INLET AIR CHILLING SYSTEM DESIGN FOR QURAYYAH INDEPENDENT POWER PROJECT (QIPP)

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ABSTRACT

The Qurayyah IPP project (QIPP) is approximately 100 km south of the Port of Dammam on the coast in the Eastern Province of the Kingdom of Saudi Arabia. The facility includes six (6) 2 on 1 combined cycle blocks consisting of twelve (12) Siemens SGT6-PAC 5000F gas turbine generating units (GTGs), twelve (12) heat recovery steam generators (HRSGs), six (6) Siemens SST6-4000 steam turbine generators (STGs), and six (6) seawater cooled condensers. Each of the twelve (12) Siemens SGT6-5000F combustion turbines is equipped with inlet air chilled water coils. Chilled water is supplied to the coils from two chilling plants where each chilling plant serves three power blocks and consists of a ten (10) million gallon thermal energy storage tank, eight (8) 5,760 refrigeration ton chiller modules, and ten (10) secondary chilled water pumps. The system is designed to lower the turbine inlet air temperature to 15 ºC (59 ºF) over a wide range of ambient conditions to increase the plant power output. This paper will explore some of the unique design aspects of the QIPP chilled water system including the following:

- In addition to the inlet air, the chilled water is also used for cooling the eighteen (18) generators.
- The turbine inlet air coil condensate is collected and reused as chiller cooling tower make up water
- The chilled water secondary loop and controls are designed to ensure both the inlet air coils and generators receive the proper amount of flow at the correct temperature under all operating conditions.
- The chiller system cooling tower blowdown is reused for HRSG quench water
- The chiller make-up water system is optimized to meet fluctuating demand.
- The chiller system sizing basis and use of the thermal energy storage tank is optimized for yearlong operation including during peak demand
- Measures were taken to ensure no water hammer occurs during multiple pump trips.

QIPP INLET AIR CHILLING SYSTEM DESIGN

1. PLANT INFORMATION

Owner	Hajr
EPC Contractor	Samsung C&T
Design Engineer	Sargent & Lundy LLC
Turbine Inlet Air Chilling Technology Provider	Stellar Energy
Turbine Supplier	Siemens
Location	Saudi Arabia (100 km south of Dammam)
Net Capacity	3927 MW
Commercial Operating Date	2015

2. CHILLED WATER SYSTEM DESIGN PARAMETERS

Item	**Value**
Chilled Water Temperature	7.2 ºC (45 ºF)
Design Entering Air Temperature to GT Coils (Dry Bulb)	46 ºC (114.8 ºF)
Design Entering Air Relative Humidity (RH)	42%
Leaving Air Conditions from GT Coils	15 ºC (59 ºF) , 99% RH
Leaving Chilled Water Temperature	22.5 ºC (72.5 ºF)
Maximum Cooling Water Inlet Temperature for Generators	25 ºC (77 ºF)
Thermal Energy Tank Storage	180,150 Refrigerant Ton-Hours Each
Total Installed Chiller Capacity	92,170 Refrigerant Tons

Item	Value
Maximum Chilled Water Flow Rate Per Gas Turbine	40,504 LPM (10,700 GPM)
Total Capacity of Coils (per GT)	43,094 kW (147,143,000 BTU/hr)
Maximum Condensate Recovery Flow (per GT)	579 LPM (153 GPM)

3. SYSTEM OVERVIEW

Two (2) chilling plants are provided where each plant serves three (3) power blocks. There are no cross ties between the chiller plants. Each chilling plant is comprised of the following components:

3.1. THERMAL ENERGY STORAGE (TES) TANK

- Provides load leveling operation to meet fluctuating demand by shifting some on-peak cooling to off-peak. Capacity is 3.9 hours of full load chiller capacity.
- When the load is less than the chiller output, the excess cooling is stored in the TES tank.
- When the load exceeds the chiller capacity, the additional demand is discharged from the TES tank.
- Total demand can be met by combination of chillers and the TES.
- The TES tank also serves as the neutral bridge to de-couple the primary and secondary loops. This allows the primary and secondary pumps to operate independently.
- In the event the TES is out of service, a 36” common pipe connecting the two loops functions as the de-coupler.
- The TES tank also provides thermal expansion for the system.

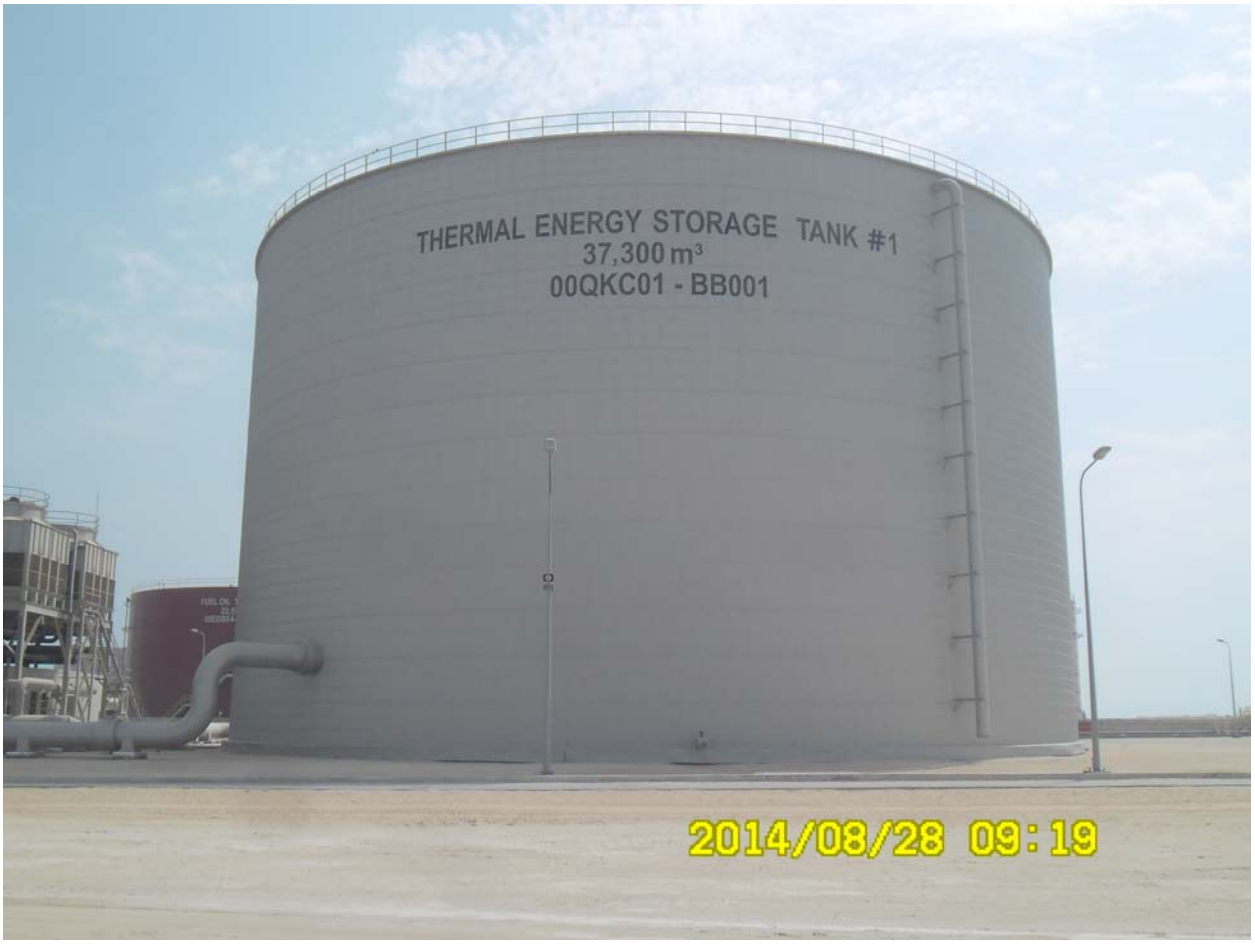

Figure 1 Thermal Energy Storage Tank

3.2. CHILLER MODULES

- Eight (8) chiller modules are provided per plant with primary chilled water pumps, condenser water pumps, evaporators, condensers, compressors, oil recovery units, oil heaters and coolers, and wet mechanical draft cooling towers.
- Each module is sized for 5,760 refrigeration tons.

Figure 2 Chiller Modules

3.3. SECONDARY CHILLED WATER PUMPS

- Ten (10) secondary chilled water pumps are provided with nine (9) working pumps with one (1) standby pump.
- The secondary pumps are constant speed but operate as a step function to vary the flow rate and overcome the pressure drop through the secondary loop.
- The intake and discharge of each pump connect to a common 56” pipe header that operates at 150 psi design pressure.

Figure 3 Secondary Chilled Water Pumps

3.4. GTG INLET AIR COILS

- Two (2) 16” connections are provided per coil.

3.5. PIPING SYSTEM

- A pneumatically operated valve located on the warm water header near the TES tank connection prevents a water hammer occurrence in the event of partial or total system trip. Valve closes within 4 seconds following a simultaneous trip of four (4) or more secondary chilled water pumps. The valve has a volume tank and UPS signal for closure during a plant blackout.
- Temperature control valves are provided at the outlet of the gas turbine (GT) inlet air chilling coils.
- An inlet air coil bypass line with a flow control valve is provided to ensure sufficient cooling water is provided to the generators during low flow demand to the coils. One bypass line is provided per power block (i.e. one per two CTs).

- A bypass line with flow control valve is provided for each block to bypass excess flow around the generator coolers when the inlet air coil flow demand exceeds the generator cooling flow.
- The chilled water flow to each block is measured by two orifice type flow meters. The generator cooler bypass flow is measured for each block. The difference between these flow measurements is the generator cooler flow. In this manner, the generator cooler flow can be regulated to a constant value.
- Condensate collected from inlet air coils is drained to two (2) sumps. Sump pumps send the condensate back to the chillers for cooling tower makeup. Up to 9100 LPM (2400 GPM) can be reclaimed from the coils.
- Chiller cooling tower blowdown is used for HRSG blowdown tank quench water.

Figure 4 Power Block Overview

4. KEY DESIGN ISSUES

4.1. INTEGRATION OF INLET AIR AND GENERATOR COOLING

A weather station is provided within each inlet air filter housing to measure the inlet air dry bulb and dew point and the downstream air temperature from the coils. This provides feedback to temperature control valves located at the outlets of the gas turbine (GT) inlet air chilling coils which regulate the chilled water flow. The system is designed such that the rate of increase or decrease in air temperature leaving the coils does not exceed 2 ºC (3.6 ºF) per minute.

A key issue in the design of the chilled water piping system was the integration of the inlet air chilling and generator cooling. The generators were cooled using chilled water in order to meet the required power factor capability at the generator terminals of 0.77. The maximum closed cooling water temperature for the plant was 43 °C (109 °F) which was too high to achieve the 0.77 power factor with the purchased generators. The generator cooling had to be integrated into the overall chilled water system in such a manner that the required cooling flow was always available to the generators and the cooling water temperature was always less than or equal to 25 °C (77 °F). The following schematic shows the piping layout for each power block:

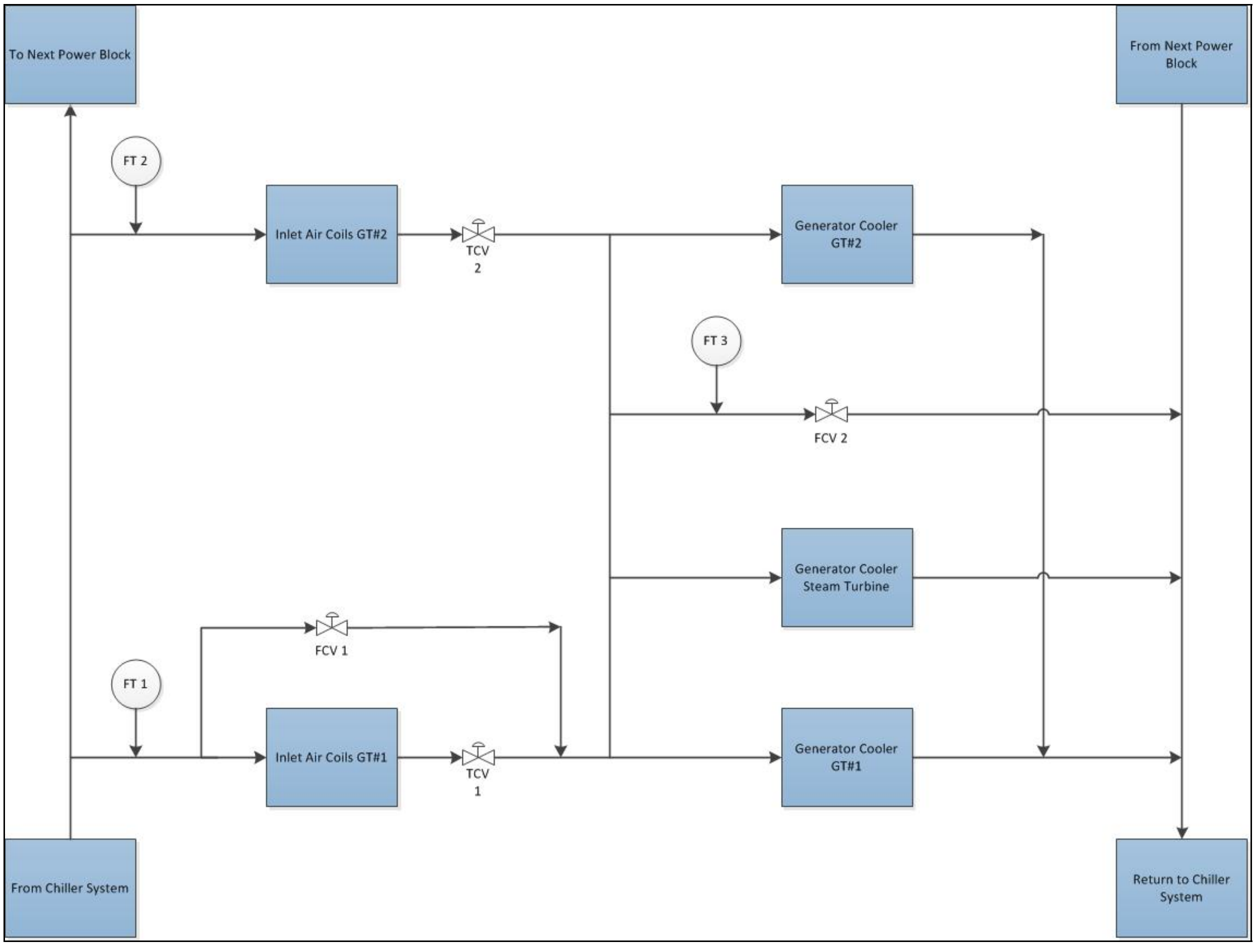

Figure 5 Power Block Chilled Water Piping Layout

The flow through the generators is calculated using the flow transmitter readings (FT 1 + FT 2 – FT 3). A pneumatically operated control valve FCV 1 opens during periods of low inlet air coil demand to ensure the total chilled water flow to the block (FT 1 + FT 2) is higher than the minimum generator cooling flow. During periods of high inlet air coil demand, control valve FCV 2 will open to bypass excess flow around the generator coolers where FT 1 + FT 2 – FT 3 is equal to the maximum generator cooling flow. Flows to the individual generator coolers are balanced using manual valves. A high generator cooler inlet temperature alarm will force control valve FCV 1 open. A lesson learned from the project is that the flow through FCV 1 should be better distributed to all of the generators. With the current configuration, Generator Cooler GT#1 sees a much lower cooling water temperature than the other generators when FCV 1 is open. Another consideration is that the design chilled water exit temperature from the coils is 22.5 °C (72.5 °F) and the maximum cooling water inlet temperature to the generator coolers is 25 °C (77 °F). This only provides a 2.5 °C (4.5 °F) margin. Thus it is critical that the chilled water system be operated at the correct temperature to avoid high temperature alarms from the generator coolers. During periods of low inlet air chilling demand, water at 7.2 ºC (45 ºF) is supplied directly to the generator coolers. This caused some condensation issues in the generator enclosures which had to be resolved. Any requirements for a minimum generator cooling water temperature should be reviewed before implementing this type of system.

The generator cooling load makes up about 34% of the yearly cooling demand for the system. During peak usage, the generator cooling load is about 18% of the overall cooling load.

4.2. WATER PRODUCTION, STORAGE, AND CONSERVATION

The chiller package is cooled using fresh water wet mechanical draft cooling towers located on top of the chiller modules. In a desert environment, the production, storage, and conservation of water are key issues. The cooling towers utilize desalinated water which is produced from seawater in a reverse osmosis (RO) treatment system. This water is slightly corrosive but with proper chemical injection and the cycling up of concentrations, the water is suitable for the towers.

4.2.1. Make-Up Water System Sizing versus Storage

The peak water use for the entire chilling system is 11,550 LPM (3,052 GPM) but it varies significantly depending on chiller load. In addition to make-up to the chiller cooling towers, desalinated water is also used for demineralized water treatment system feed, potable water production, service water, and HRSG blowdown quench water. The overall system had to be designed to ensure enough water is available to all the users while accommodating an occasional outage of the RO desalination system.

To design the overall desalinated water system, the make-up water demand for the chilling system was modeled using five (5) years of local weather data recorded on an hourly basis. Using this data Sargent & Lundy collaborated with Stellar Energy to model other parameters such as condensate water reclaimed from the inlet air coils, the level of chilled water storage in the TES tank, and cooling tower blowdown flows. By using hourly weather data instead of average data, we were able to model in detail how the system was expected to operate during peak periods.

The chilling system water usage was found to be highly variable depending on the ambient conditions which made the overall desalinated water system design a challenge. Usage in the winter months is relatively low (approximately 20% capacity) but in the summer months, the system may need to operate at peak demand on a nearly continuous basis. The chilling system water usage for both chilling plants at various conditions is provided below:

Table 1 Chiller Make Up Water Demand

Condition	Make Up Flow LPM (GPM)	Reclaim From Coils LPM (GPM)	Net Make Up Flow LPM (GPM)
Peak Demand	11,550 (3,052)	0 (0)	11,550 (3,052)
Minimum Demand (100% Capacity Factor)	2,097 (554)	0 (0)	2,097 (554)
Yearly Average (100% Capacity Factor)	5,921 (1,564)	985 (260)	4,936 (1,304)
February Average	2,464 (651)	62 (16)	2,401 (634)
August Average	10,389 (2,745)	3,172 (838)	7,216 (1,907)

To size the RO desalinated water system and storage tanks, an analysis was run using the five (5) years of weather data and various RO system capacities. The given RO system capacity would determine the required size of the desalinated water storage tanks. The results from the model were used to make a decision on the final RO system sizing which in turn set the required storage tank capacity. To minimize the effects on balance of plant equipment (such as seawater make-up pumps, auxiliary power systems, intake structure, etc.) and because sufficient space was available, rather large desalinated water storage tanks were selected in lieu of a large desalinated water system.

Figure 6 below shows how the desalinated water tank level was expected to vary through the year. At the start of the summer season the tanks would be full and the level would be drawn down throughout the summer.

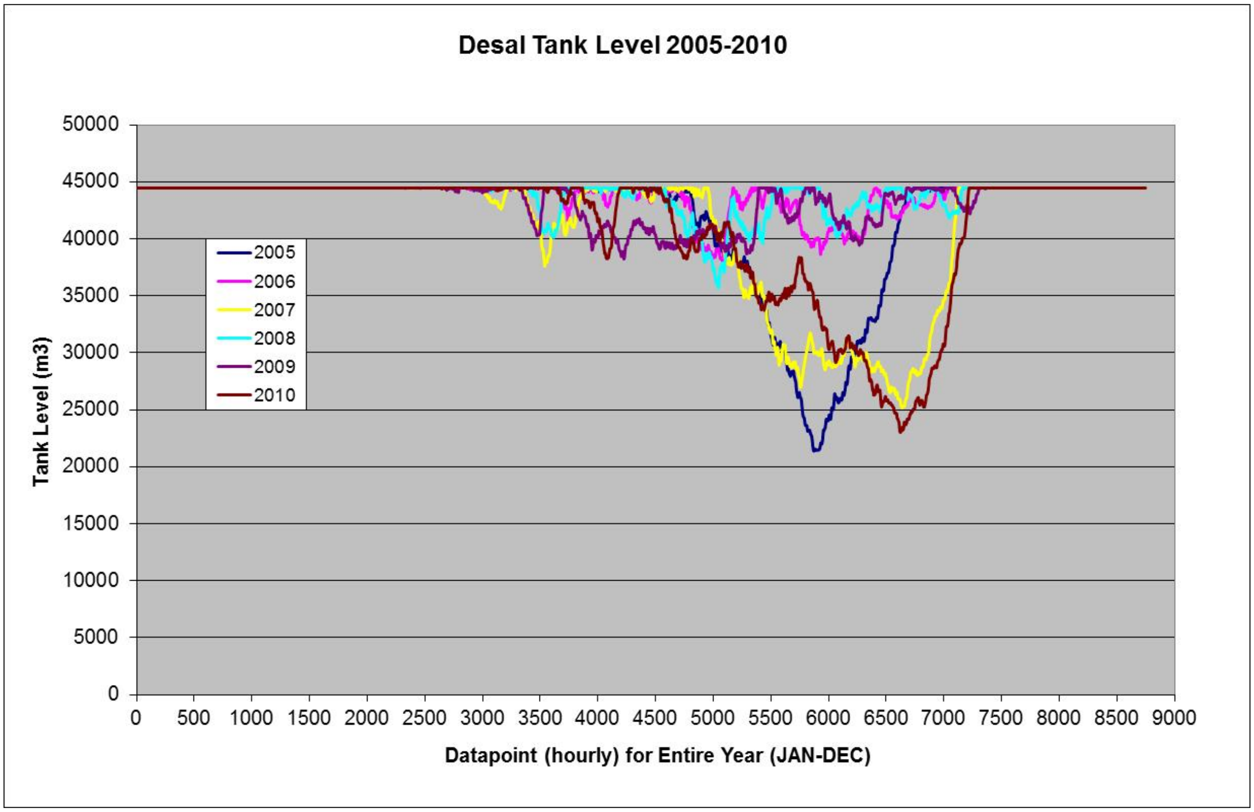

Figure 6 Desalinated Water Tank Level

4.2.2. Water Conservation

Table 1 shows that a significant amount of water can be reclaimed from the air inlet coil drains and reused as cooling tower make-up. During high humidity conditions up to 9000 LPM (2400 GPM) can be reclaimed from the coils. The coils are located behind the inlet air filter system and thus the drains will have high quality water. This water is collected in two (2) drain sumps and pumped directly to the cooling tower make-up. Reclaiming this water reduces the overall water consumption of the chilling system by about 17% over long term operation.

To reduce water usage, chiller cooling tower blowdown is sent to the HRSG blowdown tank drains as quench water. During periods of low chiller demand, desalinated water is used directly for quench water. The cooling towers could potentially be run at higher cycles of concentration to minimize make-up water, however, there are diminishing returns with this approach as any reduction in blowdown flow requires that more desalinated water be used directly for quenching.

4.3. CHILLER SYSTEM AND THERMAL ENERGY STORAGE TANK SIZING BASIS

QIPP was an EPC project where the sizing basis for the chiller system and thermal energy storage tank was established in the Minimum Functional Specification (MFS) for the project. The chiller system sizing was based on the average daily maximum ambient air enthalpy for the month of August. The TES tank was sized such that the system can supply the peak chilled water demand to the air inlet coils for five (5) continuous hours.

As noted earlier, the inlet air coils are sized based on a design entering air temperature of 46 ºC (114.8 ºF) with a relative humidity of 42% and a leaving air temperature of 15 ºC (59 ºF). The coils are amply sized and the inlet air enthalpy is only expected to exceed the coil design conditions for about 6 hours a year. Each chilling plant is sized to produce 46,085 RT of chilled water. Of this, 8,367 RT is for generator cooling, leaving 37,718 RT of chilled water for the inlet air coils. The total demand of the air coils at design conditions is about 73,520 RT and thus at this point about 50% of the chilled water comes from the chillers and the other 50% comes from the TES tank. After five (5) continuous hours of operation at the design point, the TES tank would become depleted and only the chillers would be available to supply the coils which can lead to a drop in net plant output. At 15 ºC (59 ºF), inlet conditions to the gas turbine, the net plant output is expected to be 3,927 MW. If the TES tank is empty and the inlet air is at the design conditions, a turbine inlet temperature of about 25.5 ºC (78 ºF) would be expected with the chillers running at full capacity and the net power output would drop to approximately 3,698 MW (a reduction of about 229 MW from the design point). Without any inlet air chilling, the net output drops to about 3,308 MW which is a reduction of about 619 MW from design.

Figure 7 below shows the predicted level in the TES tank when operating the plant at 100% load based on the August ambient data from 2008 to 2010. As shown, the expected chilled water storage in the tank is reduced to zero for relatively long periods of time. During this time the chillers would operate at peak load but they may not be able to reduce the turbine air inlet temperature to 15 ºC without the supplemental flow from the TES tank. Using the historical ambient weather conditions, the system performance can be predicted using a variety of chiller and thermal energy storage tank capacities which would provide valuable assistance in selecting the optimal capacity. Using the gas turbine correction curves, the plant output can be assessed at all conditions where the TES tank is depleted and the inlet temperature could exceed 15 ºC.

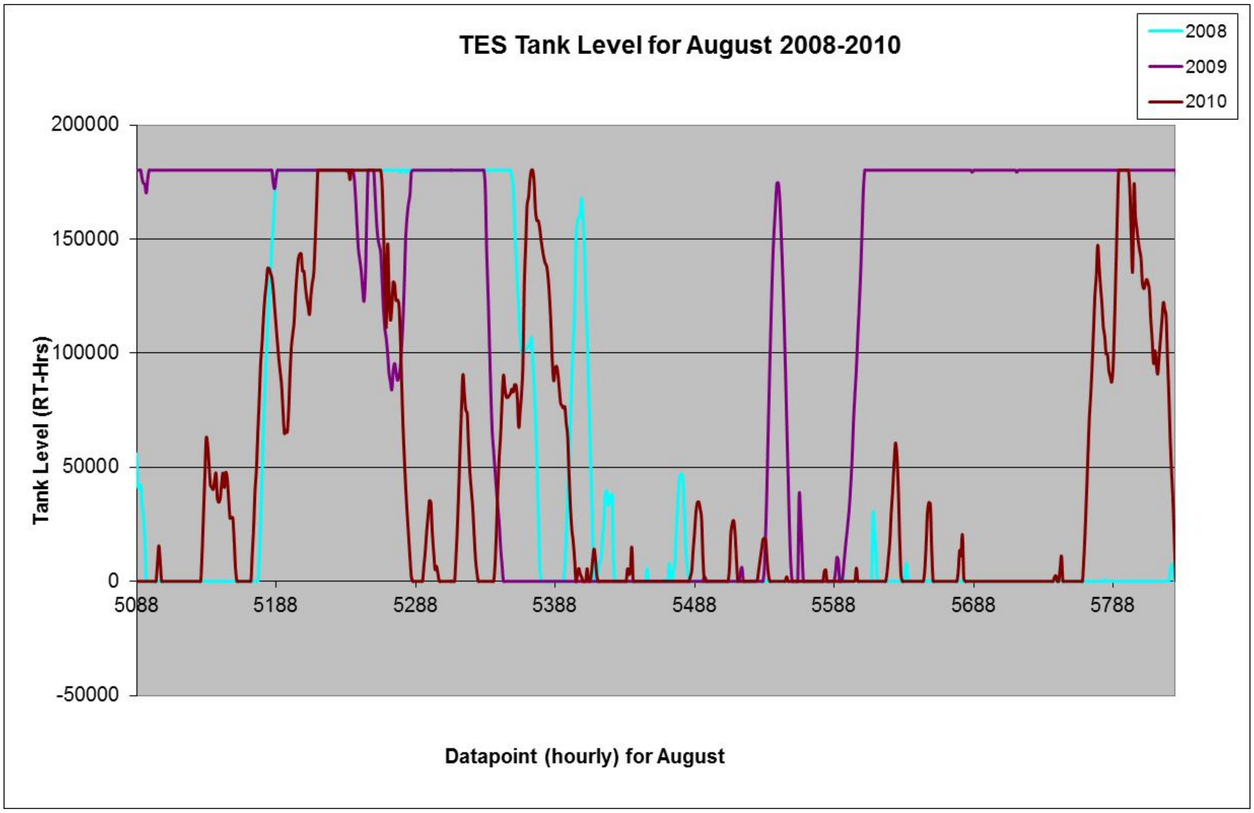

Figure 7 Predicted TES Tank Level

Sizing the chilled water system for extreme ambient conditions may not be feasible however modeling the system based on the hourly ambient conditions provides a clear picture of how the system will operate during periods of high demand. This will also allow the system operation to be checked against the requirements for establishing the maximum net dependable capacity for the plant.

4.4. WATER HAMMER PREVENTION

The secondary water flow for each chilling plant is about 243,000 LPM (64,200 GPM) and the secondary chilled water pump supply and discharge headers are 56” pipe. The chilled water return from the plant going to the chiller modules is also 56”. All of the chilled water piping is above grade. Due to the large flow rates and pipe sizes the system was analyzed for water hammer. It was found that during a multiple secondary chilled water pump trip, a severe water hammer event could originate in the return piping close to the TES tank. The hammer would then travel throughout the system where it could damage piping, supports, and other equipment. To minimize the severity of the water hammer, a 36” pneumatically operated control valve was installed on the return line near the TES tank. During the simultaneous trip of four (4) or more secondary water pumps, this valve will close in about 4 seconds. In doing so, the valve will slowly reduce the velocity of the water traveling towards the tank and prevent a water hammer. The valve has a volume tank and UPS signal for closure during a plant blackout. The diffuser in the TES tank was constructed of metallic piping instead of the plastic piping sometimes used to minimize the chance of damage during a multiple pump trip.

5. SUMMARY

- The QIPP project was successfully completed in 2015. The inlet chilling system is functioning as expected and at the design ambient conditions the plant is producing about 619 MW more than it would if a chilling system were not provided. Initially there were some tuning issues that had to be resolved but now the system is operating well.

- QIPP is currently the largest inlet air chilling system for an electrical generation plant in operation with a total capacity of 92,170 Refrigerant Tons (324.2 MW).

- A detailed analysis of the chiller system operating conditions using historical weather data can be very useful in determining the chiller capacity, TES tank sizing, expected plant output, expected maximum net dependable capacity, water consumption, water treatment capacity, and water storage tank sizing.

- Steps can be taken to reduce water consumption by reclaiming condensate from the coils and reusing cooling tower blowdown.

- Large chilling systems should be analyzed to evaluate possible water hammer events and mitigation strategies.