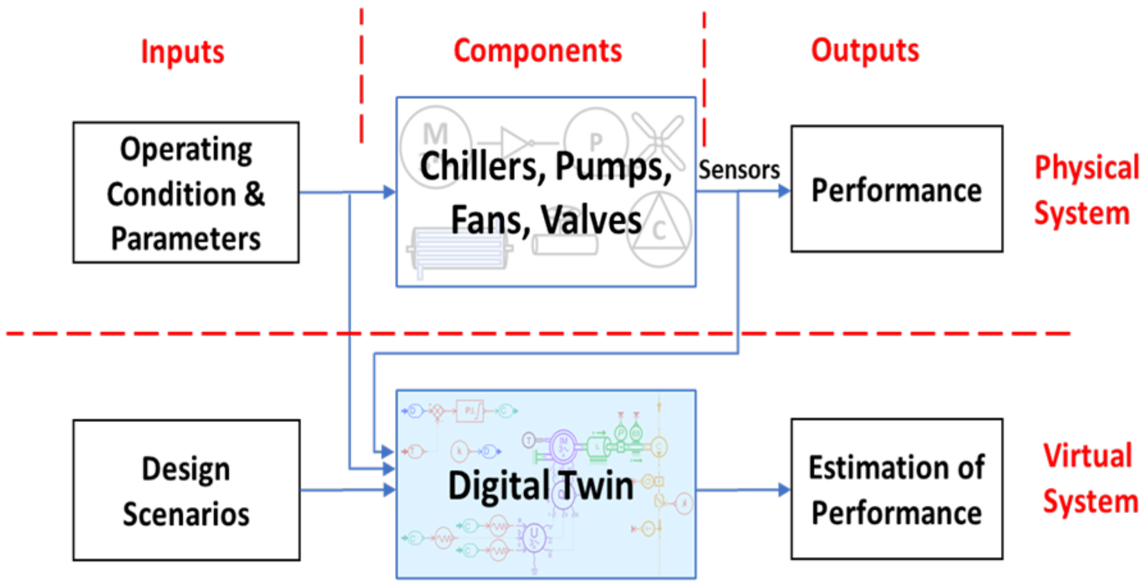


Figure 3.1: Interactions of chiller plant (components, sensors) and digital twin to estimate performance.

In a water-cooled HVAC system, primary maintenance activities involve the compressors, pumps, motors, fans, control systems, heat exchangers, and piping systems, as shown in Fig. 3.2. The rotary components are in continuous operation based on the heat load, and they consume a significant amount of electrical energy compared to other parts [43]. In addition, friction effects will generate heat requiring constant lubrication. Hence, it is necessary to inspect and maintain them to ensure their optimum operation as they provide the required flow rate of air, water, and refrigerant in their respective loops. Also, control systems need calibration to ensure correct output to the equipment [44]. The heat exchangers reject thermal energy to the water/refrigerant and air in the respective loops and must work efficiently. Real-time system monitoring can improve the operating performance of mechanical equipment [45].

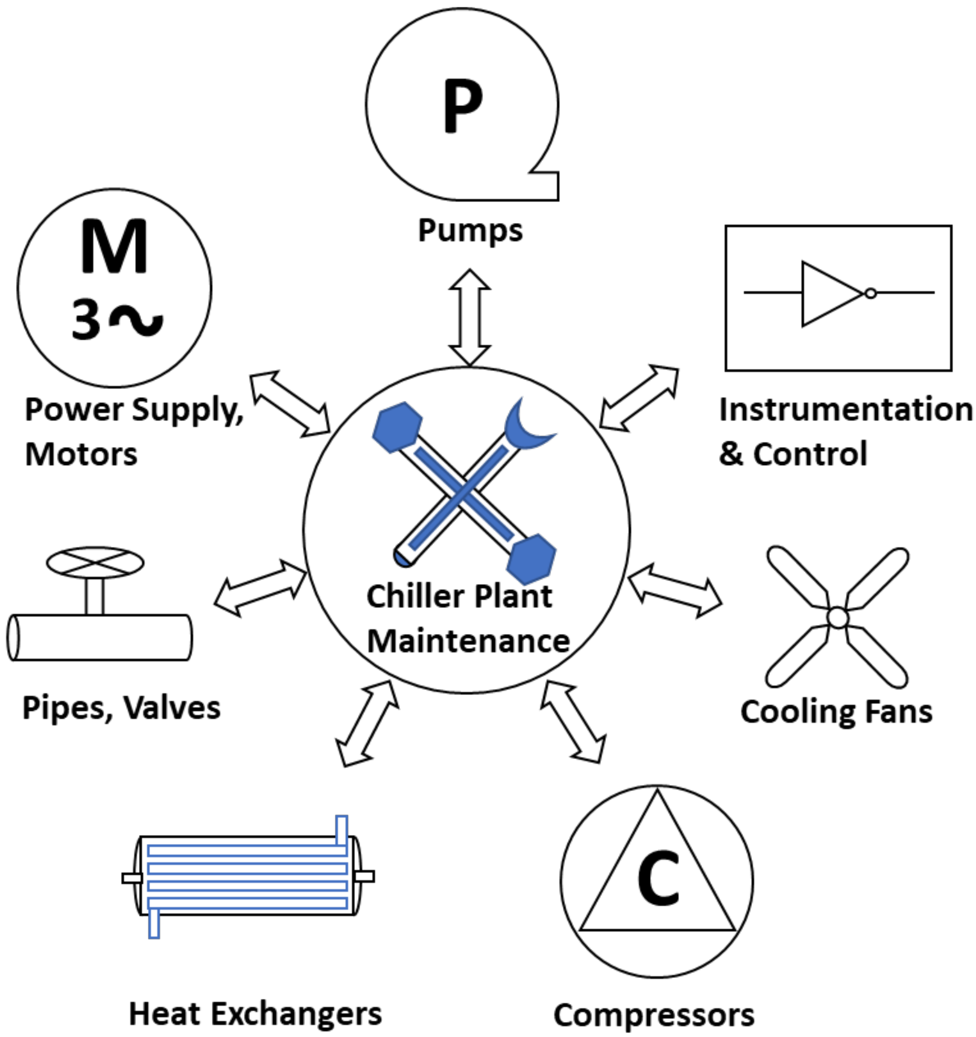


Figure 3.2: Monitoring of primary components in a chiller plant preventive maintenance strategy.

This research demonstrates a preventive maintenance approach using a digital twin tool to forecast threshold limits and eventually maintenance schedules. The remainder of the paper is organized as follows. Maintenance forecasting approaches and a digital twin are discussed in Section 2. The operation of HVAC systems and the computer-aided engineering (CAE) model are presented in Section 3. Section 4 offers a case study with five component degradations to help establish error-bound conditions. Section 5 provides final remarks on the capabilities of digital twin tools in the predictive maintenance field.

3.2 Maintenance Forecasting Approach

Operation and maintenance include regular monitoring of systems and servicing or troubleshooting the machines (if required.) The facility or utility department is the critical department that handles the operation and maintenance of the plant. Associates periodically monitor multiple parameters and checkpoints to ensure optimum performance of the water-cooled chiller plant. Plant maintenance can happen in three ways – Periodic, Preventive, and Major [46]. Periodic or routine maintenance can decrease the probability of undergoing shut-down or abrupt failure of the plant. Preventive maintenance is in-advance forecasted maintenance employed based on analysis of outliers in the obtained sensor data or system performance. If an operational plant experiences a system or component failure, activities conducted to repair that system is called breakdown or major maintenance. Maintenance practice is necessary to control the operating costs and maximize the life cycle with optimum performance.

The efficient operation of a plant is accomplished through unison activity of methods used to implement prognosis and diagnosis strategies. The predictive approach helps to forecast in advance with the help of statistical analysis and model-based methods, as shown in Fig. 3.3. Preventive maintenance strategies include evaluating the machine condition and replacing affected parts before equipment's failure [47]. On the contrary, the diagnostic procedure is post-failure breakdown investigating the cause and employing the required solutions. Predictive and preventive maintenance activities can be accounted as prognosis, whereas routine and reactive maintenance activities are part of a diagnosis strategy. Increasing the use of predictive ways can deter the probability of the diagnostic procedure. The initial investment can be higher in prognostic, but operational and lifecycle costs will be lower than that of the diagnostic approach as post-failure investigation causes a system's shut-down and higher losses [48].

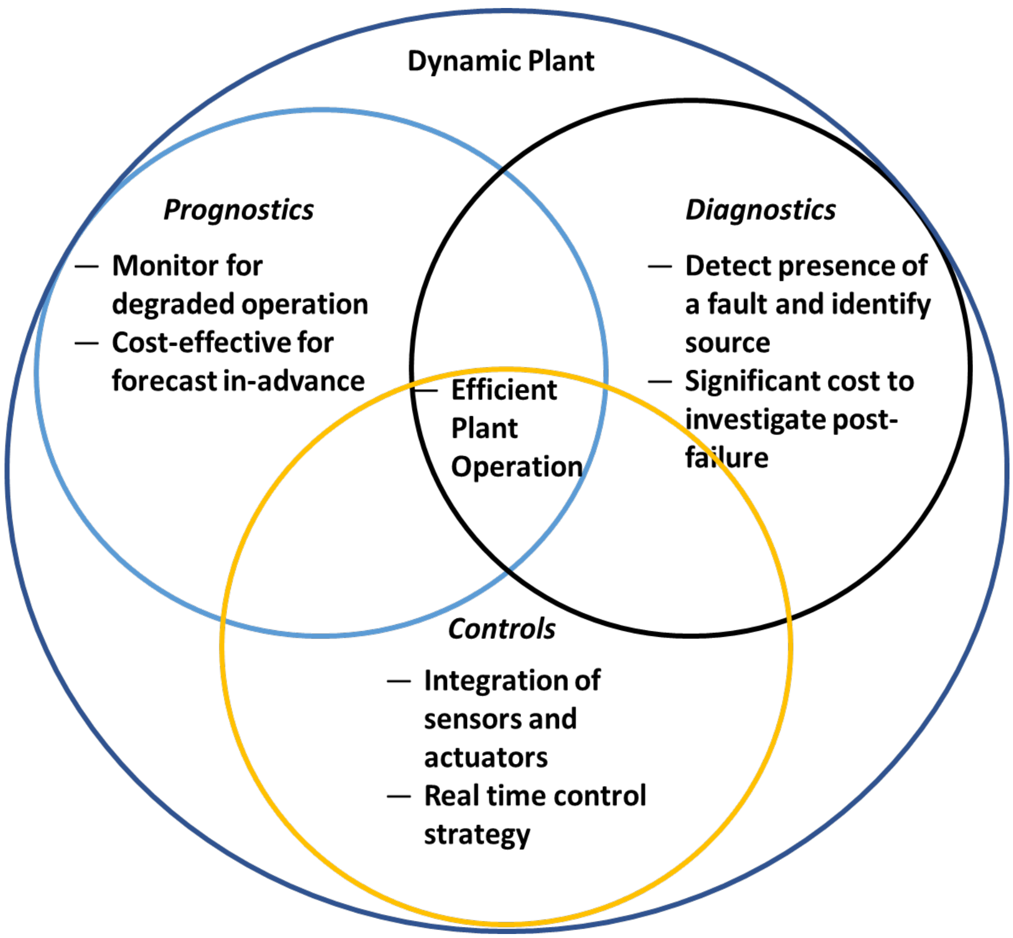


Figure 3.3: Prognosis and diagnosis can be performed using several methods including model-free, model-based, statistical analysis, and machine learning when attached to a plant control system.

The machinery in an integrated chiller plant generally requires a regular maintenance strategy to ensure optimum operation. According to criticality, prioritization of specific components in the refrigeration and chilled water loops is essential for monitoring purposes if resources are limited [49]. Prolonging and optimum performance of equipment require implementing a dynamic maintenance strategy [50] [51]. Traditional control systems use an array of sensor signals with controller algorithm to command relevant actuator operation based on the prescribed set points, as shown in Fig. 3.4. A digital twin can receive in-field information from input parameters, sensors, and controllers. Further, the user can forecast the effectiveness of the equipment and the maintenance schedule with this virtual tool for different operating conditions [52]. Also, a digital twin can keep track of historical sensor data and scan for errors leading to successful maintenance forecasts in a data mining approach. Component faults are easier to handle with the digital twin monitoring strategy.

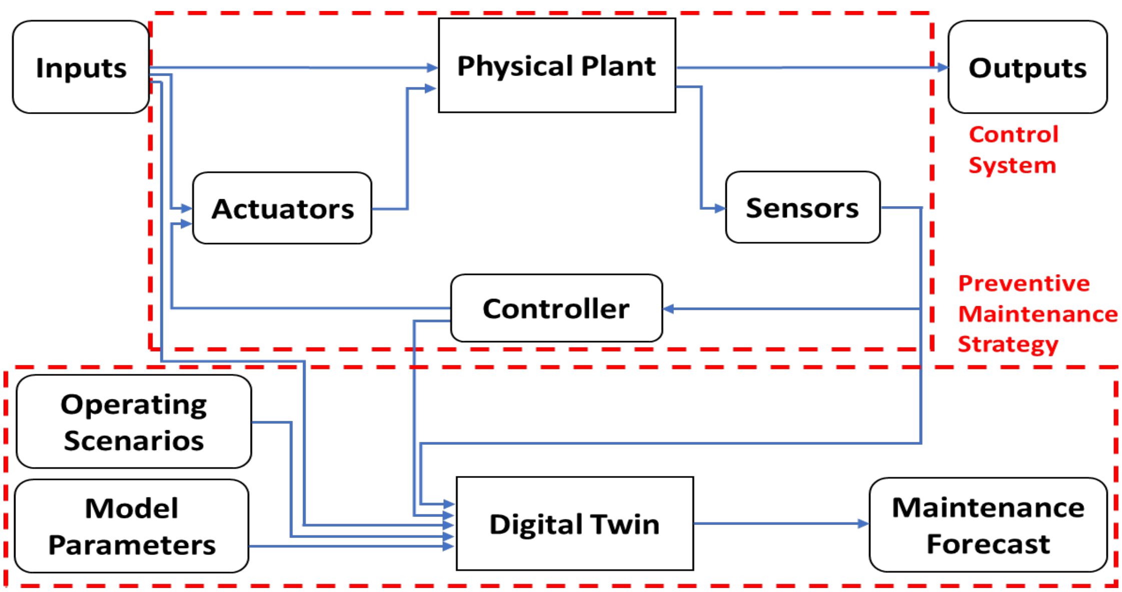


Figure 3.4: Application of digital twin technology for preventive maintenance (PM) in either off-line or real time configurations.

3.3 HVAC Systems and Creation of a Digital Twin

The water-cooled HVAC systems combine several loops to absorb and extract heat with the respective fluid (water, refrigerant) circulated in each circuit by a pump or compressor with the help of electrical energy. The chiller compressor uses the highest power, followed by primary water pumps, condenser water pumps, and cooling tower fans based on the electric power consumption order. All these components work in continuous cycles that are interdependent. Chilled water absorbs heat from the building air loop and rejects it to the chiller loop. The refrigerant in the chiller loop carries that heat and exerts it to the condenser water, ultimately leaving it to the environment. The negligence in maintaining any specific component can lead to partial or complete abruption of the system. Continuous health monitoring with advanced forecasting of required maintenance leads to a durable lifecycle of the plant.

Simcenter Amesim™ is a computer-aided engineering tool that helps in developing digital twin models. Comprehensive libraries are available – thermal, thermo-hydraulic, pneumatic, two-phase, refrigeration, electric, and control. Components from available libraries are tuned to specific desired parameters to model the individual loops. The tool has the additional functionality of providing values in a multi-dimensional table format, which enables dynamic inputs to the system. Distinct loops are interconnected using thermal-library elements that make the chiller plant digital twin. Integration of the plant model with other CAD software leads to a virtual digital twin. The extracted data from physical sensors can showcase real-time input-output parameters that can help determine overall equipment effectiveness. This industry-leading virtual twin tool help in health monitoring and predictive maintenance of the system.

The thermal and signal-control library components form the building side HVAC loop (Loop 1). The signal-control library has constant, staged inputs, transmitters, receivers, and control circuit components. Initial ongoing information provides pressure and relative humidity to the 600m^3 of medium sized classroom. A dynamic signal that consists of a two-dimensional table of variable heat load values provides the desired heat load at various instances. Reversed air (15% of the total air) is supplied to the AHU using the return loop and a constant signal source. The classical controller helps to regulate the blower speed provided to the AHU. Target temperature and feedback sensor give information to the controller.

The chilled water loop (Loop 2) includes a centrifugal pump driven by an induction motor with VFD and heat exchangers. Electrical, control-signal, and mechanical library components were utilized to assemble the VFD and 3-phase electric motor circuit, as shown in Fig. 3.5. For instance, the 4-pole induction motor has a delta configuration and provides a maximum RPM of 1800 RPM at 60 Hz. The classical controller output signal varies between 30 Hz and 60 Hz, thereby controlling the rotation of the centrifugal pump between 900 and 1800 RPM, respectively [53]. The VFD and a butterfly valve in the circuit are used to control the chilled water flow rate based on the requirement. Signal transmitters and receivers supplied desired input to the motor using the PI circuit. In general, VFDs are advantageous when compared to the constant frequency circuit as they reduce the electrical power consumption, ultimately saving the operational cost. A variety of sensors (e.g., temperature, pressure, and flow rate) monitor the chilled water behavior.

The chiller loop (Loop 3), which includes a compressor, condenser, expansion valve, and evaporator, utilizes the components from the two-phase library. Refrigerant R134a was selected as the flowing medium in the chiller loop, although other fluids are available in the library. A gearbox with 1:3.5 ratio couples the motor and the compressor to deliver the desired RPM to the compressor. An induction motor with a simplified VFD circuit drives the compressor. After compression of the refrigerant, gained heat is rejected as it flows through the shell of the condenser. Post expansion valve, low-temperature R134a is supplied to the evaporator in liquid form. The refrigerant flowing in the evaporator tubes absorbs the heat from chilled water (Loop 2.) Installed sensors in the loop monitor the refrigerant parameters (temperature, pressure, flow, and enthalpy) at each stage.

The last loop, referred as an open loop that directly interacts with the environment, is the condenser water loop (Loop 4.) This loop exerts the accumulated refrigerant heat from the condenser to the environment. Using thermo-dynamic library components, a constant condenser water flow is assumed at 25°C.

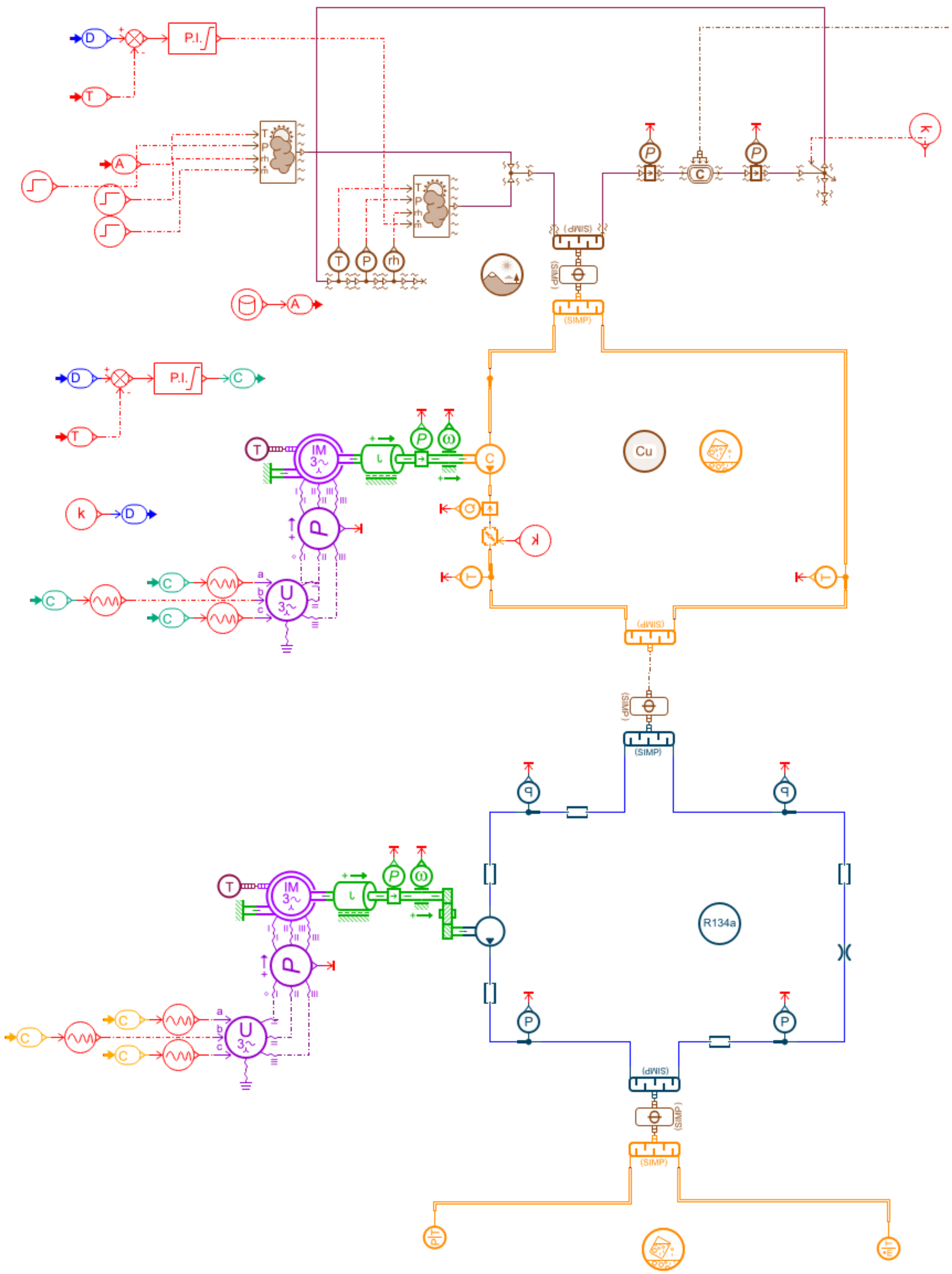


Figure 3.5: CAE chiller plant model consisting of four loops with PI-control introduced for electric motor operation in Loops 1, 2, and 3.

3.4 Case Study: Component Degradations

A CAE model for a single-chiller HVAC system was created and simulated for a 24 hrs. period. The database corresponded to a period from 00:00:00 to 03:00:00 will be represented in the paper for the customized anomaly scenarios. Independent cases of (1) Motor friction, (2) Pipe blockage, (3) Pump efficiency, (4) Sensor failure, and (5) Expansion valve choking were considered, and the error-bound conditions were employed by 3% and 5% in each case to study the reduced performance conditions. The ambient cold air at 18.2 °C (85% fresh air, 15% return air) was provided as the system reached a steady state around 01:23:33 (hh:mm:ss) to introduce a minor thermal disturbance to study the effect. Before this, the room temperature was 22.39 °C, and only return air (15% of total) was recirculated until the fresh air supply with a constant equipment heat load of 2.20 kW. At 02:20:00, the heat load was increased by 2.30 kW, totaling to 4.50 kW of the load (including the additional equipment and associates heat load) due to ongoing cleaning activities in the building. A combination of transient and steady-state behaviors based on the heat load can be seen in the independent cases. Respective simulations of the abnormal conditions were simulated and plotted against the ideal conditions. The results obtained for three hours were analyzed against the nominal results. Table 3.1 summarizes all the cases and performance degradations related to the respective scenario.

Case	Description	Loop	Component	Impact on Operation
1	Motor friction increase	2	Pump motor	Pump speed is reduced and lower chilled water flow rate, so greater control action needed
2	Pipe blockage	2	Water pipe	Reduction in chilled water flow rate, higher fluid pressure, electrical power consumption increases
3	Pump efficiency decrease	2	Pump impeller	Pump mechanical power increases resulting in more electrical energy consumption for the required flow rate
4	Blower fan air flow rate	1	Blower fan electric motor	Blower motor degradation reduces the air flow rate leading to thermal discomfort
5	Expansion valve choking	3	Expansion valve	Increases pressure and enthalpy ratio across compressor, resulting in higher amount of compressor work

Table 3.1: Summary of five degradations considered in the chiller plant and building HVAC system.

3.4.1 Case 1 – Motor Friction Increase

At nominal conditions, the maximum speed of the pump was 1759 RPM at 60Hz. For the test, as a friction increase of 3% was induced at the coupling, the pump rotary speed decreased to 1693 RPM at 60 Hz. At the 5% error, the pump speed dropped to 1665 RPM. It further varied because of the frequency variation, as shown in Fig. 3.6. The sudden spike was observed post 01:30:00 as the pump accommodated the incoming heat load due to ambient air interaction in the AHU coils. A pump with lower RPM can limit the chilled water flow rate while consuming more electrical energy. Also, continuing with the problem can induce vibrations in the shaft that can cause abrupt failure and harm both the centrifugal pump and induction motor.

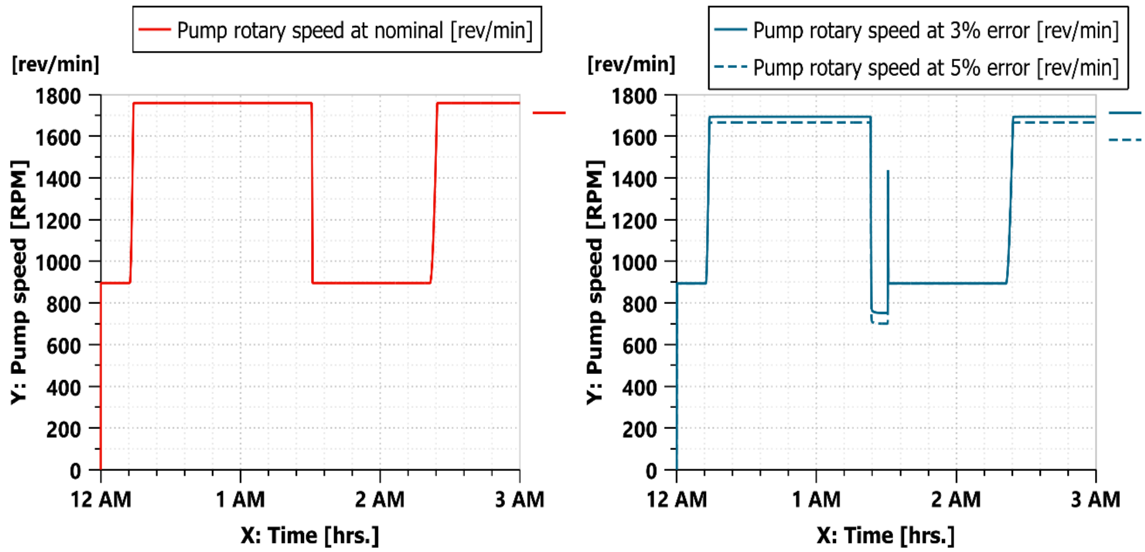


Figure 3.6: Case 1 – Pump speed for friction error test at (a) Nominal, and (b) Friction induced case in motor and pump coupling.

3.4.2 Case 2 – Pipe Blockage

The control signal varies the butterfly valve opening angle to regulate the chilled water flow. In a fully open position, the water flow rate was 0.183 m^3/s, whereas it decreased to 0.165 m^3/s and 0.154 m^3/s at 3% and 5% error, respectively. This can be seen in Fig. 3.7. A decrease in chilled water flow was observed as an ambient cold air supply of 18.2 °C was started at 01:23:33. A reduced flow rate affects the required chilled water demand at the heat exchanger attached to the AHU (Loop 1). It also increases the return water temperature, which can increase the condenser load.

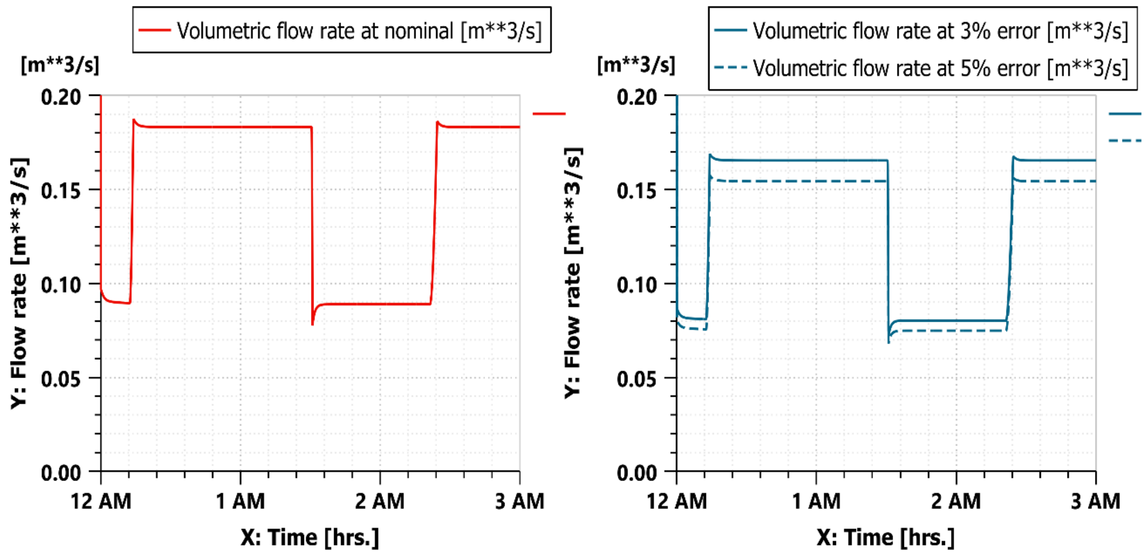


Figure 3.7: Case 2 – Chilled water flow rate for pipe blockage at (a) Nominal, and (b) Butterfly valve opening angle reduction conditions.

3.4.3 Case 3 – Pump Efficiency Decrease

Reduction in pump efficiency requires more mechanical power output to fulfill the necessary chilled water flow rate. Consequently, the electrical power consumption increases due to this. Pump operating at a nominal condition supplied water with the mass flow rate of 181.3 kg/s at 108 kW of mechanical power. As the efficiency decreased by 3% and 5%, the mechanical energy required for the same flow rate was 113 kW and 116 kW, respectively, at 60Hz, as shown in Fig. 3.8. An increase in energy consumption is directly proportional to the rise in operational costs.

3.4.4 Case 4 – Blower Motor Sensor Failure

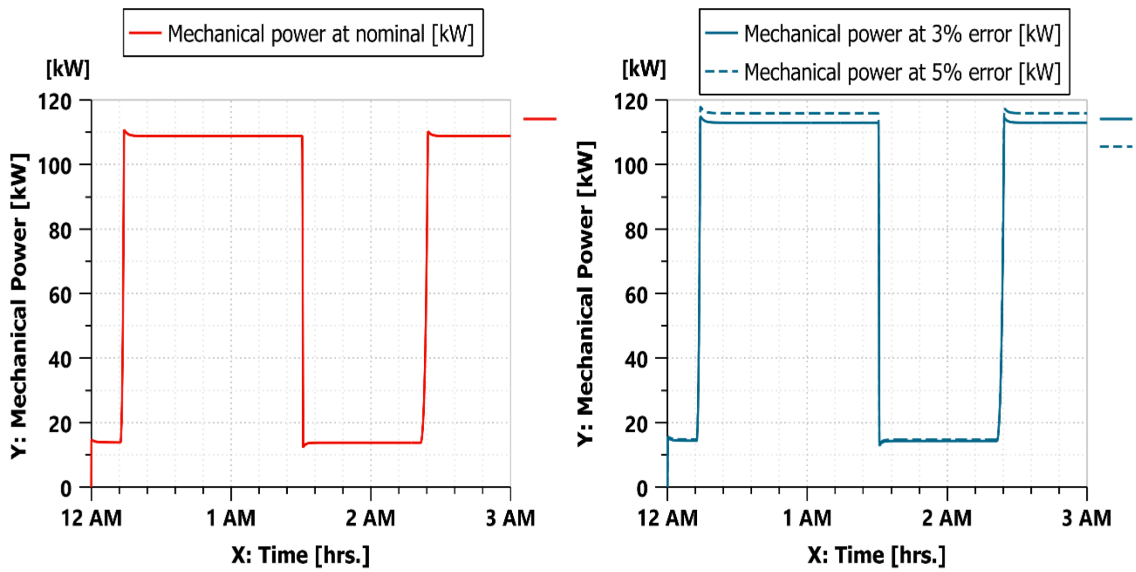


Figure 3.8: Case 3 – Mechanical power consumption for pump efficiency test at (a) Nominal, and (b) Reduced efficiency conditions.

A blower fan regulates the airflow rate supplied to the building, with air flowing through a filter for dust removal and heat exchanger. An additional classic control circuit was implemented to regulate the supply airflow rate through the electric motor speed. At the nominal performance, the flow rate varied between 1.5 kg/s and 3.0 kg/s, as shown in Fig. 3.9. After implementation of the degradation (e.g. partial sensor failure), the flow rate varied from 1.45 kg/s and 2.91 kg/s for 3% and 1.42 kg/s and 2.85 kg/s for 5%. Against the temperature of 22.39 °C in an optimum condition, a 0.3 °C rise was observed in the 5% degradation condition. In the constantly varying heat load scenarios during the daytime, this delta temperature will increase, causing thermal discomfort to individuals in the confined space. Moreover, constant running of a motor at a slower speed than desired can harm the bearings and incur unscheduled maintenance. Also, reduced motor speeds indicate a possibility of a capacitor malfunction in the blower motor. Due to problems in a motor, it may have to work at a greater rate to provide the required airflow rate and can lead to higher energy consumption.

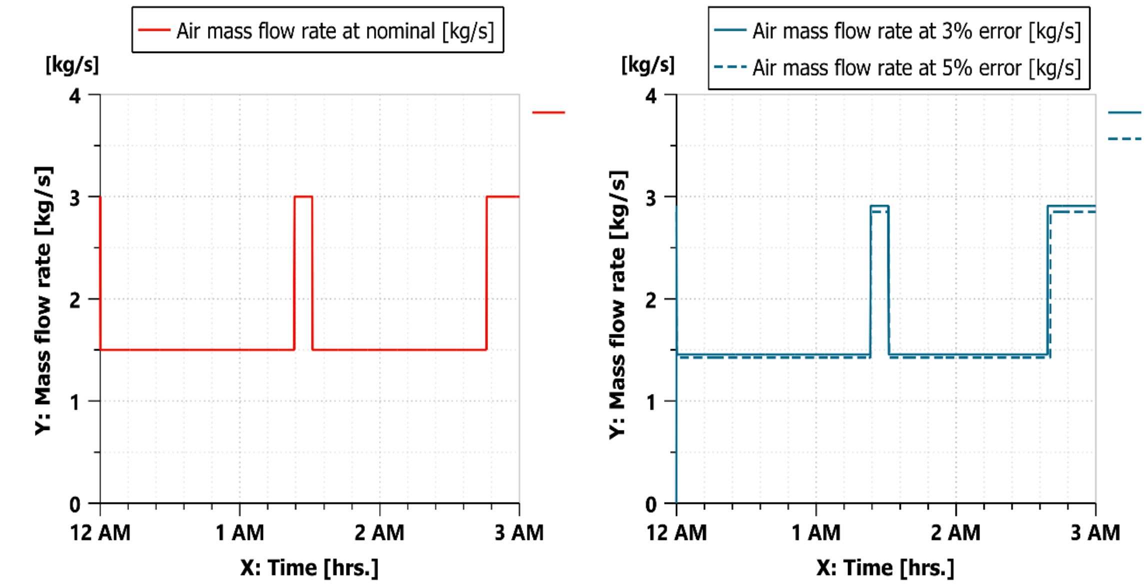


Figure 3.10: Case 4 – Air mass flow rate for blower motor failure test at (a) Nominal, and (b) Degradation conditions.

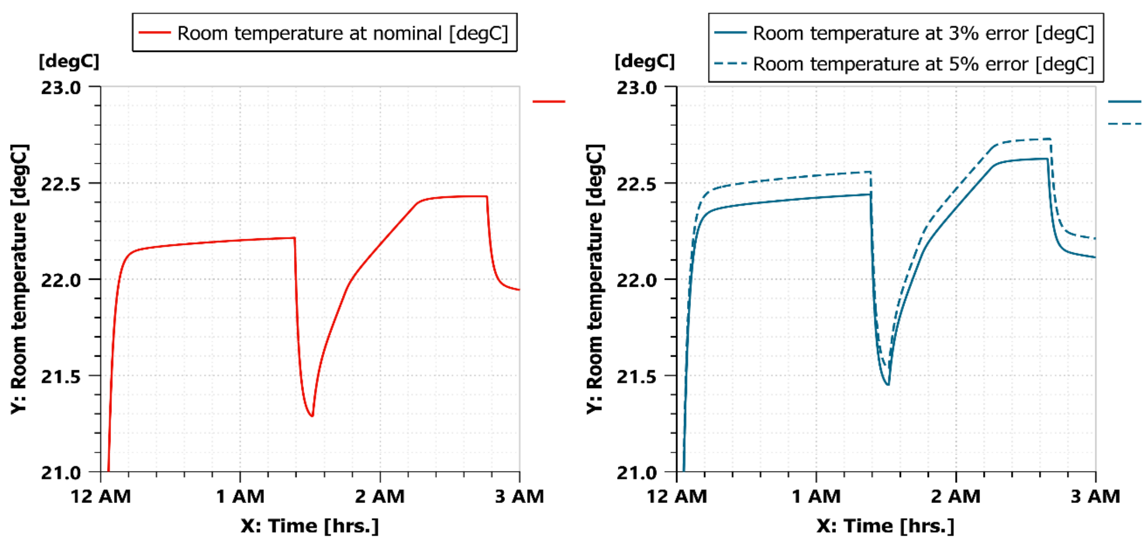


Figure 3.9: Case 4 – Effect of blower motor on room air temperature at (a) Nominal, and (b) Degradation conditions.

3.4.5 Case 5 – Expansion Valve Choking

A crucial loop in the commercial HVAC system is the chiller (Loop 3), as the others are primarily dependent on the refrigerant flow. For this case, expansion valve choking was considered, which may arise due to icing conditions from moisture in the system. The expansion valve area was reduced by 3% and 5% to witness the effects on refrigerant flow rate across the chiller system. Nominally, the refrigerant flow rate was 4.19 kg/s. As the component was degraded, it reduced the flow to 4.08 kg/s and 4.02 kg/s at 3% and 5% degradations, respectively. The refrigerant flow got streamlined as the compressor reached a steady state around 00:20:00, as shown in Fig. 3.11. The reduction in mass flow rate of the refrigerant increased the pressure ratio and enthalpy difference across the system. Compressor work depends on this pressure ratio and enthalpy difference. The expansion valve choking can reduce the compressor efficiency, increasing the associated operational costs. If the expansion valve blockage keeps rising, it may harm the system's reliability by damaging the other components and cause abrupt failure.

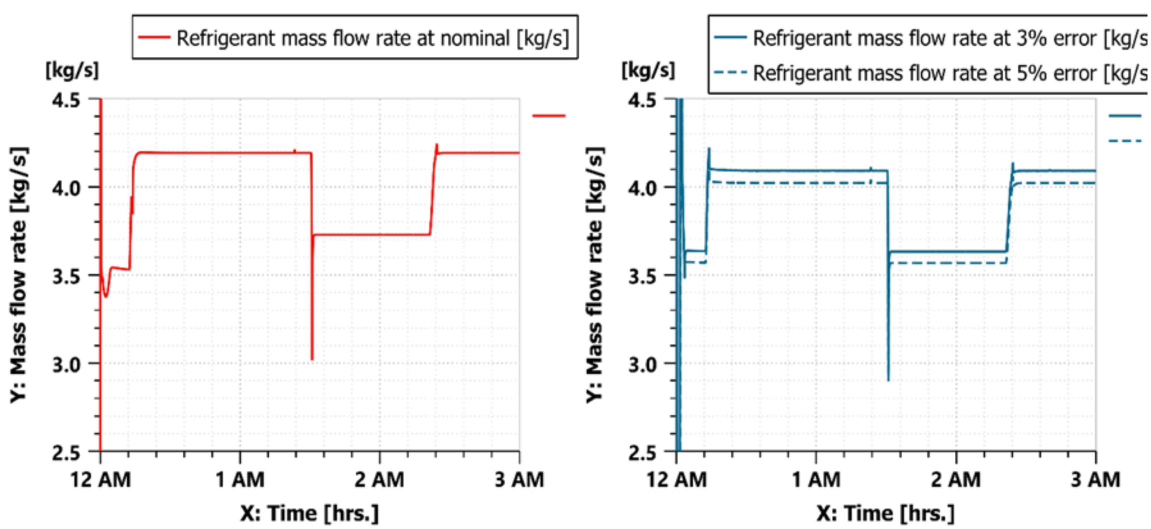


Figure 3.11: Case 5 – Refrigerant mass flow rate for expansion valve choke test at (a) Nominal, and (b) Degradation conditions.

Although the HVAC system showed a combination of transient and steady-state behavior in all the degradation scenarios based on the dynamic heat load, only steady-state behavior at maximum capacity is considered to analyze the multiple operational regions based on degradation percentage. Fig. 3.12 shows the nominal, and degraded pump speed due to the increased friction in Case 1. The nominal operation can experience variation between ± 2% when operating under dynamic conditions. But as the pump speed approached -5%, the chilled water flow rate effectively degraded. So the threshold below 5% is required to control the operation of the pump to have the required flow rate. In the control system approach, if the controller receives low flow rate feedback, then it monitors the gains applied to have the needed chilled water flow; but it makes the equipment work harder. For the graphs, the steady-state operation is considered at maximum capacity of each component in HVAC system.

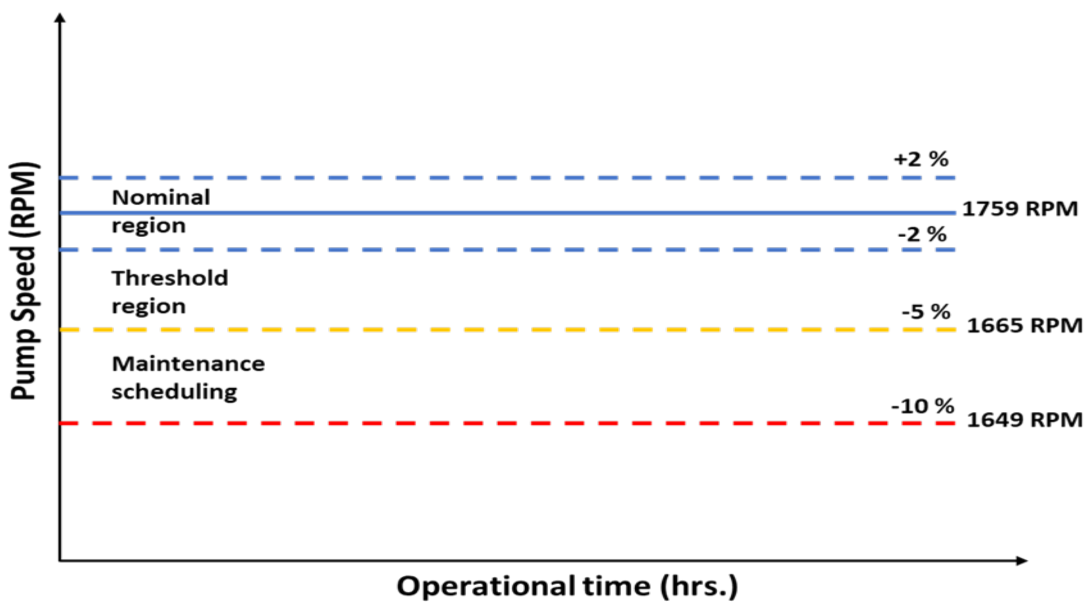


Figure 3.12: Different regions of steady state operation for pump speed in chilled water loop for preventive maintenance strategy.

Chilled water flow rate for different percentage degradations can be seen in Fig. 3.13. As the butterfly valve blockage increased to 10%, the flow rate dropped to 0.123 m^3/s affecting the chilled water supply to the AHU coils.

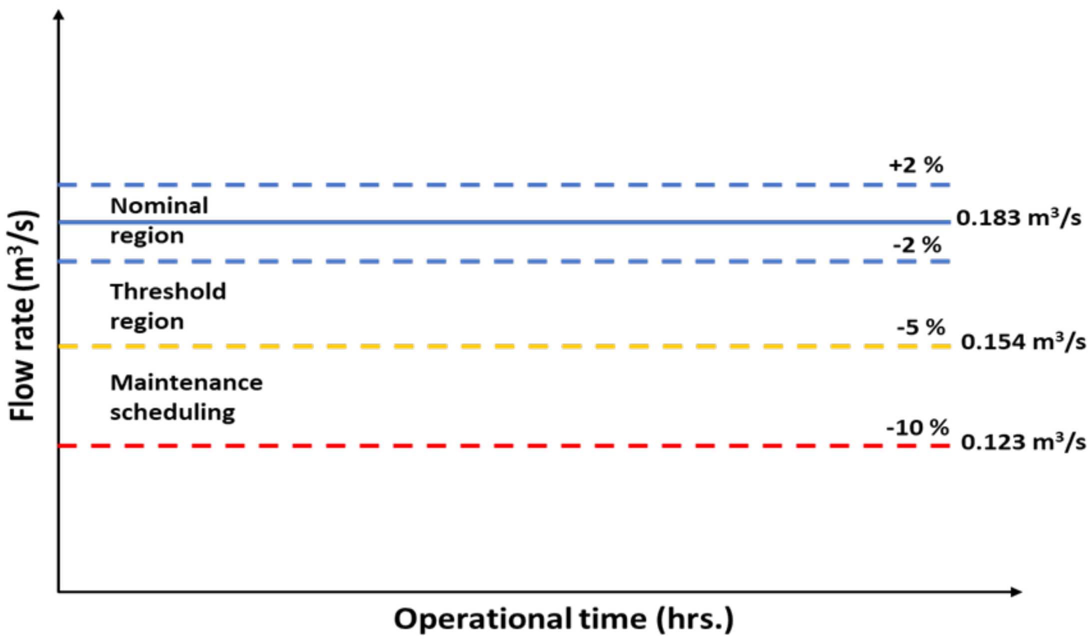


Figure 3.13: Different regions of steady state operation for butterfly valve in chilled water loop for preventive maintenance strategy.

Mechanical power output for centrifugal pump in the chilled water loop increases with the decreasing efficiency as seen in Fig. 3.14. As the virtual twin tool detects the anomaly, the user can forecast maintenance as the power approaches 125 kW at 10% efficiency.

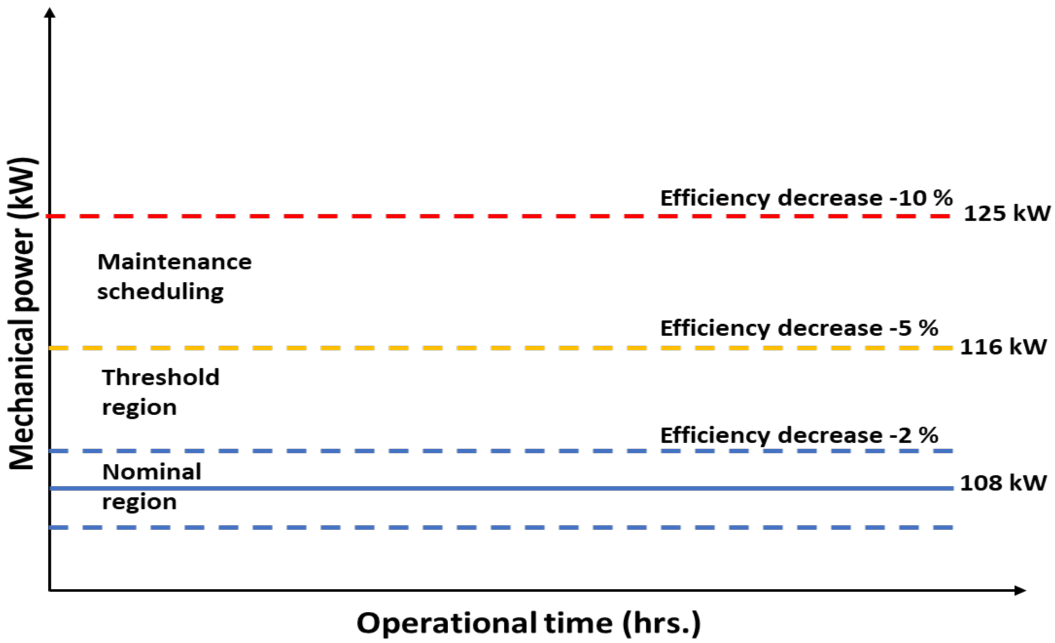


Figure 3.14: Mechanical power output required in chilled water loop based on decreasing pump efficiency and regions for preventive maintenance strategy during steady state operation.

The sensor failure caused the blower motor to work less than required, resulting in a room temperature increase. Fig. 3.15 presents different regions as the sensor failed by -5% and -10% and affected the airflow rate to the building. As the temperature approached 22.98 °C amidst mid-night heat load (from 12:00 to 03:00 hrs.), it can certainly go higher during the morning and afternoon cycle. Preventive measures can be taken in the threshold region to avoid significant maintenance and thermal discomfort.

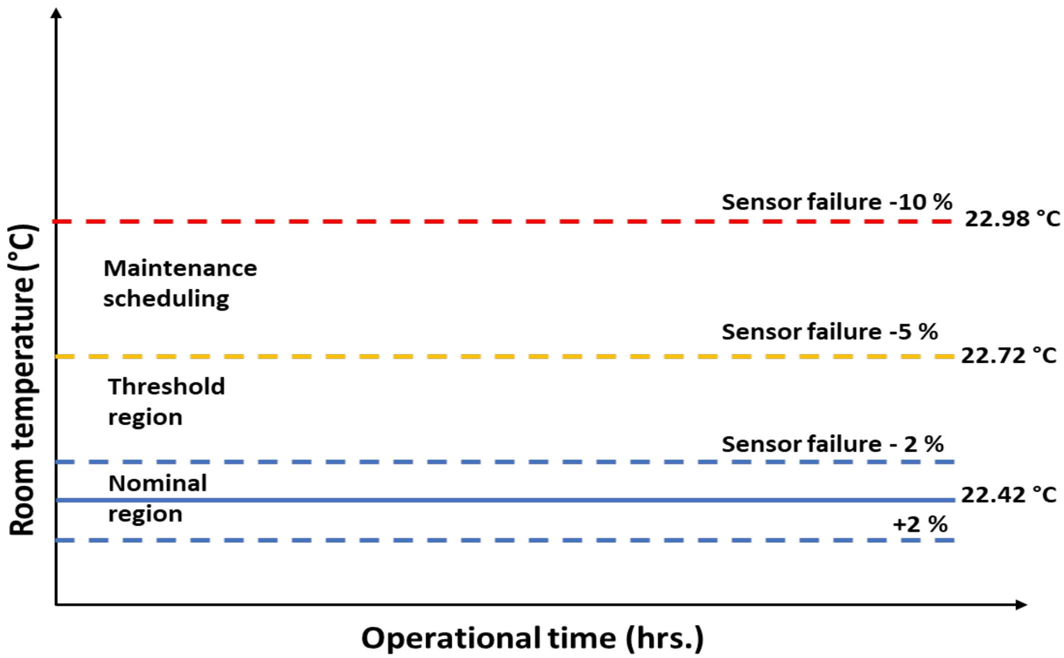


Figure 3.15: Effect on the room temperature due to variation in steady state mass air flow based on the sensor and associated regions to identify threshold and forecast maintenance.

As the expansion valve blockage increased due to frosting, the refrigerant flow rate drastically decreased to 4.02 kg/s and 3.85 kg/s at 5% and 10% blockage, respectively. The chiller is the primary component of any HVAC system. If it experiences blockages circulating the refrigerant, the system may incur failure and affect the compressor and heat exchangers associated with the loop. This tool helps spot the mass flow rate outliers, as shown in Fig. 3.16. Users can identify degradation and initialize additional procedures to undergo prognostics at the desired threshold value. The digital twin enables different operating scenarios to be considered and showcases other effects on various variables in the system.

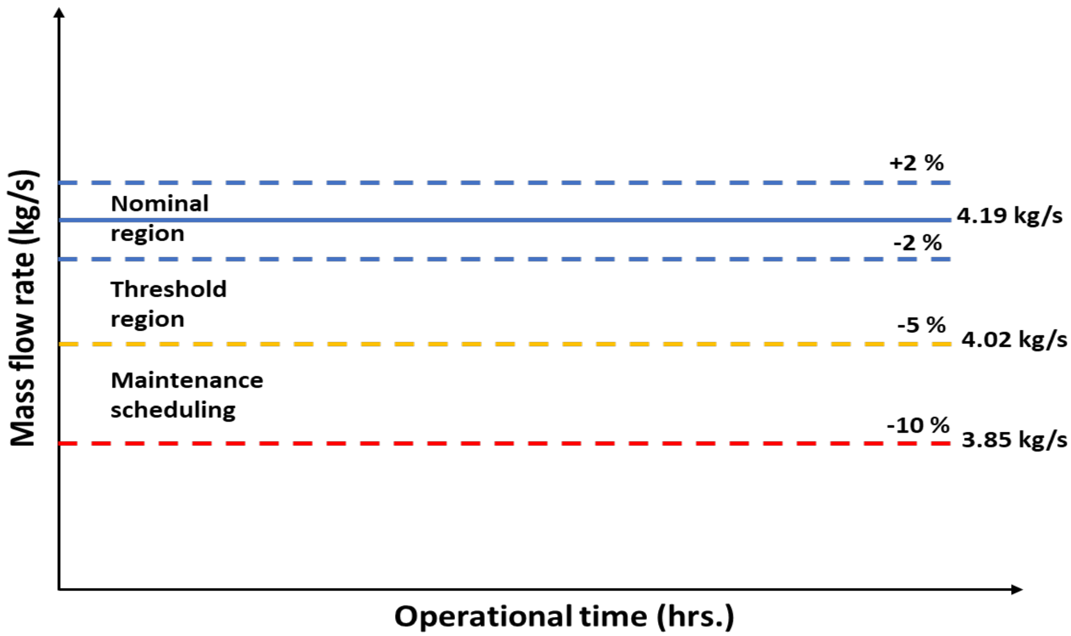


Figure 3.16: Decrease in refrigerant mass flow rate due to expansion valve choking and regions representing nominal, threshold and maintenance scheduling in steady state condition.

To further analyze the independent degradation effects for selected variables such as pressure, temperature, and flow rate for building side HVAC loop (Loop 1), and chilled water loop (Loop 2) are summarized in Table 3.2. Also, pressure, temperature, flow rate, and enthalpy readings for the chiller loop (Loop 3) are presented. The friction increase in Loop 2 resulted in an increase in the room temperature in Loop 1. It decreased the supply pressure and flow rate of the chilled water. Chilled water piping blockage increased the supply pressure and return water temperature and reduced the flow rate in Loop 2. The decrease in pump efficiency resulted in a supply pressure decrease and increased the return water temperature in Loop 2. Fan blower motor failure reduced the chilled water temperature in Loop 2. A higher return water temperature was observed when the expansion valve choked in Loop 3. The expansion valve choking increased the compressor work. All other degradations increased the condenser side enthalpy in Loop 3, resulting in greater compressor work except for fan motor blower failure.

	Description	Loop 1 HVAC			Loop 2 Chilled Water			Loop 3 Chiller							
Sensor / Case		P	T	$\dot{A}$	P	T	$\dot{W}$	P_e	P_c	T_e	T_{co}	T_{pc}	$\dot{R}$	H_e	H_c
1	Motor friction increase	~	↑	~	↓	↑	↓	~	~	~	~	~	~	~	↑
2	Pipe blockage	~	~	~	↑	↑	↓	~	~	~	~	~	~	~	↑
3	Pump efficiency decrease	~	~	~	↓	↑	~	~	~	~	~	~	~	~	~
4	Blower motor	~	↑	↓	~	↓	~	~	~	~	~	~	~	~	~
5	Expansion valve choke	~	~	~	~	↑	~	↓	↑	↓	↑	↓	↓	↓	↑

Table 3.2: Effects of independent degradation cases on variables in Loops 1, 2, and 3 representing effects by symbols ↓ for decrease, ↑ for increase, and ~ for no change with P – pressure, T – temperature, $\dot{A}$ – mass flow rate of air, $\dot{W}$ – chilled water mass flow rate, P_e – pressure across evaporator, P_c – pressure across condenser, T_e – temperature across evaporator, T_{co} – temperature post compressor, T_{pc} – temperature post condenser, $\dot{R}$ – refrigerant mass flow rate, H_e – refrigerant enthalpy post evaporator, and H_c – refrigerant enthalpy post compressor.

3.5 Summary

The performance digital twin of a chiller plant simulated for 3% to 5% degraded conditions for various equipment in chilled water loop (Loop 2) and building side (HVAC) loop (Loop 1). It showed a promising result for both nominal and error-bound conditions. From the variation in simulation, the chiller plant model showed a convincing result when detecting an error in equipment in the water-cooled HVAC system. Similarly, when provided stream data, these variations can be seen if any outliers are present. This digital twin, in the future, if integrated with other CAE tools, can take live variables directly from the streaming on-field data. The live-fed data will be helpful for the health monitoring of commercial HVAC systems, leading to a successful preventive maintenance strategy.

Case	Description/ System Behavior	Nominal Values	Degradation Observed	
			3% Error	5% Error
1	Motor friction increase/ Pump speed effected	N = 1759 RPM	N = 1693 RPM Δ= -3.75%	N = 1665 RPM Δ= -5.34%
2	Pipe blockage/ Water flow rate effected	$\dot{W}$ = 0.183 m^3/s	$\dot{W}$ = 0.165 m^3/s Δ= -9.83%	$\dot{W}$ = 0.154 m^3/s Δ= -15.84%
3	Water pump efficiency decrease/ Power consumption effected	E = 108 kW	E = 113 kW Δ= +4.62%	E = 116 kW Δ= +7.4%
4	Blower motor failure/ Room temperature effected	T = 22.42 °C	T = 22.62°C Δ= +0.89%	T = 22.72°C Δ= +1.33%
5	Expansion valve choke/ refrigerant flow rate effected	$\dot{R}$ = 4.19 kg/s	$\dot{R}$ = 4.08 kg/s Δ= -2.62%	$\dot{R}$ = 4.02 kg/s Δ= -4.05%

Table 3.3: Numerical results of case study with varying levels of component degradations and percentage change to set thresholds with N – pump speed, $\dot{W}$ – chilled water mass flow rate, E – pump power, T – temperature, and $\dot{R}$ – refrigerant mass flow rate.

CHAPTER FOUR

CONCLUSION AND FUTURE WORK

The increasing use of virtual technology for design, analysis, and performance estimation is a potential solution to map the chiller system's operational behavior. The CAE model of a single-chiller water-cooled HVAC system was simulated successfully under dynamic heat load conditions using a digital twin tool. The digital twin tool helped model the pumps, compressors, heat exchangers, and building side components with internal connections to unify the interdependent loops into a single chiller water-cooled HVAC system. The system's normal operation was simulated for 24 hours, and results for the morning time cycle were presented along with dynamic heat load variation. Chiller plant tonnage capacity was 1493 Ton (17916000 BTU/hr., 5250 kW).

The application of performance digital twin in operation and maintenance offers enhanced features that can be used as next-gen health monitoring and predictive maintenance for the HVAC system. This CAE model was used to degrade specific components in Loop 1, Loop 2, and Loop 3 by 3% and 5% virtually to witness their effects on the other equipment variables in the respective and dependent loops. Independent error-bound cases were simulated and analyzed against the nominal performance of the machinery. The obtained results were summarized and compared in a tabular format. This digital twin tool will help set thresholds for the crucial components and enhance the existing monitoring systems. Forecasting in-advance maintenance schedules will help in ensuring optimum performance of the plant for its lifecycle.

FUTURE WORK

The investigation of a digital twin for a single-chiller water-cooled HVAC system has demonstrated the capability to assemble multi-domain models and estimate the performance of the machinery involved in a complex plant. A virtual replica of the Clemson University campus East side chiller plant can be created by improving the current digital twin through the addition of blower motor fans (Loop 1), VFDs, and an enhanced condenser water loop (Loop 4) with an accompanying cooling tower. Some further enhancements may include:

1. Building side (HVAC) loop (Loop 1) with multiple rooms and buildings connected to the chilled water loops and validated using the Johnson Controls Metasys platform. This action would enable the entire HVAC system to be considered, excluding heat from a steam plant.
2. The integration of a steam plant (boiler, Duke Energy co-gen plant) to heat the building air to the proper temperature in Loop 4.
3. Scale up the digital twin model to fully represent the complete East side chiller plant with two compressors and interdependent VFDs showcasing dynamic heat load conditions for different seasons in the year.
4. A set of individual component detailed virtual twins can be created for select components based on the cruciality of the machine. The troubleshooting of a separate subsystem can rapidly enable prognostics and diagnostics to ensure optimum operation of the plant.

5. Integration of the CAD and CAE software can help create an interactive virtual reality (VR) toolset for designing, simulating, and additive manufacturing the parts in a refrigeration system. This next-gen VR tool could also help train associates and employees on plant operation and safety protocols.
6. Expansion of the preliminary preventive maintenance method with available operating data and machine learning diagnostics. The enhancement of predictive maintenance will benefit the facilities team and save energy.
7. On the software side, by working with OptiCX (Optimum Energy), live streaming data from the plant can be extracted to the Siemens Simcenter Amesim^{TM} models using the MathWorks MATLAB platform.
8. Implementation of machine learning and artificial intelligence can automate the commands required to detect and change the necessary parameters in complex equipment.

APPENDICES

Appendix A

Test Data of the East Side Chiller Plant

The East-side chiller plant streaming data for selected parameters directly obtained from OptiCX by Optimum Energy for 12th Oct 2021 are shown in Figures A-1 to A-8.

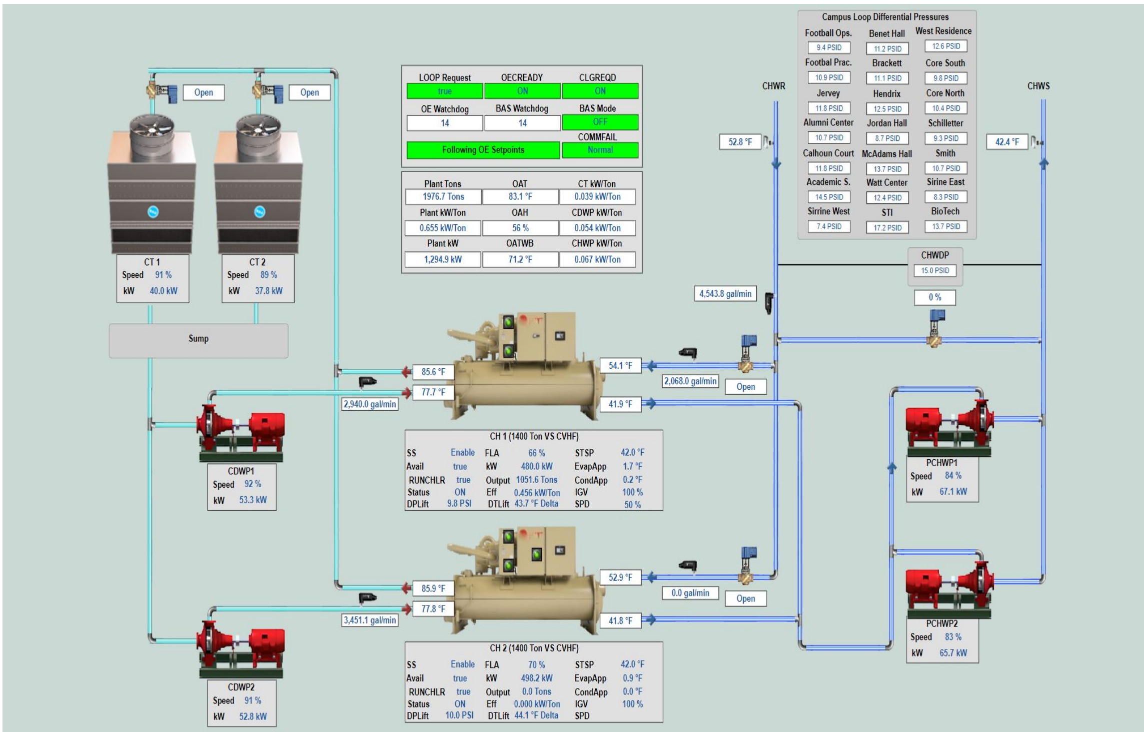


Figure A-1: East side chiller plant at a glance – Live parameters.

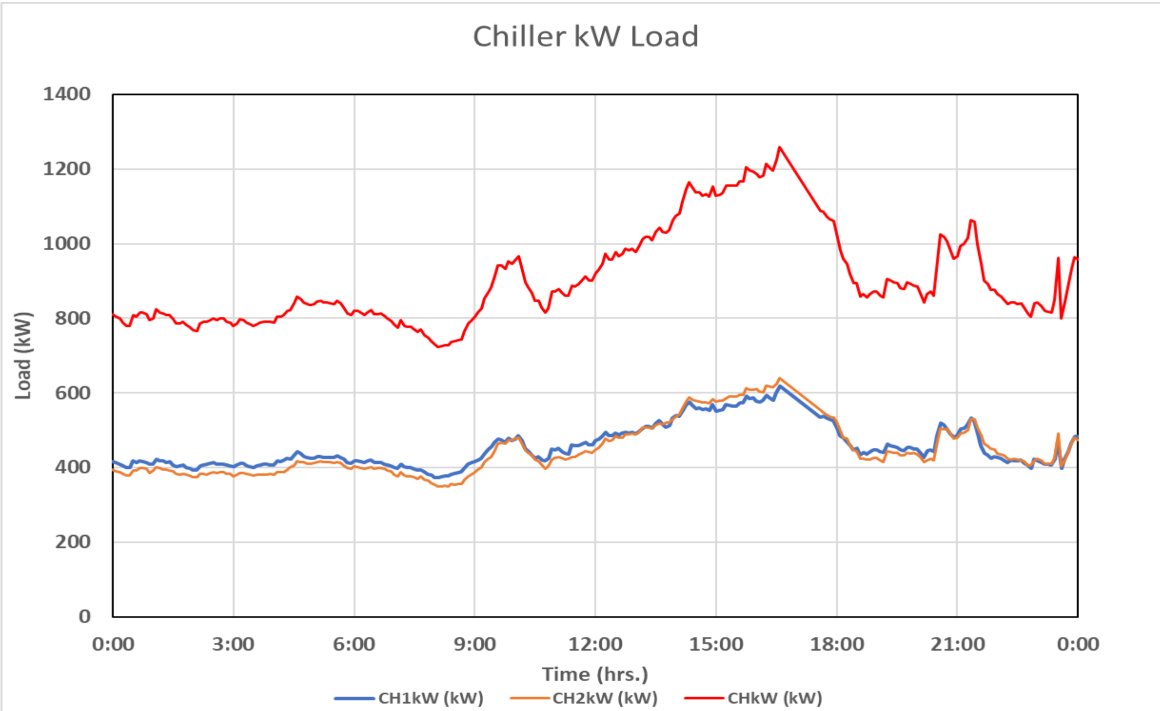


Figure A-2: Total chiller kW usage versus time for chiller 1, chiller 2, and combined consumption.

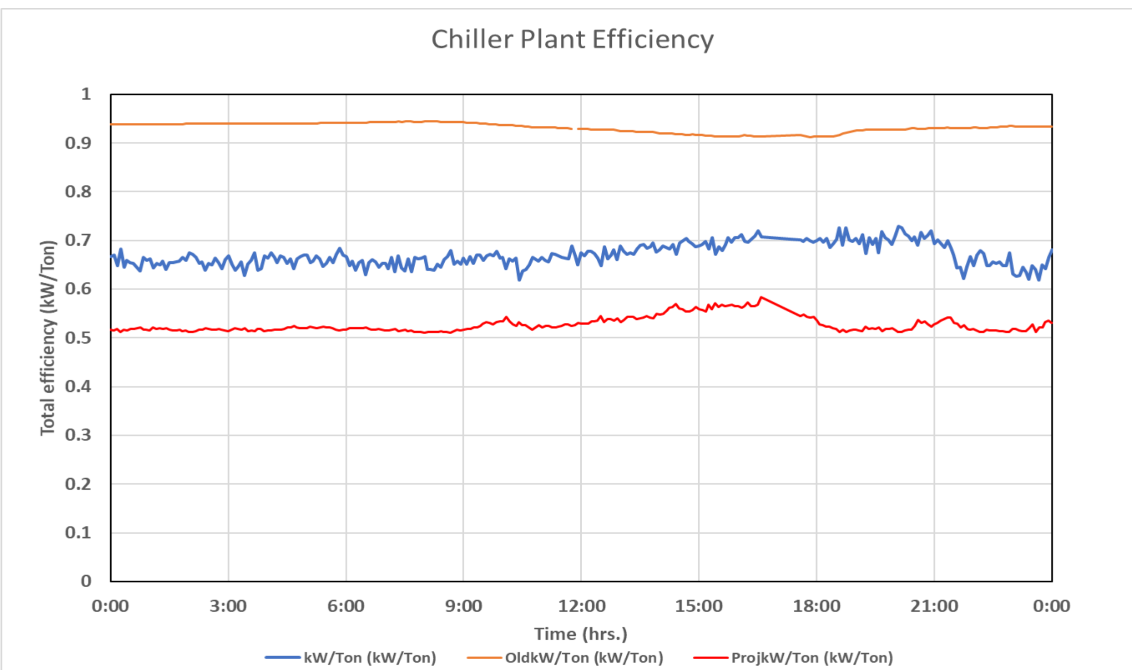


Figure A-3: Total chiller plant old, current, and projected efficiency versus time for chiller 1, and chiller 2 combined.

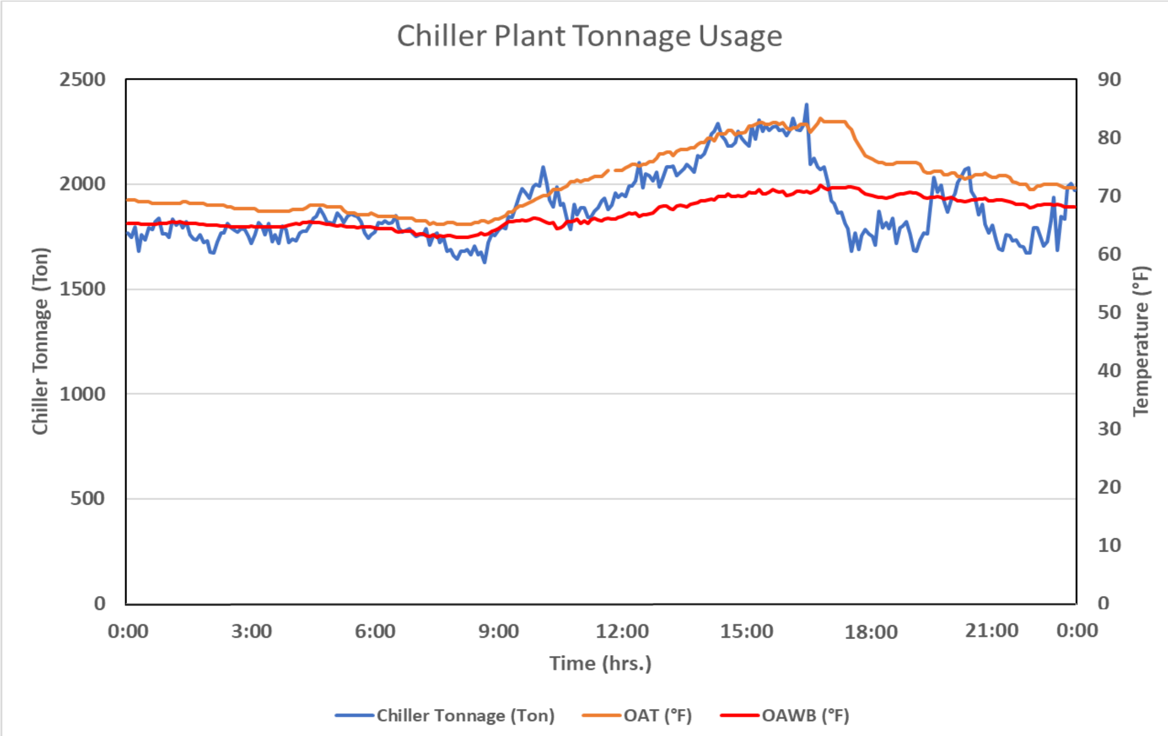


Figure A-4: Total chiller plant tonnage loading and outside air temperature versus time for chiller 1, and chiller 2.

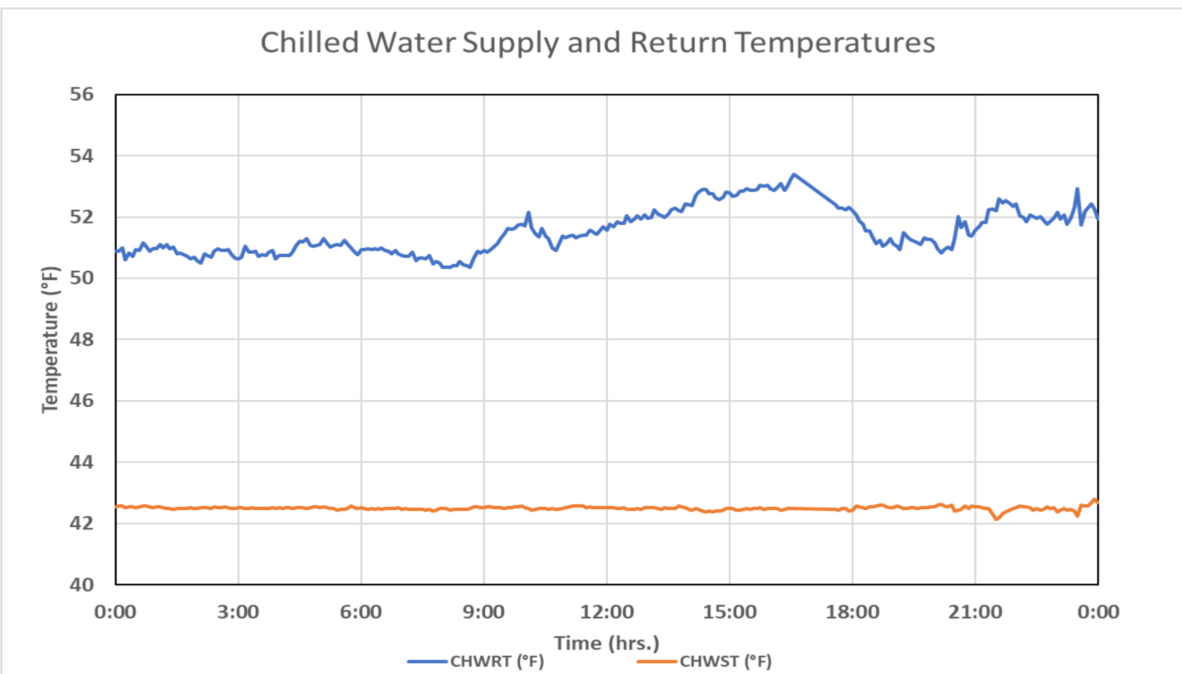


Figure A-5: Chilled water supply and return temperatures versus time in Loop 2.

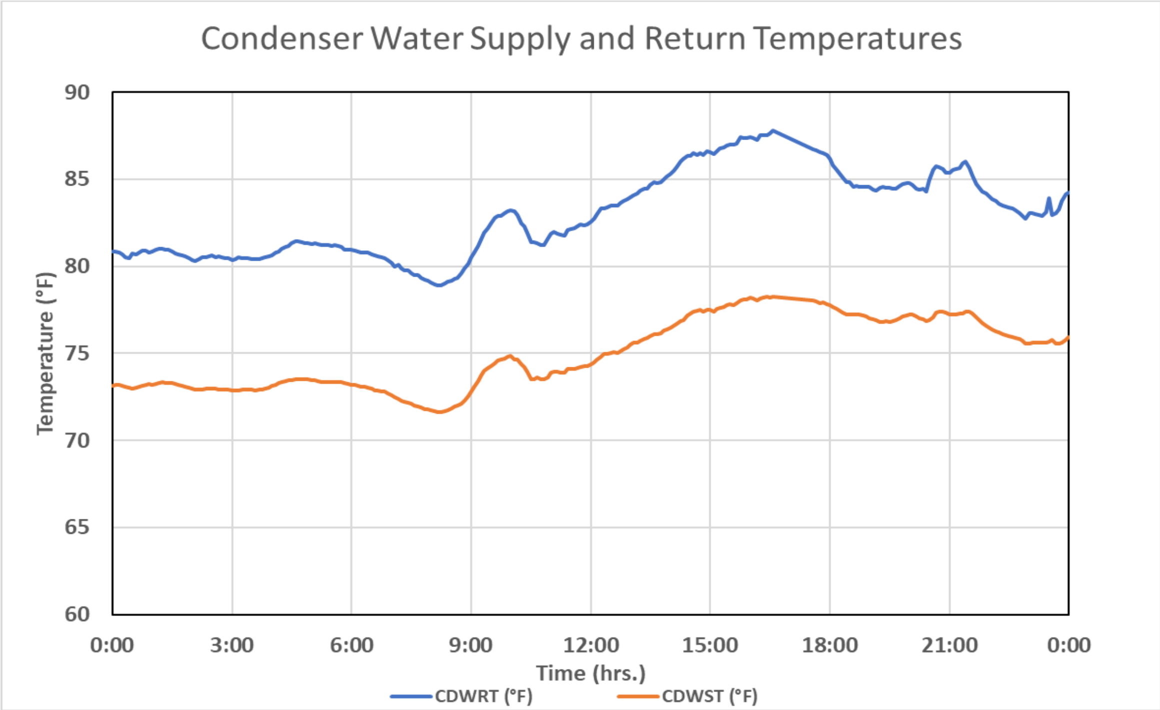


Figure A-6: Condenser water supply and return temperatures versus time for Loop 4.

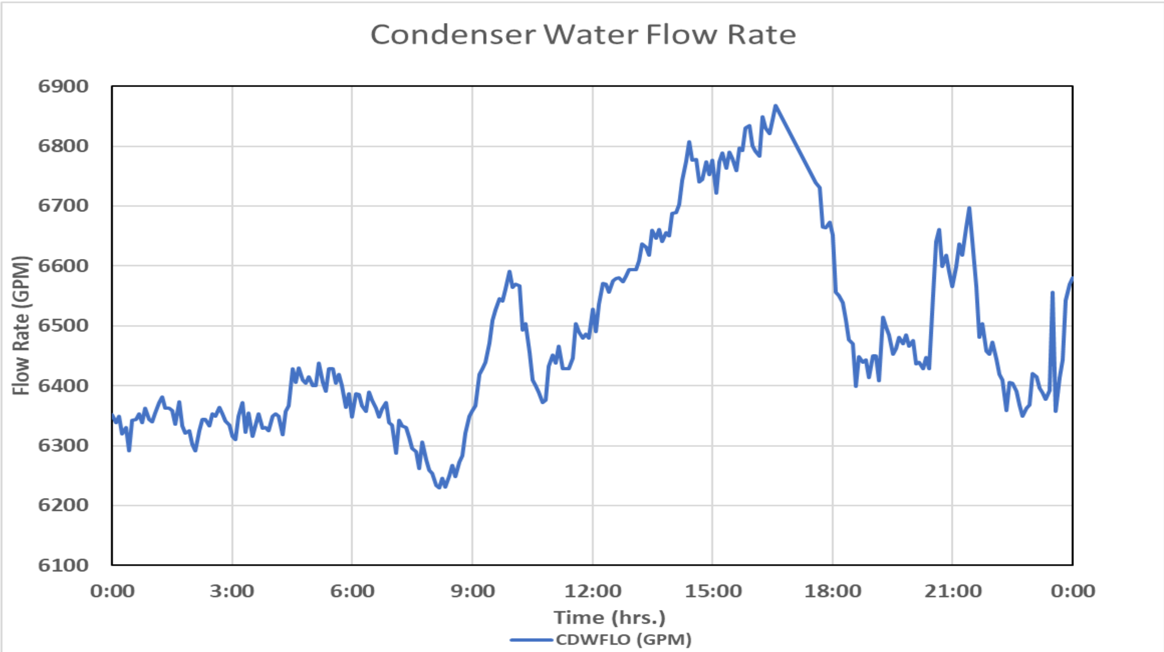


Figure A-7: Condenser water flow rate versus time for Loop 4.

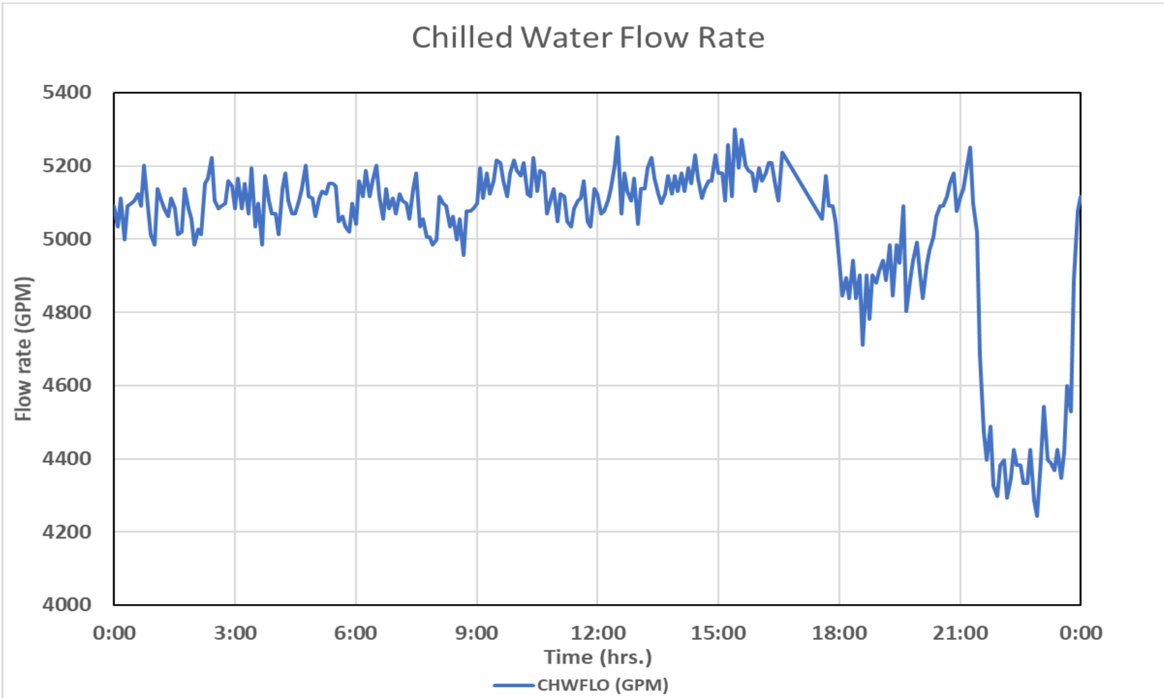


Figure A-8: Chilled water flow rate versus time for Loop 2.

Appendix B

Simcenter Amesim^{TM} Model Parameters

This section represents details about components such as the building room, compressors, pumps, motors, and control systems in the digital twin of the chiller plant model. The detailed parameters of the equipment are shown in Figures B-1 to B-8.

Parameters of th_ma_chamber [THMAC00-1]

Title	Value	Unit
(#) mass flow rate at port 1	0	kg/s
(#) pressure at port 1	**101.3**	**kPa**
(#) Room temperature	**17**	degC
setting of chamber dynamics	**advanced**	
(#) initial relative humidity	40	%
chamber volume	**600**	m**3
filename or expression for water production[g/h] = f(t[s])	**1000**	

Figure B-1: Room chamber parameters for Loop 1.

Parameters of tf_centrif_pump [TFPU000-1]

Title	Value	Unit
pressure at port 2	**1000**	**kPa**
temperature at port 2	**10.5556**	degC
index of thermal hydraulic fluid	**2**	
characterization mode	f(qv)	
fluid volume associated with the pump	0.001	L
time constant	1e-05	s
pump diameter	**13.5**	**in**
reference parameters		
reference pump diameter	**13.5**	**in**
reference speed	**1780**	rev/min
reference density setting	direct	
reference density	1049	kg/m**3
pressure difference table	AMETable	
interpolation type	linear	
discontinuity handling	active	
linear data out of range mode	extrapolation	
filename for pressure increase[bar] = f(qv[L/min], w[r...	**PumpCurveVFDTest4.data**	
efficiency		
efficiency setting	constant	
constant global efficiency	0.8	null

Figure B-2: Centrifugal pump parameters in Loop 2.

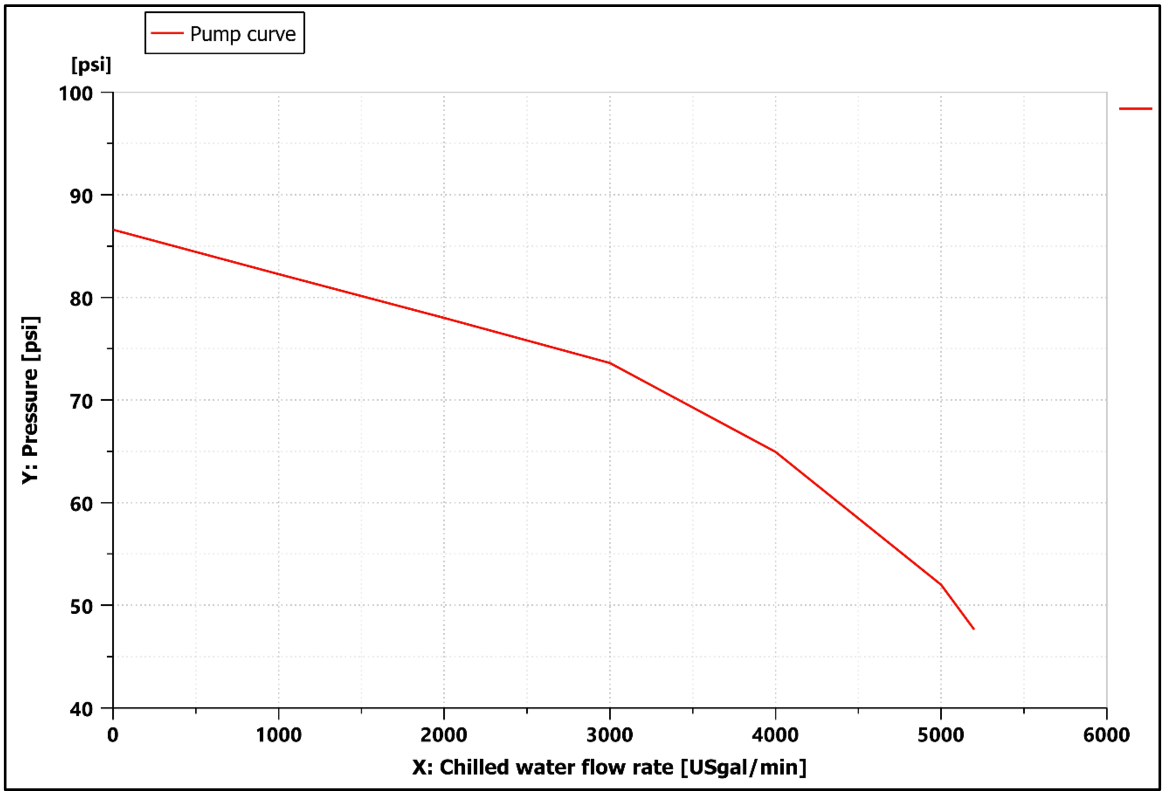


Figure B-3: Centrifugal pump curve in Loop 2

Parameters of emd_InductionMachine [EMDSCIM11-1]

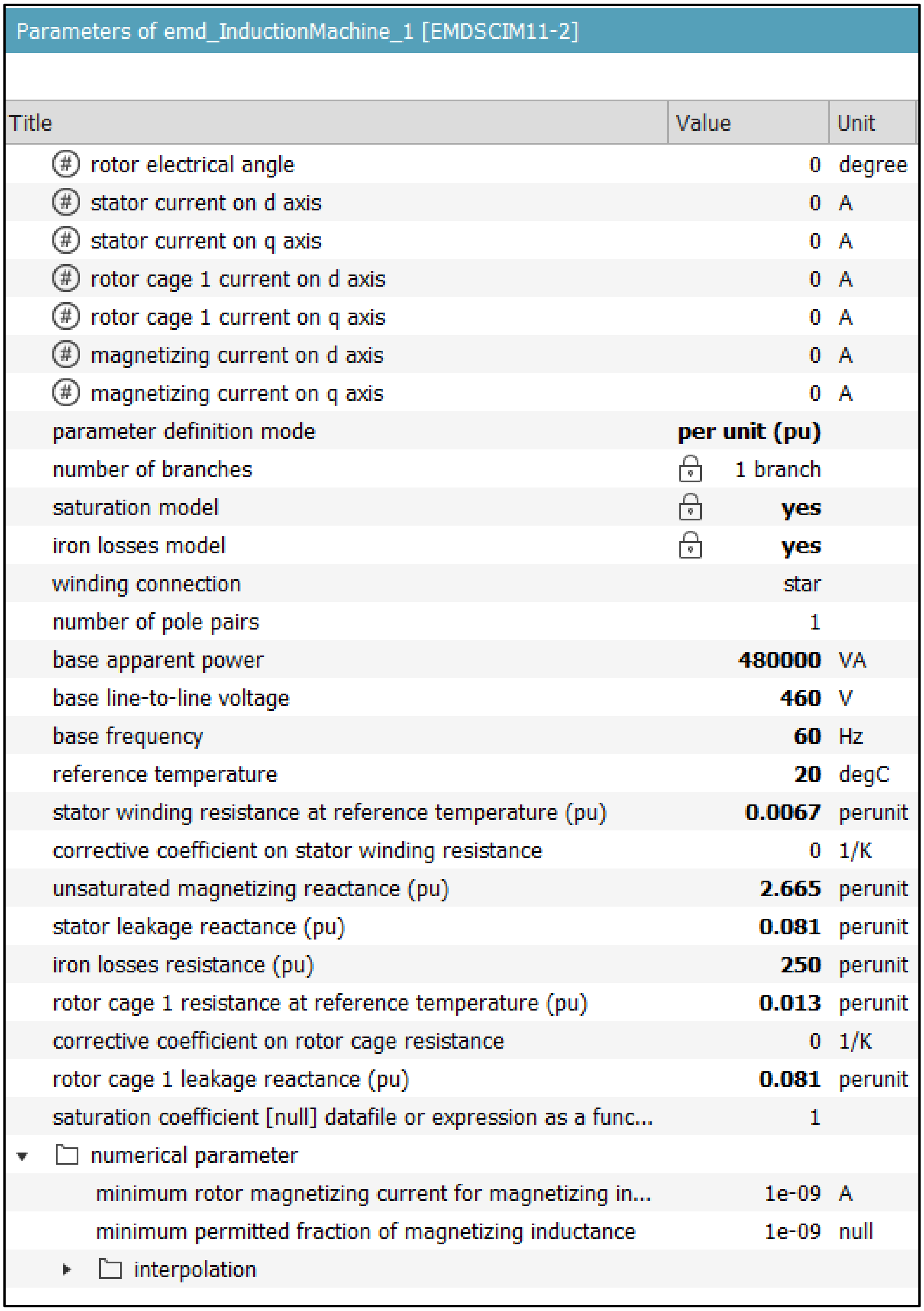
Title	Value	Unit
(#) rotor electrical angle	0	degree
(#) stator current on d axis	0	A
(#) stator current on q axis	0	A
(#) rotor cage 1 current on d axis	0	A
(#) rotor cage 1 current on q axis	0	A
(#) magnetizing current on d axis	0	A
(#) magnetizing current on q axis	0	A
parameter definition mode	**per unit (pu)**	
number of branches	1 branch	
saturation model	**yes**	
iron losses model	**yes**	
winding connection	star	
number of pole pairs	**2**	
base apparent power	**100000**	VA
base line-to-line voltage	**460**	V
base frequency	**60**	Hz
reference temperature	**20**	degC
stator winding resistance at reference temperature (pu)	**0.0067**	perunit
corrective coefficient on stator winding resistance	0	1/K
unsaturated magnetizing reactance (pu)	**2.665**	perunit
stator leakage reactance (pu)	**0.081**	perunit
iron losses resistance (pu)	**250**	perunit
rotor cage 1 resistance at reference temperature (pu)	**0.013**	perunit
corrective coefficient on rotor cage resistance	0	1/K
rotor cage 1 leakage reactance (pu)	**0.081**	perunit
saturation coefficient [null] datafile or expression as a func...	1	
▾ numerical parameter		
minimum rotor magnetizing current for magnetizing in...	1e-09	A
minimum permitted fraction of magnetizing inductance	1e-09	null
▸ interpolation		

Figure B-4: Induction motor parameters for centrifugal pump in Loop 2.

Parameters of tpf_pump [TPFPUCOMP00-1]

Title	Value	Unit
index of fluid	1	
input data out of range	extrapolate	
discontinuity handling	active	
use minimum flow rate	no	
coefficient definition	no	
flow rate calculation	displacement	
displacement	**0.00492104**	**m**3**
▾ efficiencies		
inputs for efficiency's definition	tau, N[rev/min]	
filename or expression for volumetric efficiency = f(tau...	**0.55**	
filename or expression for isentropic efficiency = f(tau,...	**0.7**	
filename or expression for mechanical efficiency = f(ta...	**0.85**	

Figure B-5: Compressor parameters in Loop 3.



Parameters of emd_InductionMachine_1 [EMDSCIM11-2]

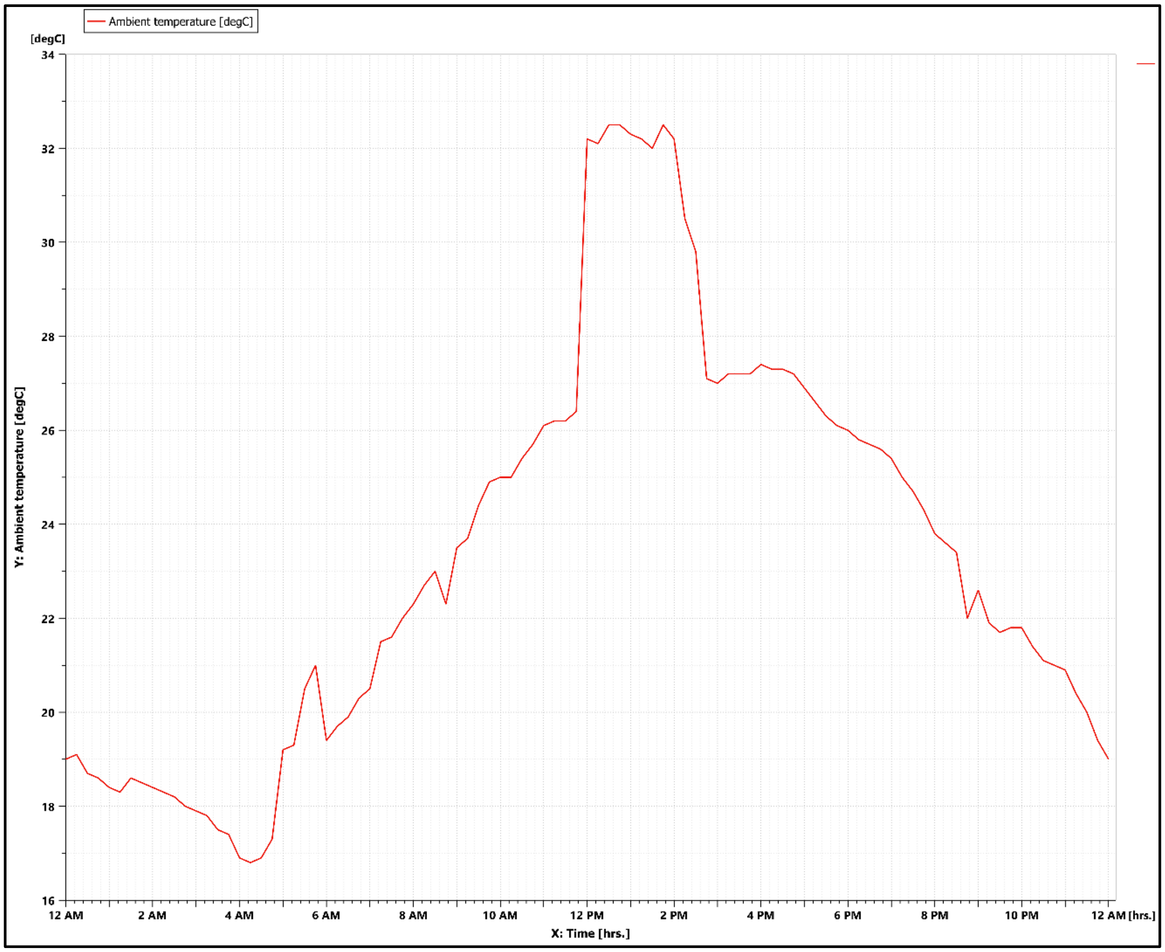
Title	Value	Unit
rotor electrical angle	0	degree
stator current on d axis	0	A
stator current on q axis	0	A
rotor cage 1 current on d axis	0	A
rotor cage 1 current on q axis	0	A
magnetizing current on d axis	0	A
magnetizing current on q axis	0	A
parameter definition mode	**per unit (pu)**	
number of branches	1 branch	
saturation model	**yes**	
iron losses model	**yes**	
winding connection	star	
number of pole pairs	1	
base apparent power	**480000**	VA
base line-to-line voltage	**460**	V
base frequency	**60**	Hz
reference temperature	**20**	degC
stator winding resistance at reference temperature (pu)	**0.0067**	perunit
corrective coefficient on stator winding resistance	0	1/K
unsaturated magnetizing reactance (pu)	**2.665**	perunit
stator leakage reactance (pu)	**0.081**	perunit
iron losses resistance (pu)	**250**	perunit
rotor cage 1 resistance at reference temperature (pu)	**0.013**	perunit
corrective coefficient on rotor cage resistance	0	1/K
rotor cage 1 leakage reactance (pu)	**0.081**	perunit
saturation coefficient [null] datafile or expression as a func...	1	
numerical parameter		
minimum rotor magnetizing current for magnetizing in...	1e-09	A
minimum permitted fraction of magnetizing inductance	1e-09	null
interpolation		

B-6: Induction motor parameters for the compressor in Loop 3.

Parameters of pid_1 [PID001-1]

Title	Value	Unit
integral part	0	null
controller type	PI	
limit output	**yes**	
proportional gain	**35000**	null
integral gain	**0.01**	null
saturation		
maximum permitted output value	**60**	null
minimum permitted output value	**30**	null
anti windup method	back calculation and tracking	
backtracking gain	1	null

B-7: PI-controller parameters for the pump in Loop 2.



B-8: Ambient temperature values for Loop 1.

Appendix C

Digital Twin Architecture

This section shows the methodology for assembling a multi-domain plant model with the help of a digital twin tool and associated libraries. Selected components for the creation of digital twin architecture are shown in Figures C-1 to C-11.

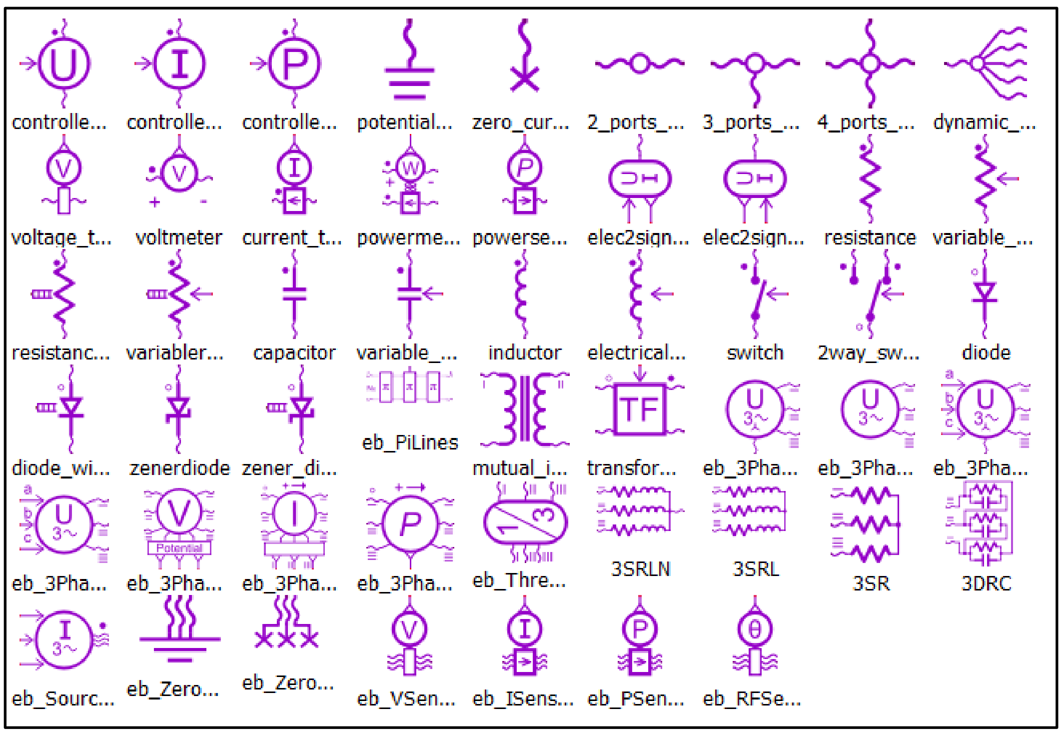


Figure C-1: Basic electrical library used for Loops 2, and 3.

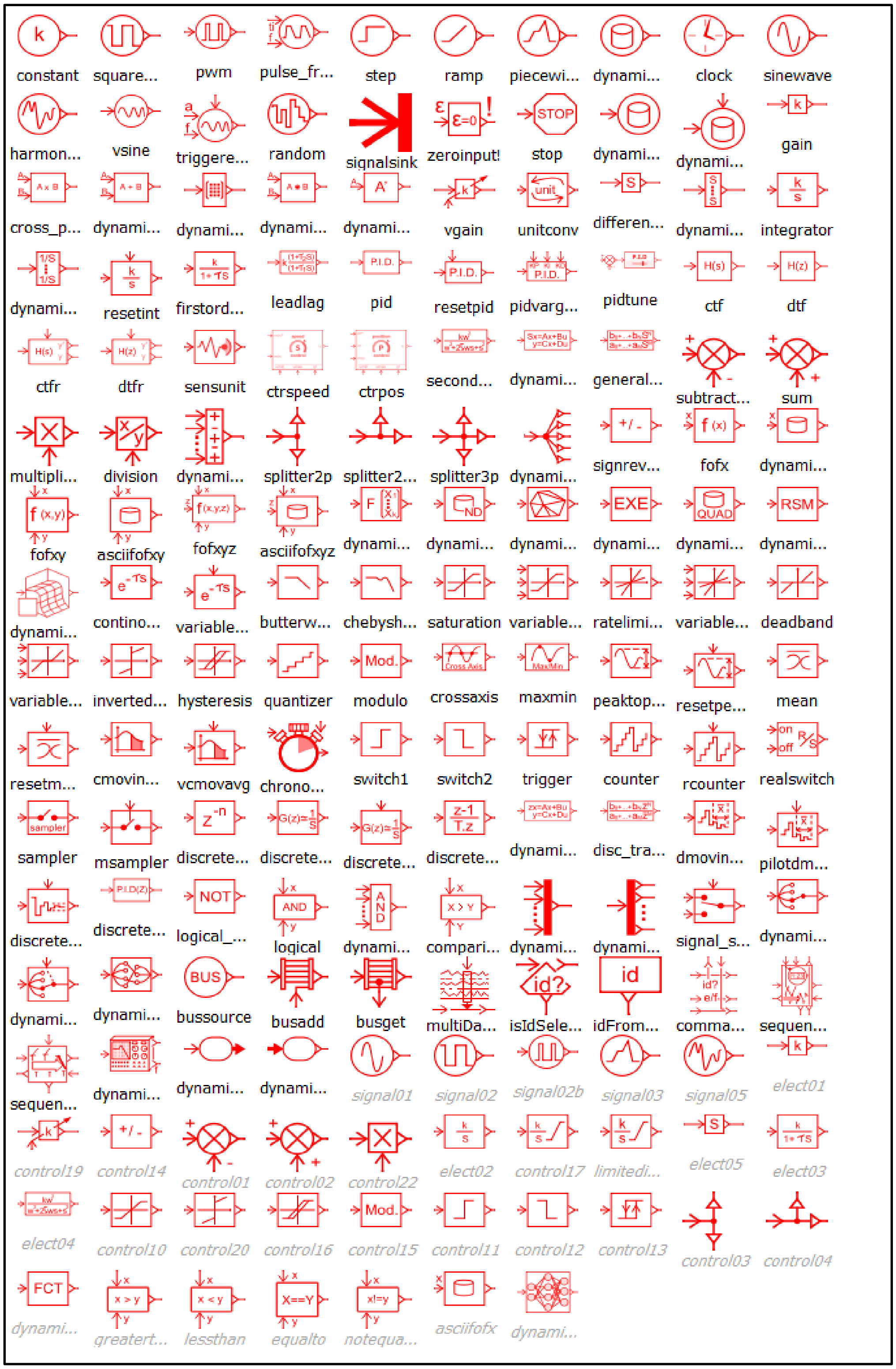


Figure C-2: Control system library used for Loops 1, 2, 3, and 4.

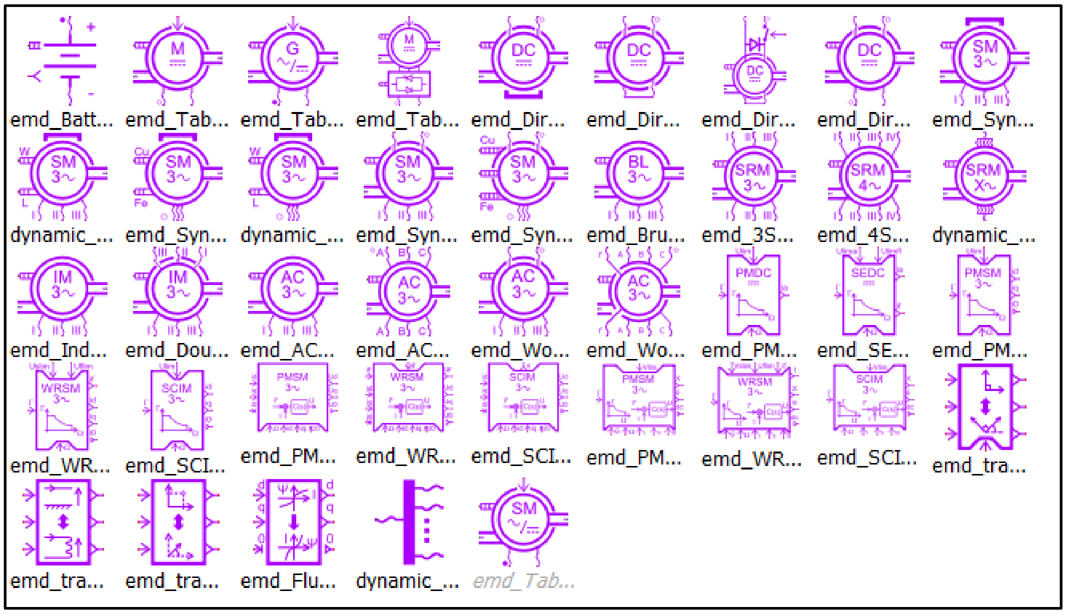


Figure C-3: Electrical components library utilized for Loops 2, and 3.

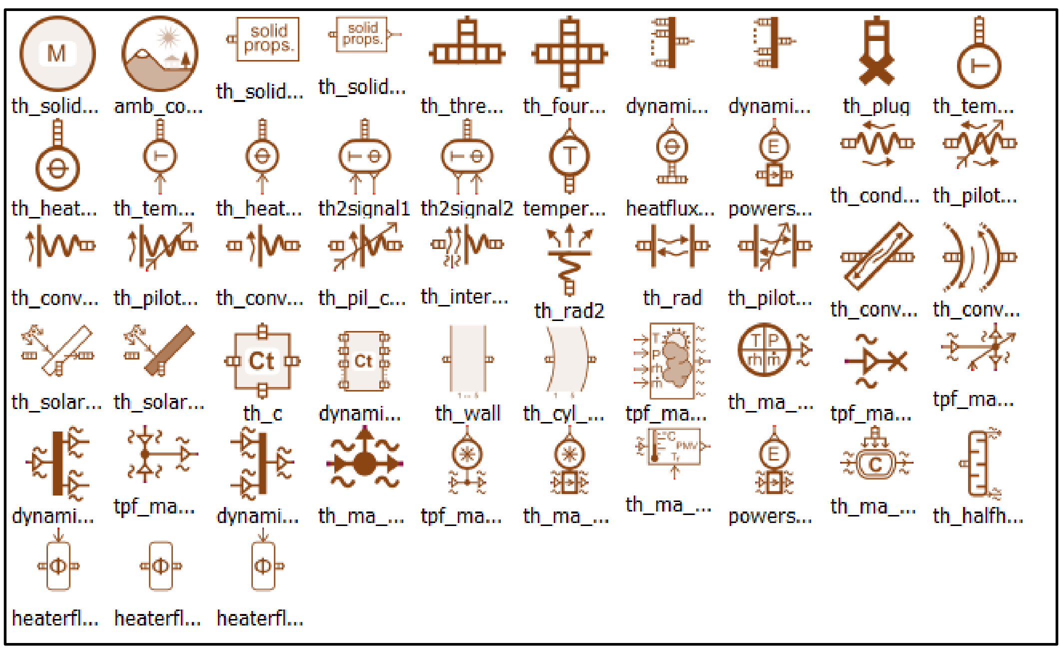


Figure C-4: Thermal library used for Loop 1, and interconnections between Loops 1, 2, 3, and 4.

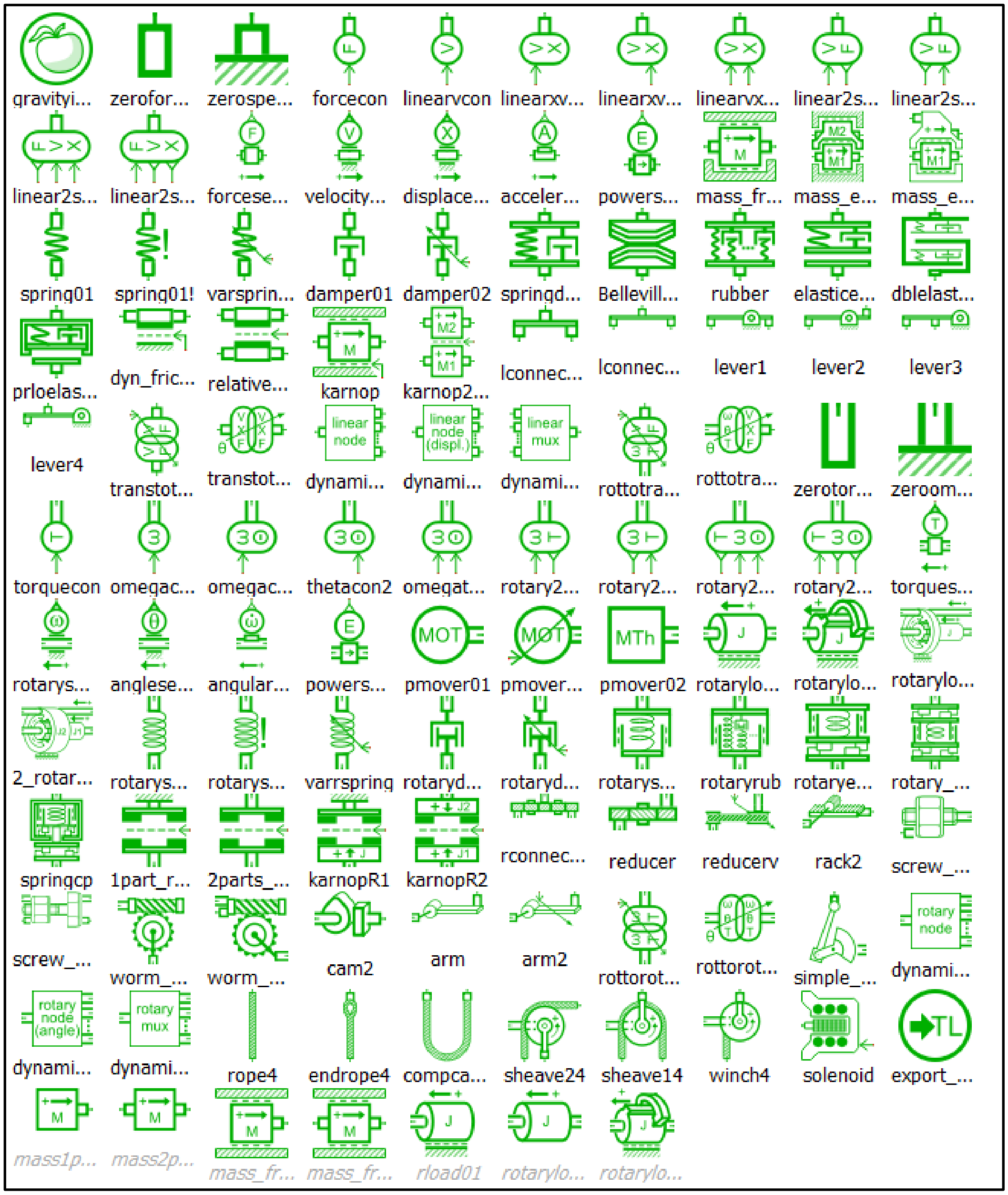


Figure C-5: Mechanical library used for Loops 2, and 3.

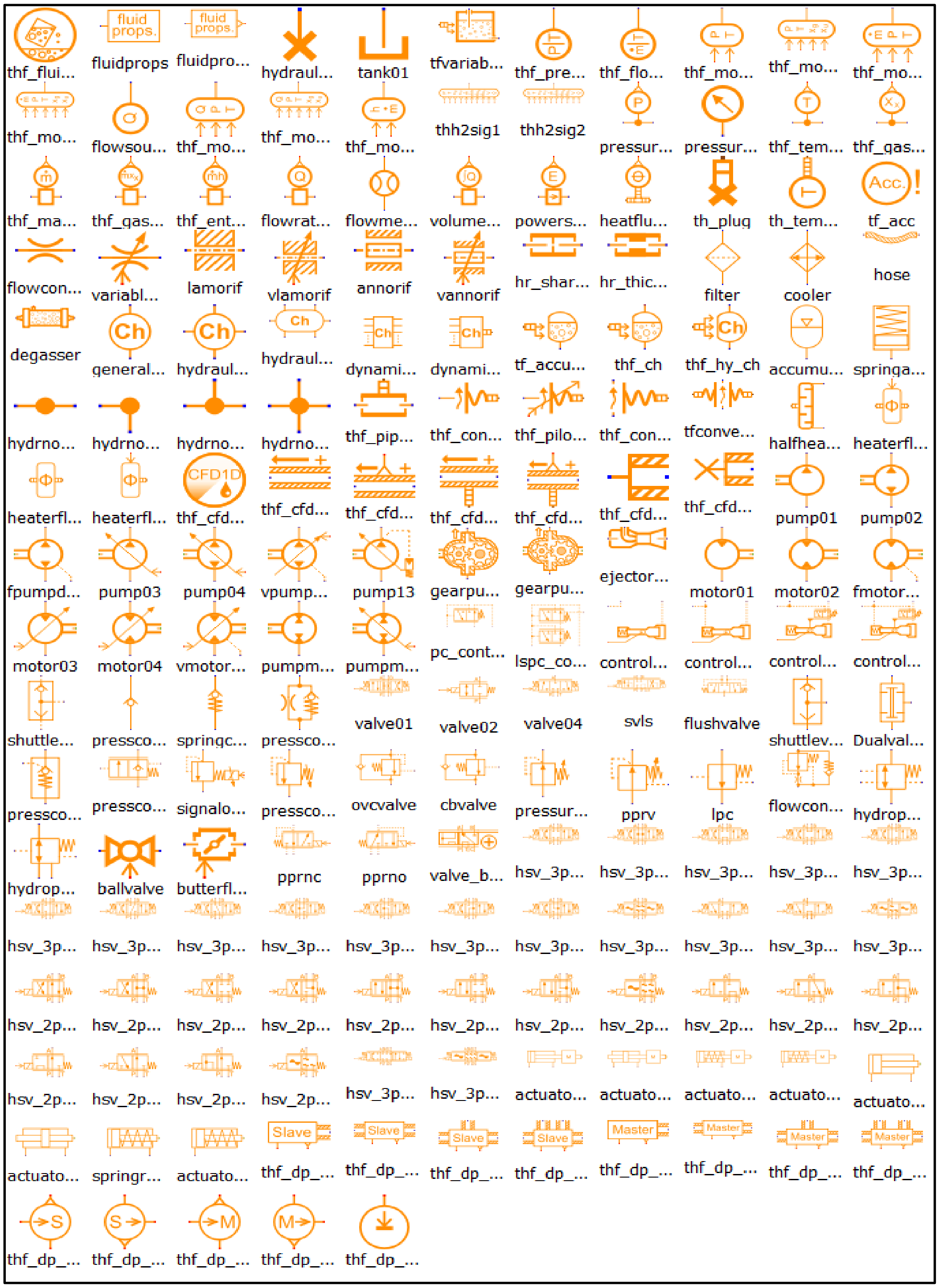


Figure C-6: Thermo-hydraulic library utilized for Loops 2, and 4.

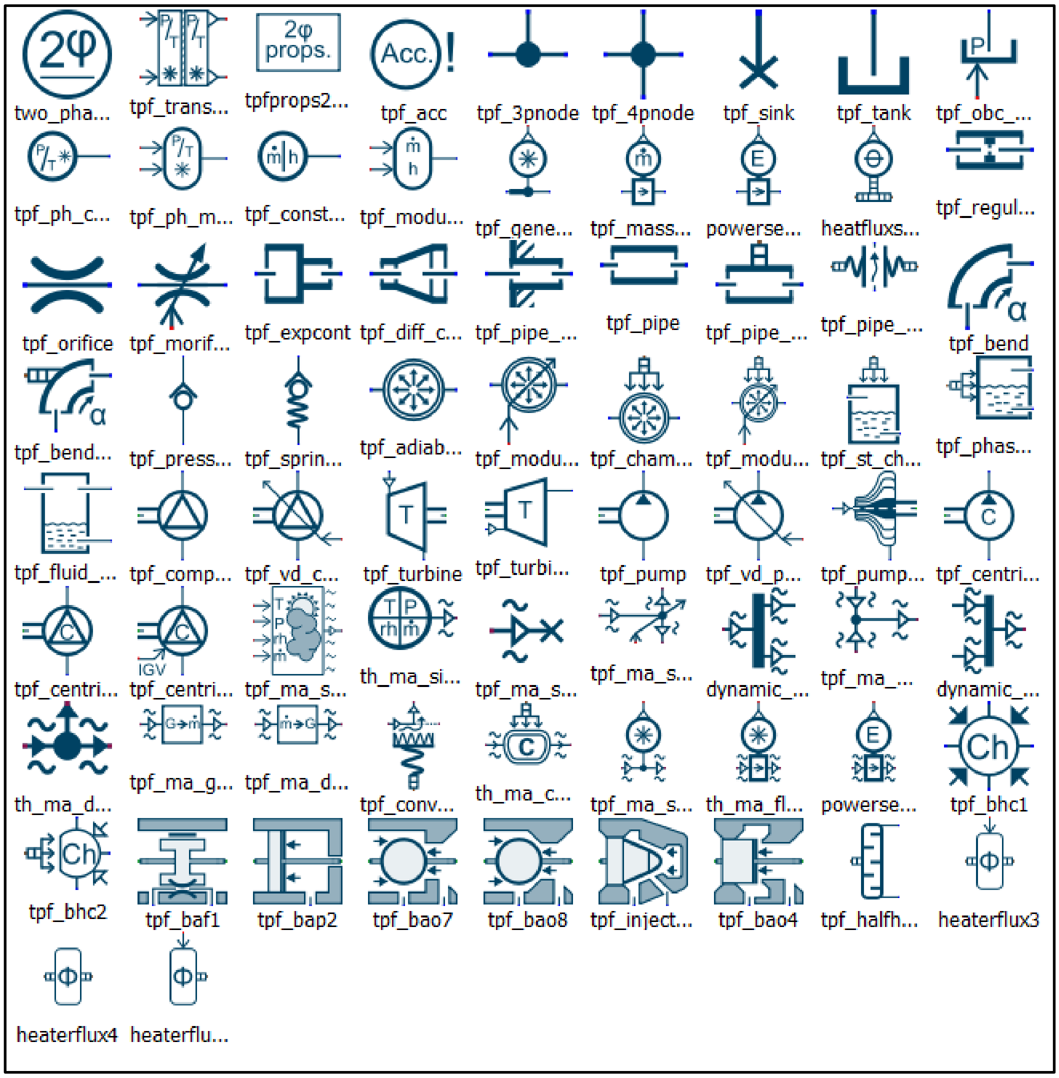


Figure C-7: Two-phase flow library for Loop 3.

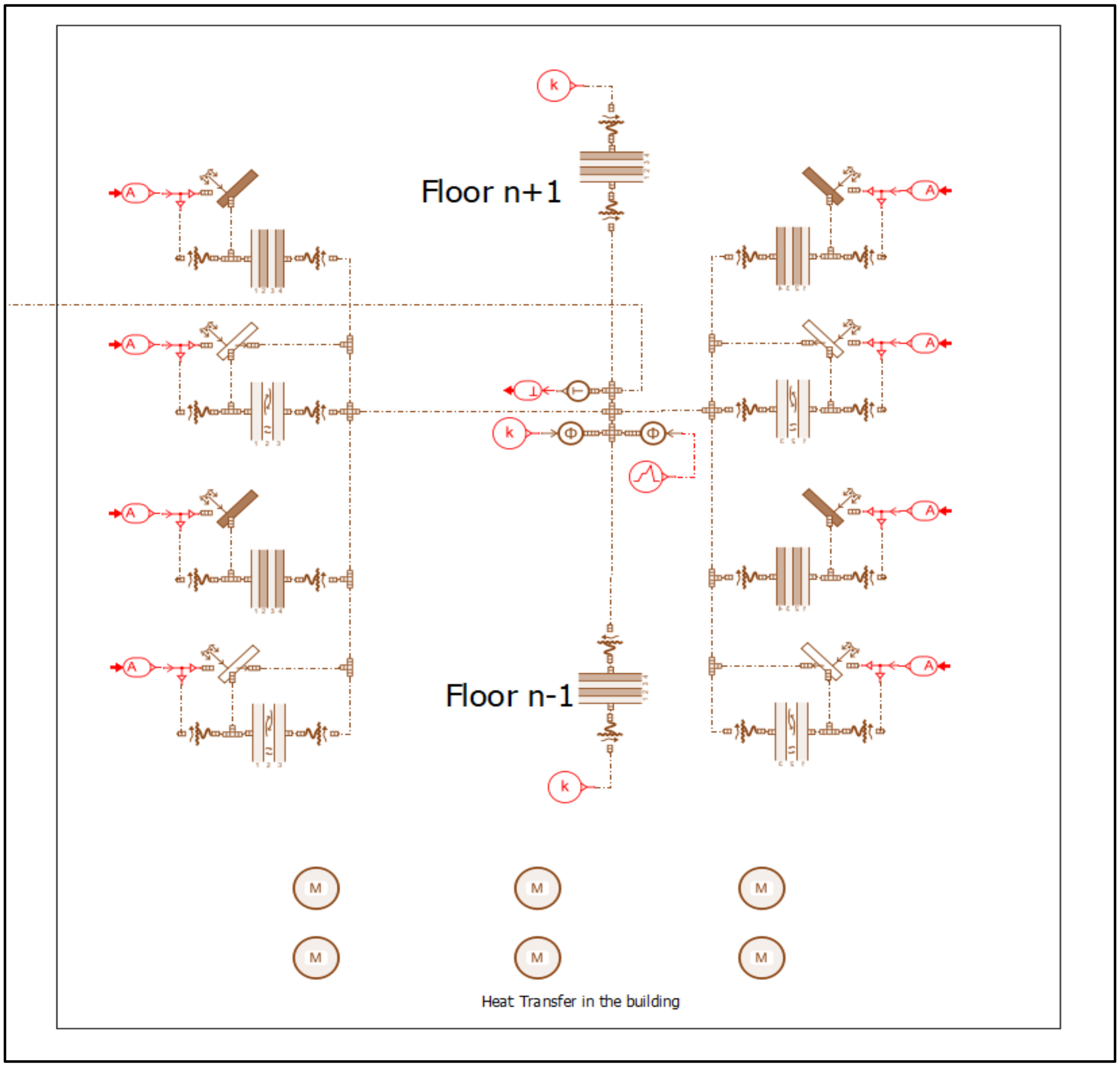


Figure C-8: Heat transfer in the building – model from Simcenter Amesim^{TM} (Loop 1).

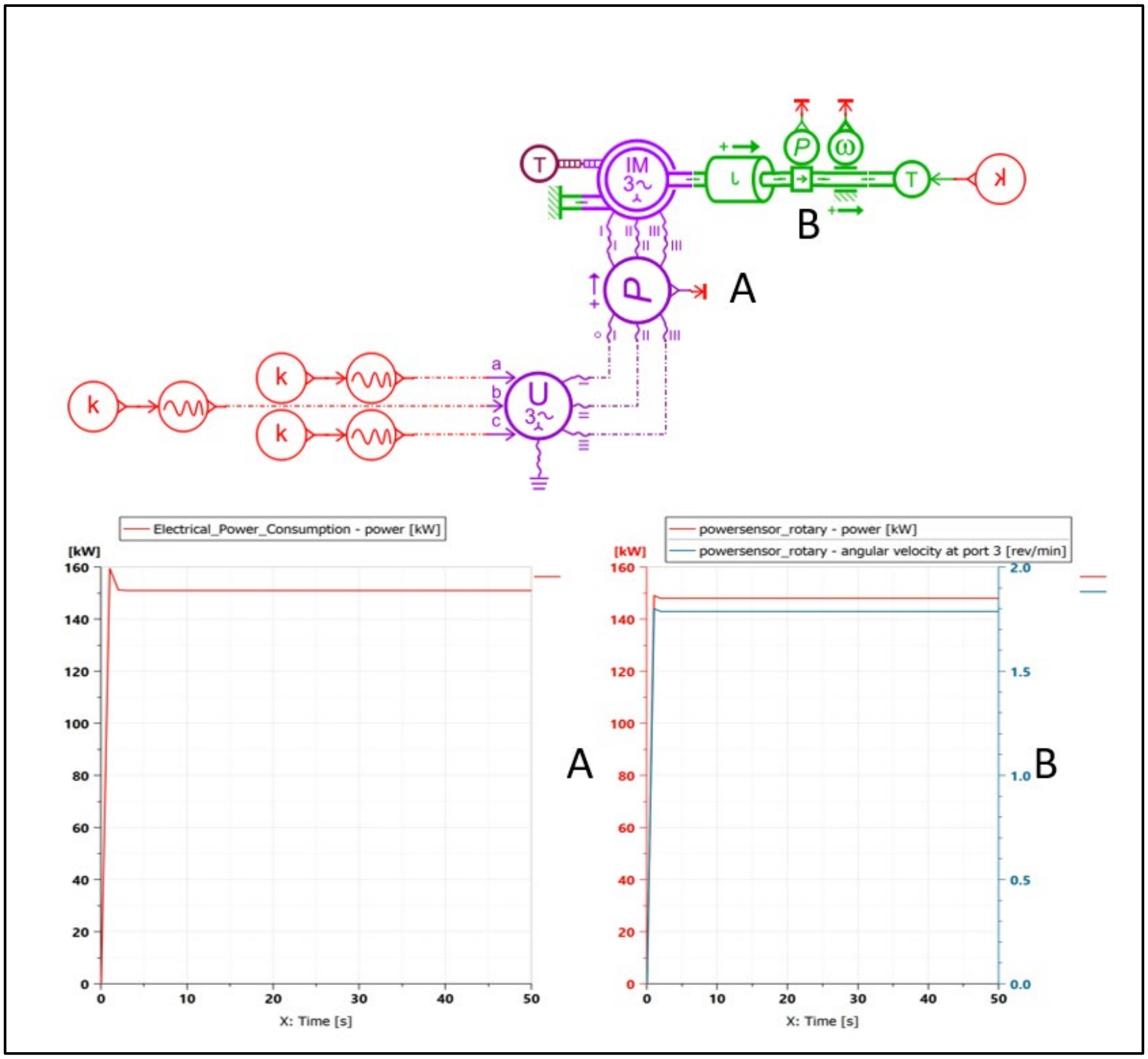


Figure C-9: VFD and induction motor architecture and tuning for Loop 2.

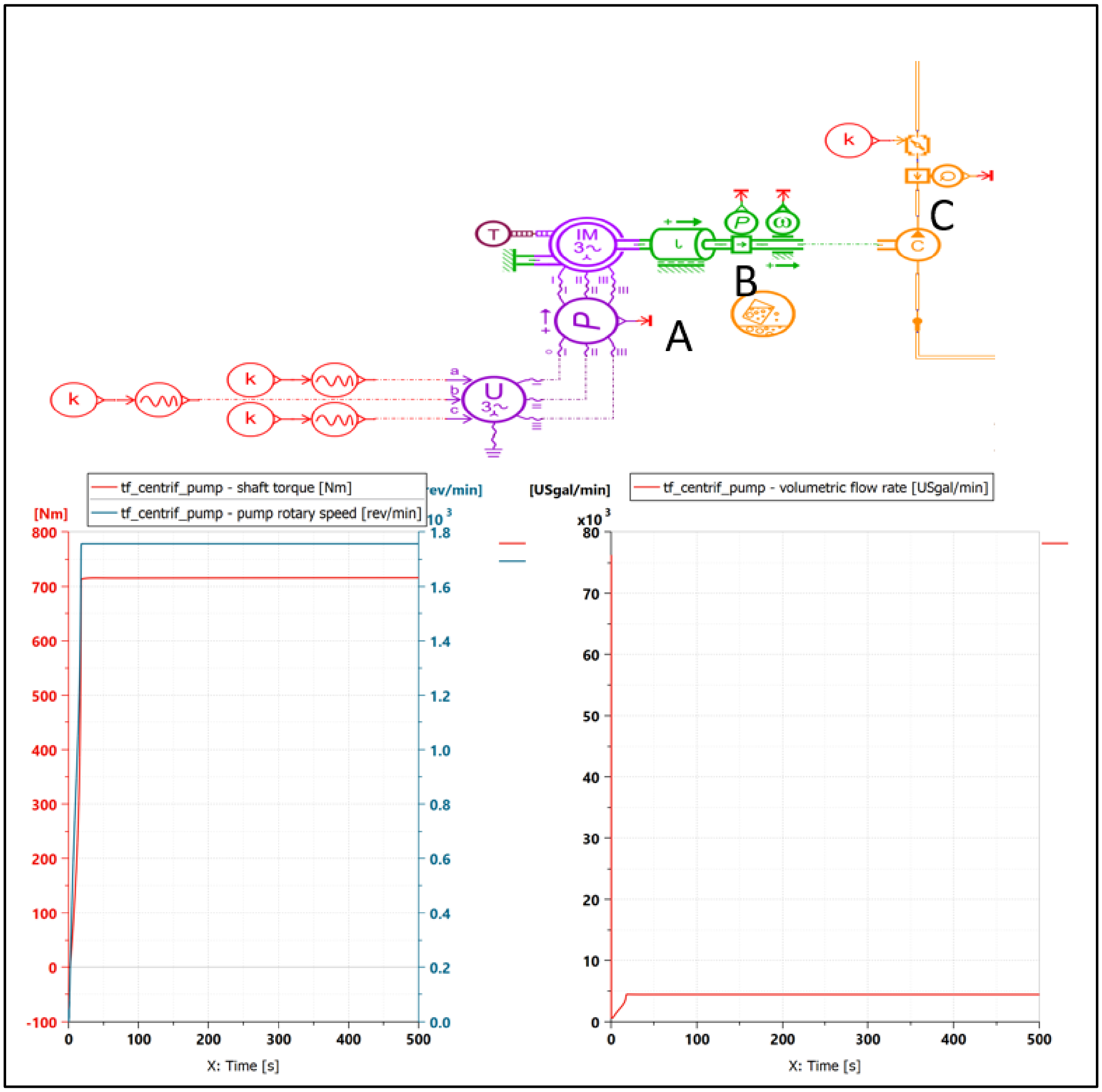


Figure C-10: Integration of VFD with centrifugal pump for Loop 2.

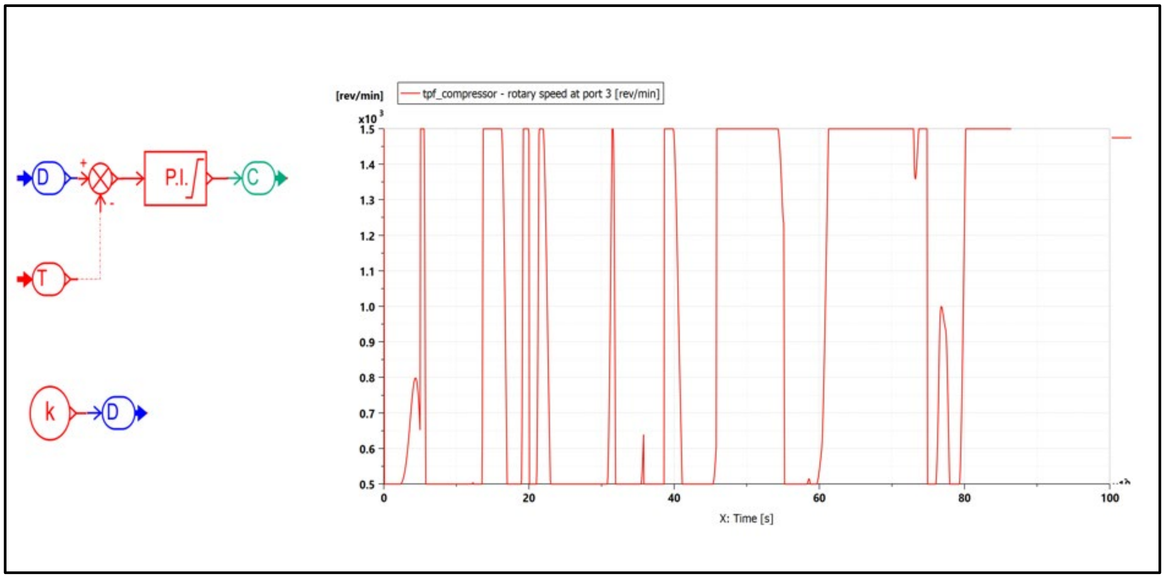


Figure C-11: PI control test for the compressor in Loop 3.

Appendix D

East Side Chiller Plant Specifications

In this section, east-side chiller plant specifications are presented. It includes general site and installation information, chiller, compressor, pump curves, and building side HVAC interface (Metasys by Johnson Controls), etc. (Courtesy of Clemson Facilities Group) are offered in Figures D-1 to D-10.

General Site Information

Customer Name:	Clemson University
Site Name:	Clemson University Campus
Site Short Name:	ClemsonSC
City:	Clemson
State:	S.C.
Postal Code:	29634
Country:	USA
Latitude:	34.68
Longitude:	-82.84017

Figure D-1: East side chiller plant site information.

General Installation Information

Installation Name:	East Plant LP
Short Name:	EastLP
Commissioned Date:	06/02/2015
Expiration Date:	
Partner Name:	JCI
Plant Profile	
Total Capacity:	2,800.000 Tons
Free Cooling:	No
CO2 lbs. per kWh:	1.846 lbs
Minimum CHW Flow:	879.0 gal/min
Square Footage:	1,000,000.0 sq ft
Performance Only:	No
Mobile Ready:	Yes
Customer Access Granted:	Yes
Predictive Free Cooling:	No
PFC Turned Over To Customer:	No

Figure D-2: East side chiller plant installation information.

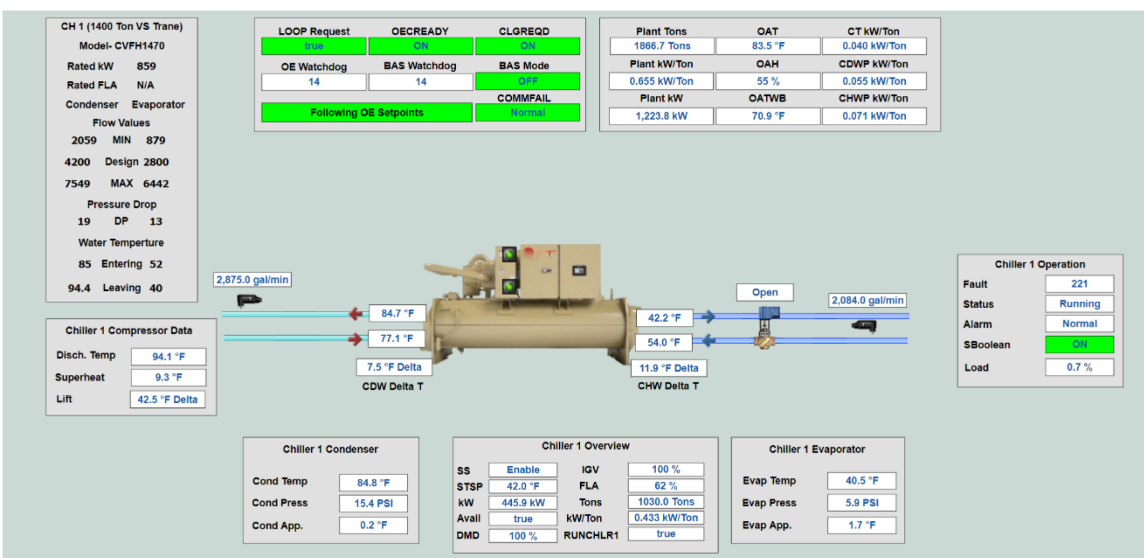


Figure D-3: Chiller 1 specification.

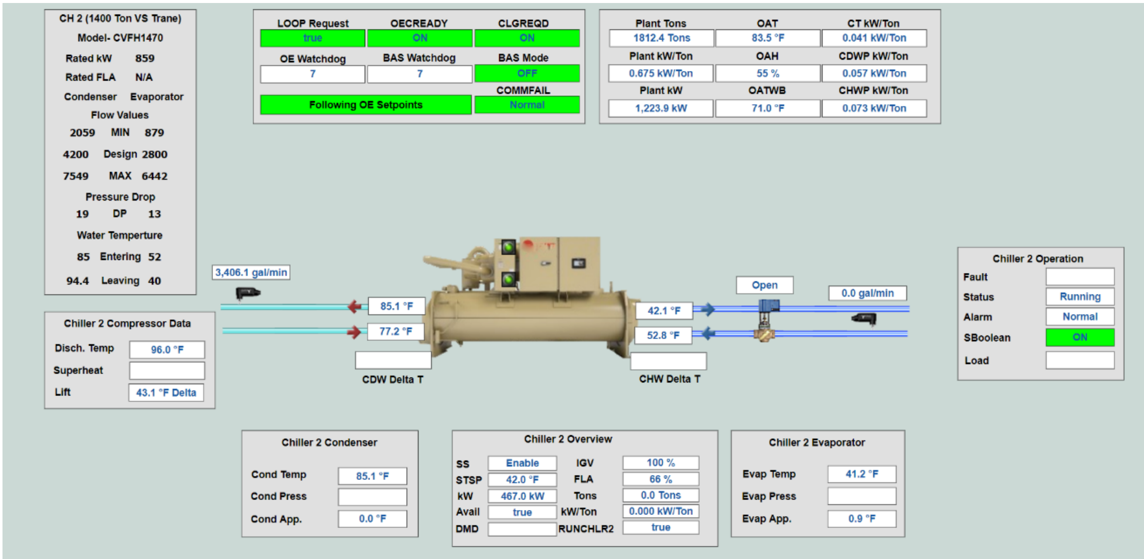


Figure D-4: Chiller 2 specification.

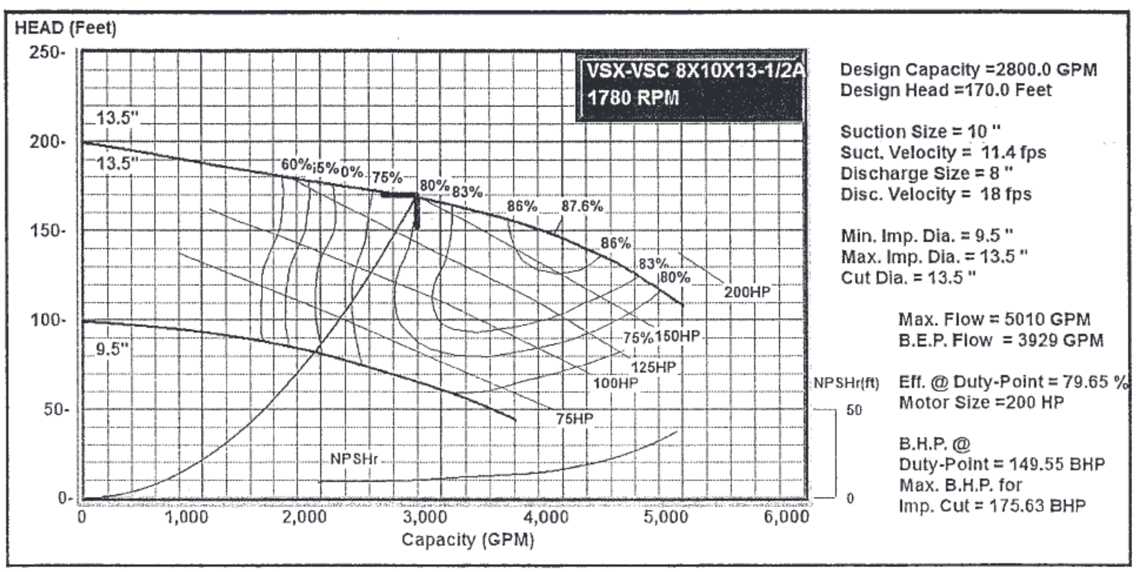


Figure D-5: Primary pump curves of chilled water loop (Loop 2).

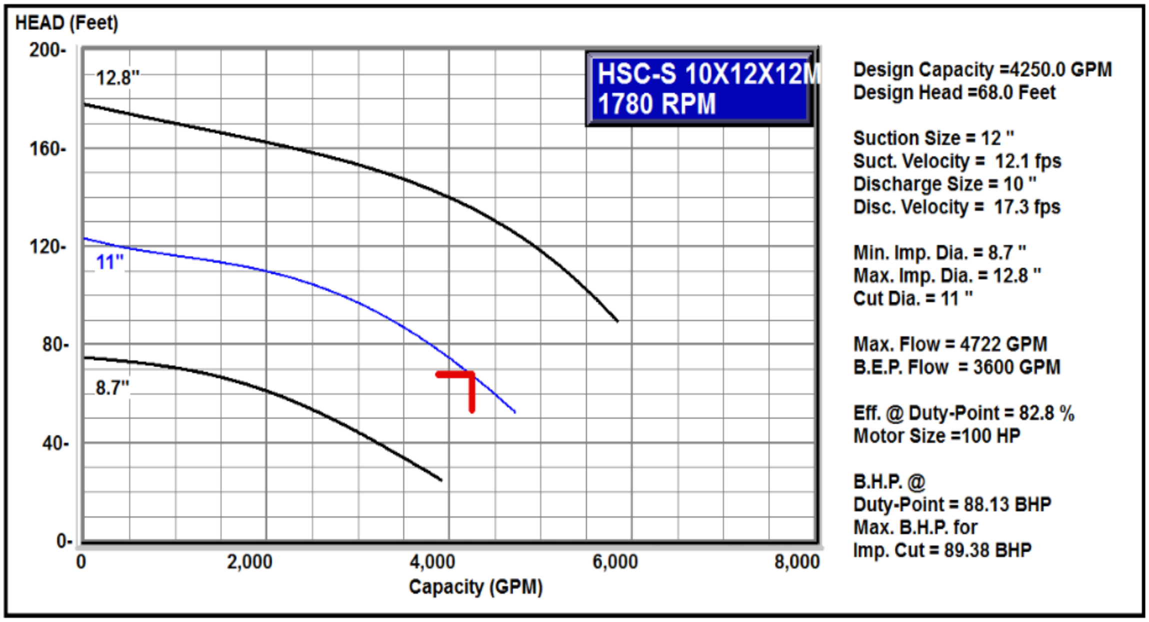


Figure D-6: Condenser pump curves for condenser water loop (Loop 4).

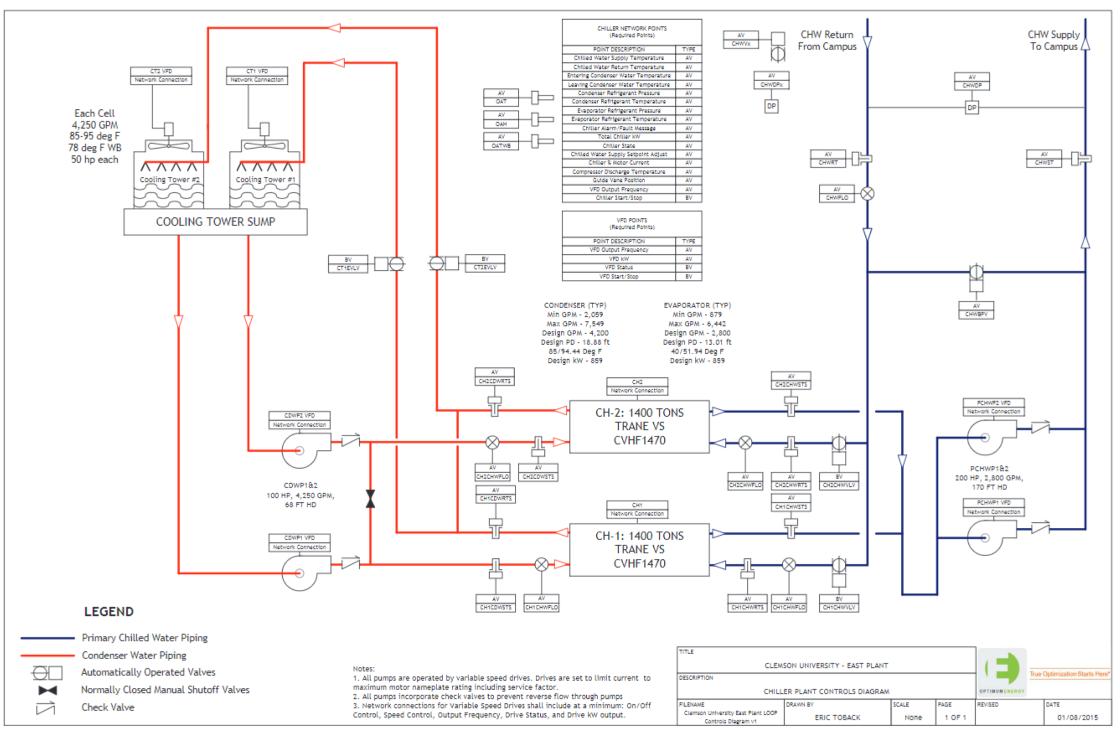


Figure D-7: Chiller plant controls diagram.

Figure D-8: East side chiller plant photographs.

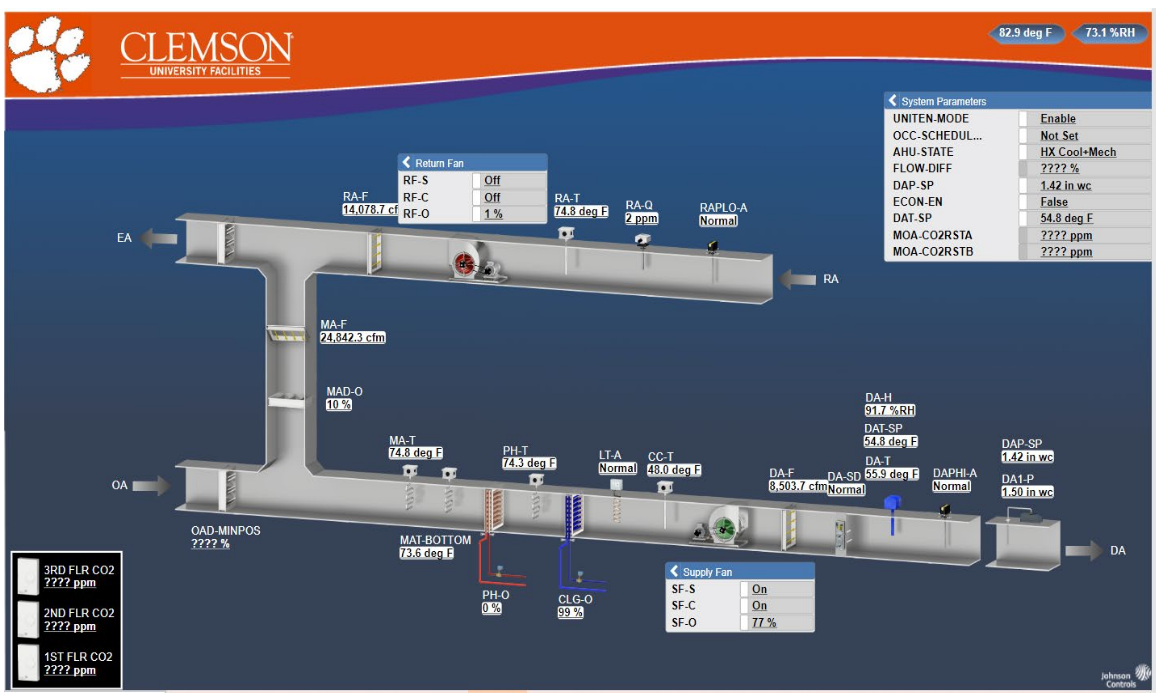


Figure D-9: Johnson-Control Metasys platform for Academic Success Center under East side chiller plant.

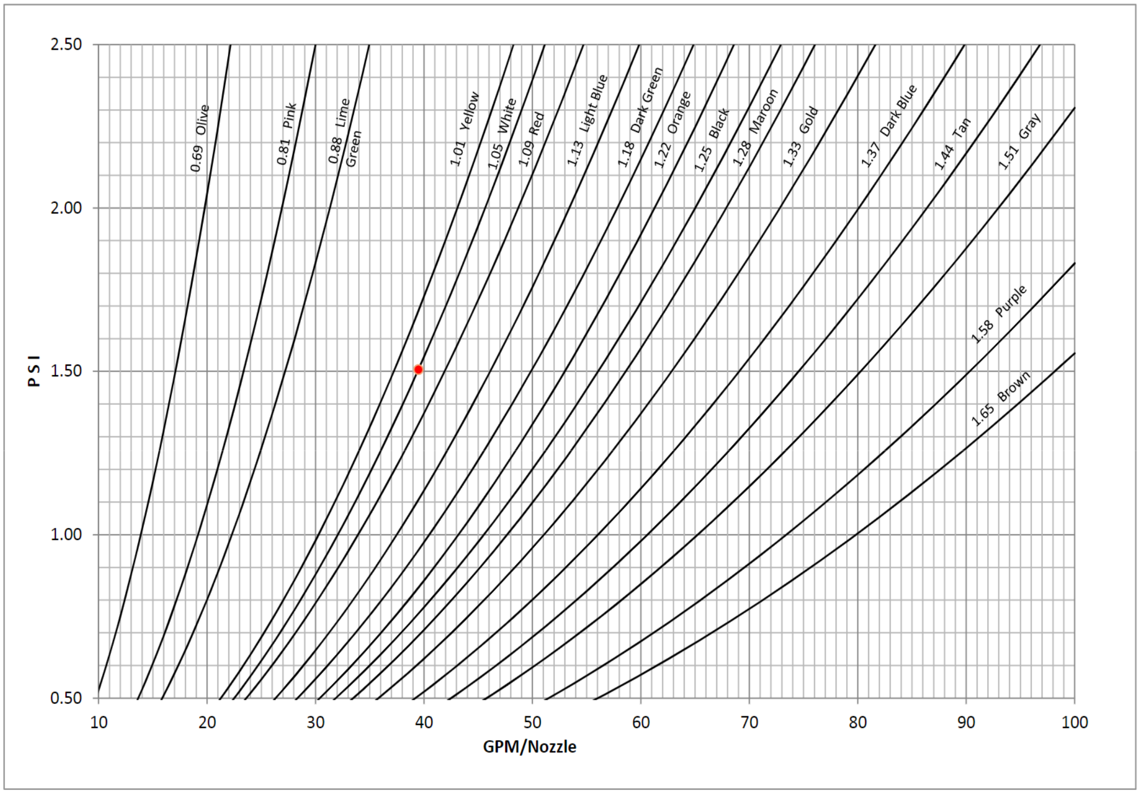


Figure D-10: Cooling tower nozzle selection curves for condenser water loop (Loop 4) – pressure versus flow rate.

Appendix E

Software Access

This section includes snapshots of some CAE models from the help section of Simcenter Amesim™. These CAE models from E1- E8 are used as a reference to develop the single-chiller HVAC system with VFD.

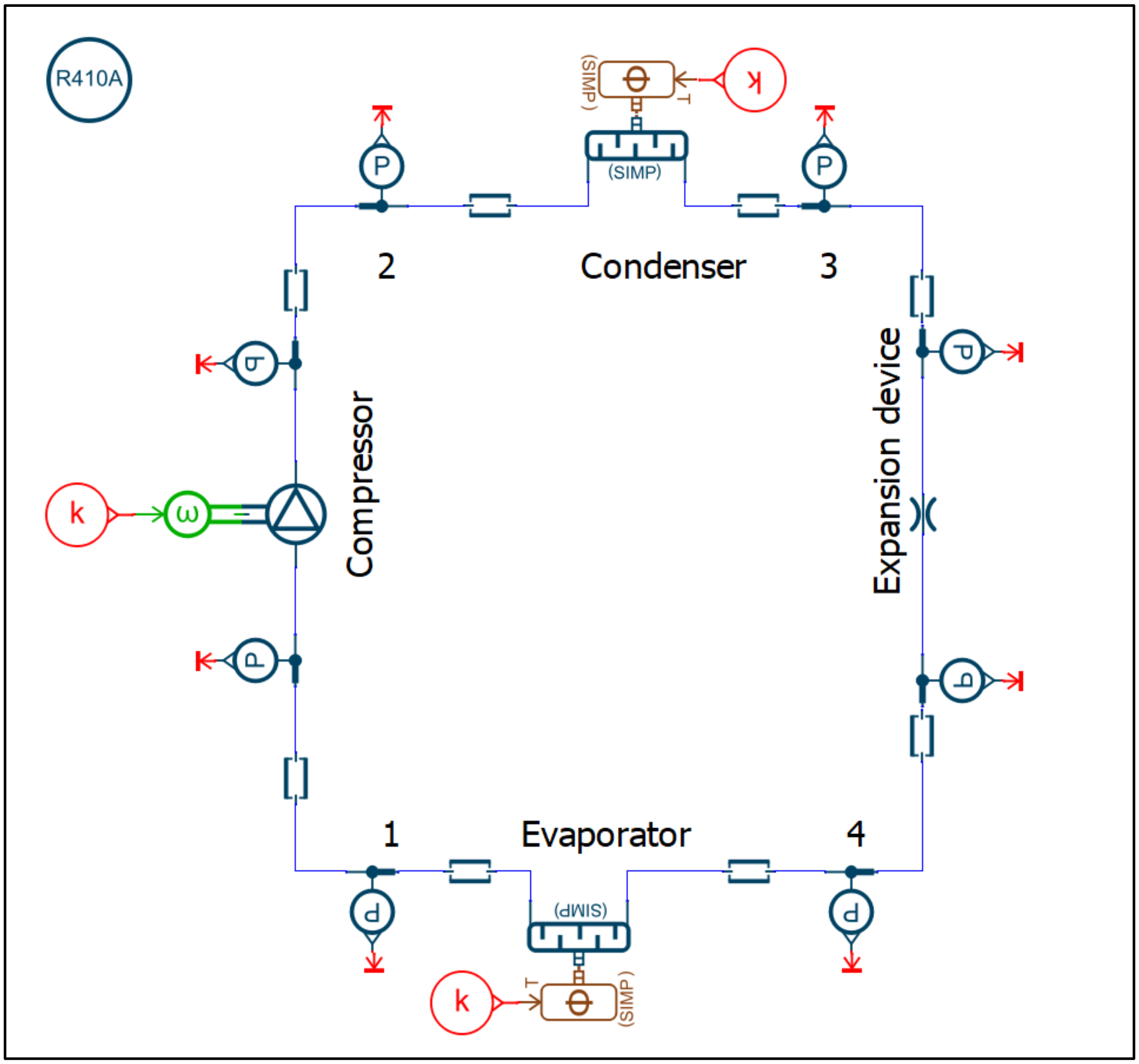


Figure E-1: Heat pump (reversed refrigeration loop) model with orifice as an expansion valve.

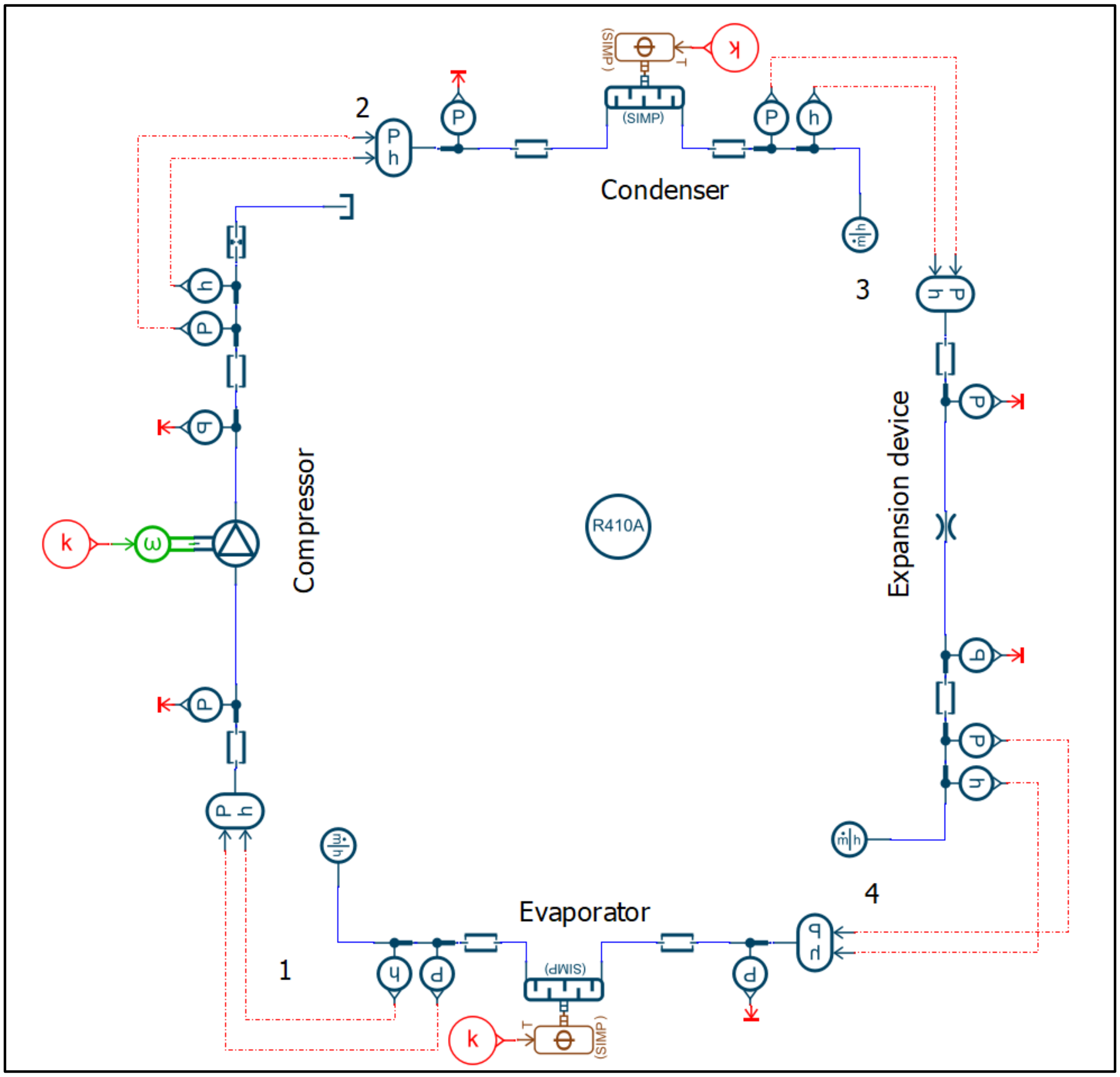


Figure E-2: Heat pump (reversed refrigeration loop) circuit with provision of supplying output variables of prior stage as input variables to the next stage.

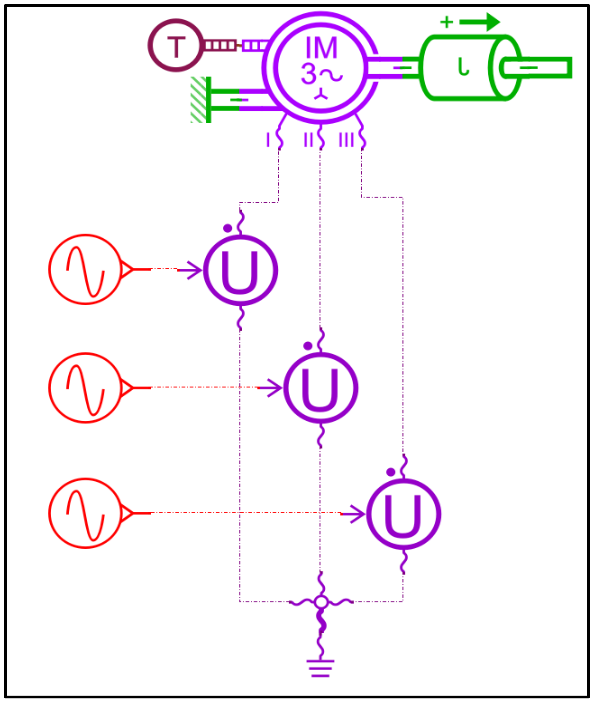


Figure E-3: Basic induction motor model with 3-phase AC voltage source and coupling attached.

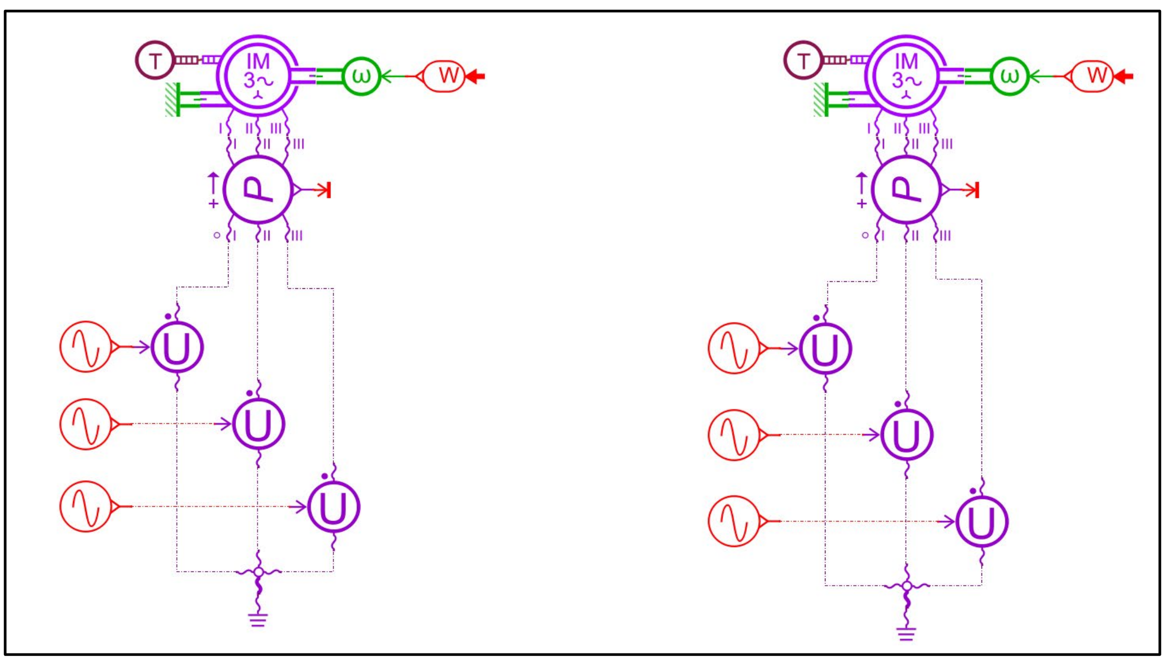


Figure E-4: Induction motor model with 3-phase AC voltage source and torque resistor attached to tune the motor for the required power output.

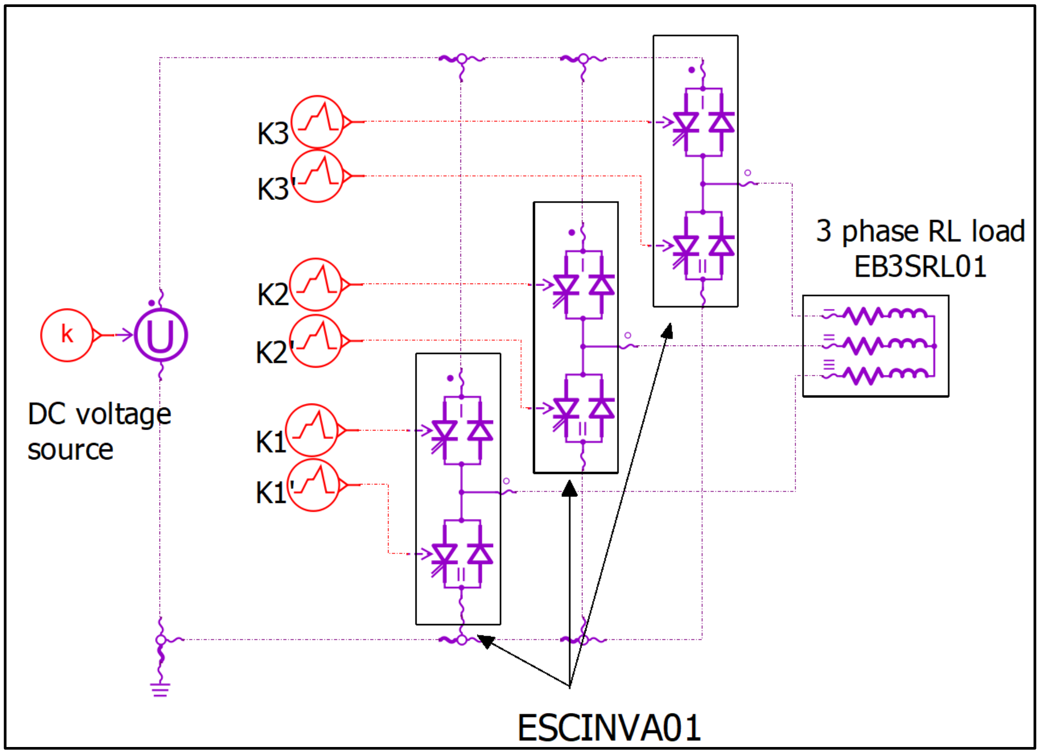


Figure E-5: AC-DC conversion circuit used in VFD.

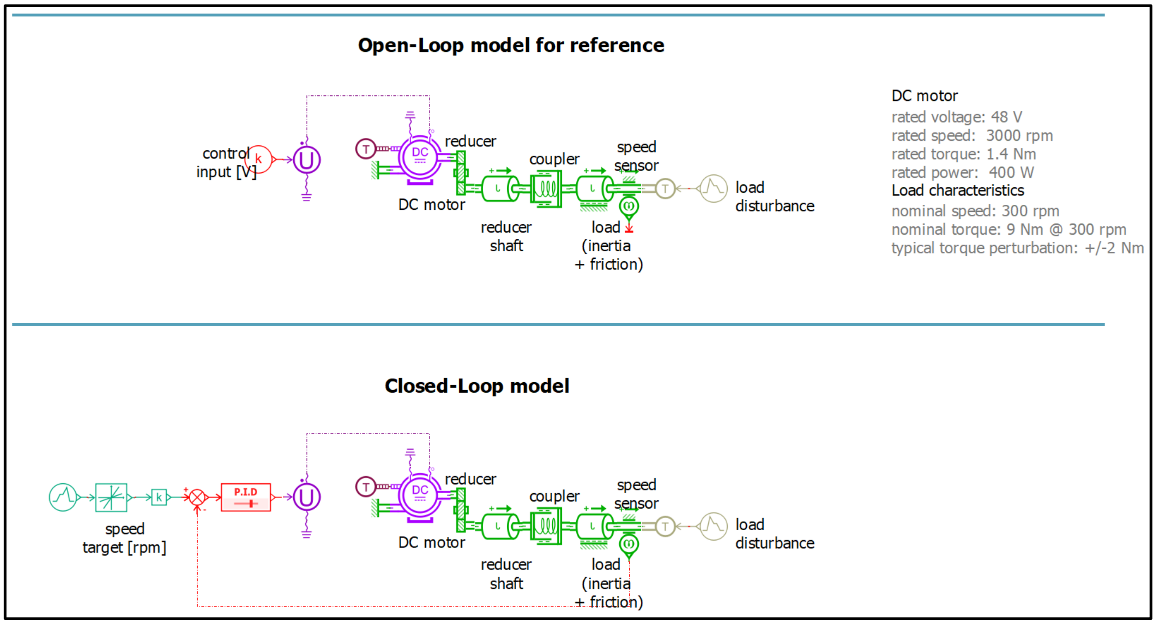


Figure E-6: Open loop and closed loop models of DC motor with implementation of coupling and gear reducer to measure the load.

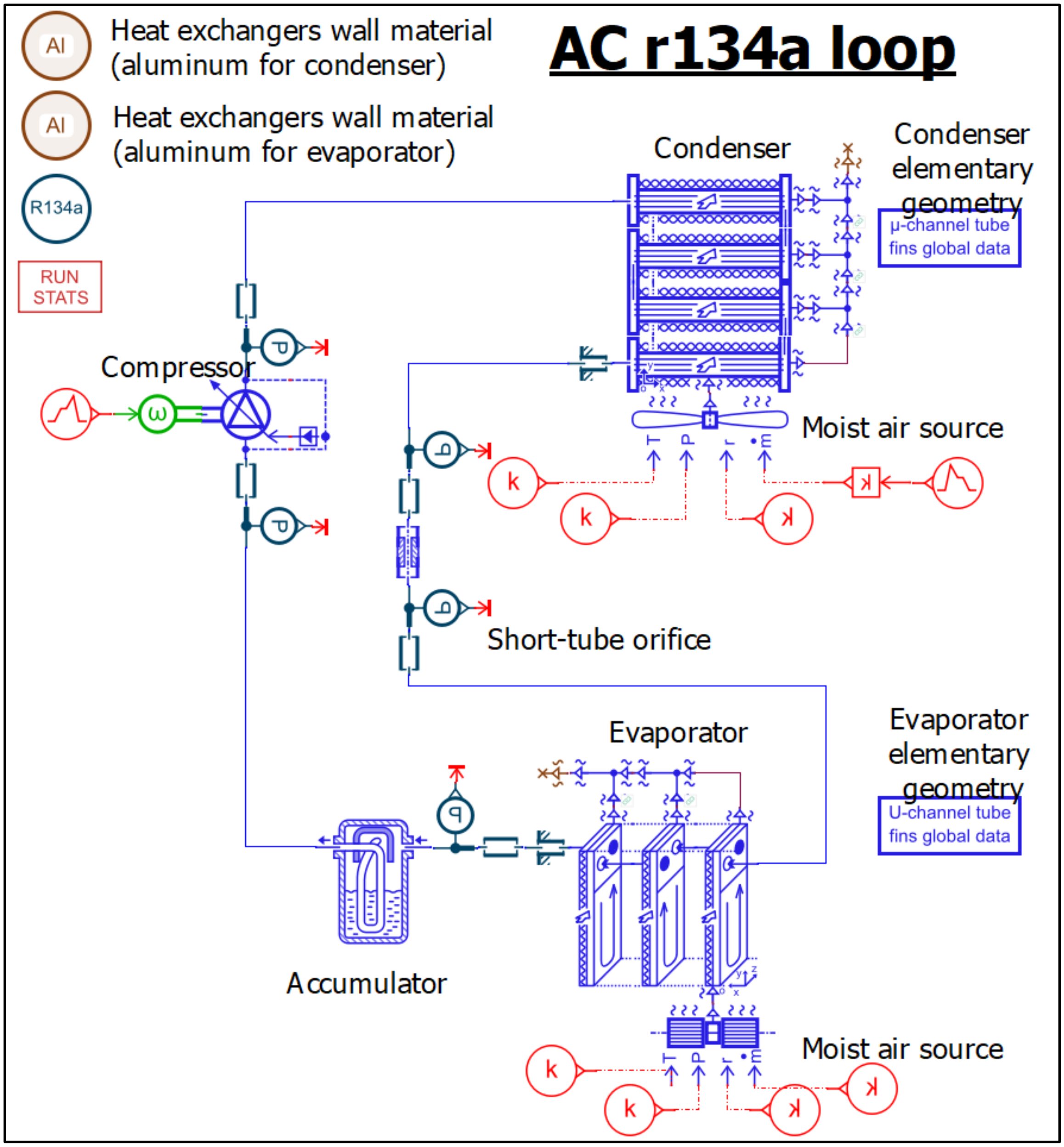


Figure E-7: CAE model of household refrigerator with evaporative cooling method for condenser.

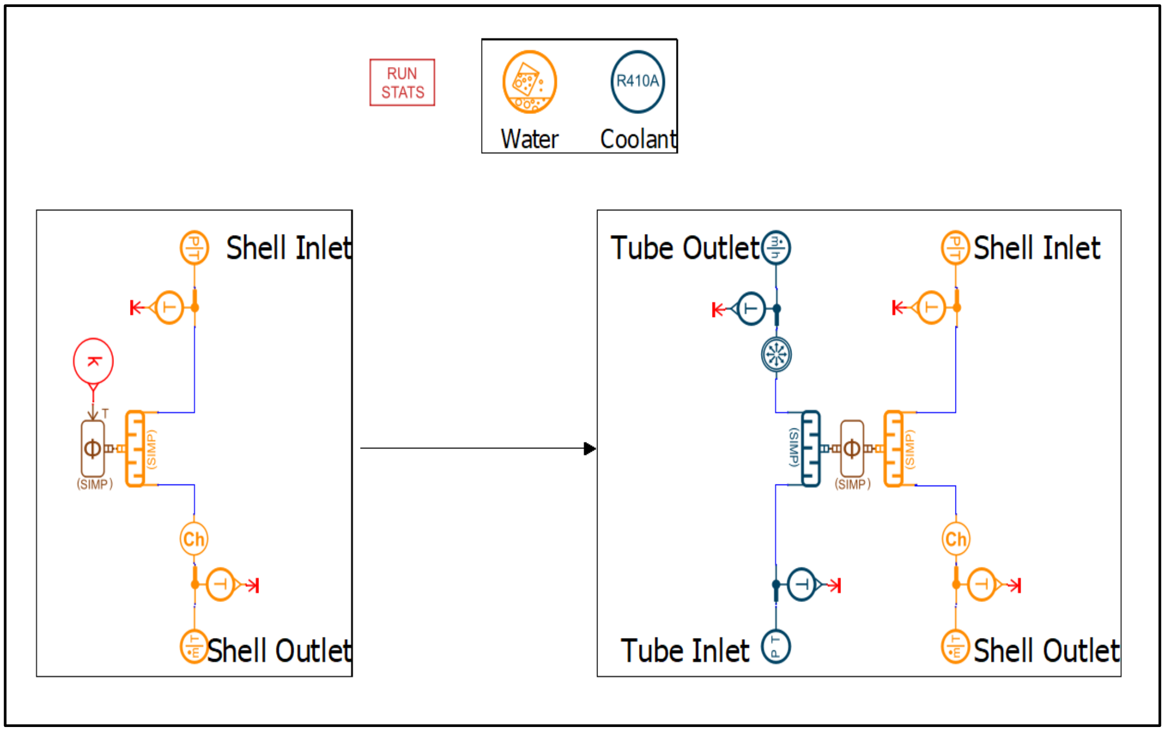


Figure E-8: Tube and shell heat exchanger configuration model with water as a fluid in the shell and R410A as a coolant in tubes.

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