Case Study On Power Output Enhancement Through Thermal Energy Storage & Cooling Of Gas Turbine Inlet Air On Siemens V 94.2 Gas Turbines

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Abstract

The Performance of Gas Turbines, operated either as a simple cycle or a combined cycle, is critically constrained by the prevailing ambient temperature, particularly in arid and tropical climates. The gas turbine performance is highly sensitive to the compressor inlet temperature. The output of gas turbines falls to a value that is less than the rated output under high temperature conditions that often occur during the summer season. The gas turbine engine output improves if the air temperature is decreased at the compressor inlet to increase the air density. Cooling the inlet air to the gas turbine increases the mass flow rate and improves the gas turbine performance. Using the Thermal Energy Storage for gas turbine inlet air-cooling offers an economical solution when short duration capacity enhancements are required.

This paper reviews the (Thermal Energy Storage Inlet Air Cooling) TESTIAC impact on the performance of a 445 MW gas turbine located at the M/S Konaseema Gas Power Limited (KGPL) in Deverapalli (village) Ravulapalem Andhra Pradesh, India.

The study of the power demand in each month indicates the same pattern. They show the peak time, at the time interval from 10:00 to 16:00.The high temperature ambient substantially reduces the power plant output, in the Summer Season (March 1st to May. 31) when the power sale is most valuable. Inlet air chilling with TESTIAC will be installed in the KGPL to increase the output during "on-peak" (5 hours/day) in the summer when maximum unit performance is required. .

The designed TESTIAC system is capable of lowering the inlet air temperature of SIEMENS BM 380 V 94.2Gas turbine (GT) to 15^oC at the 45^0C ambient temperature of a hot summer day. The gas turbine capacity enhancement will be around 72MW. A Chilled Water Storage System uses inexpensive off-peak (19 hours/day) power at night to generate the stored energy in the chilled water for inlet air-cooling during peak demand (5 hours/day) periods.

Keywords: *Gas turbine, power enhancement, Thermal energy storage, Chilled water*

1. Introduction

Gas turbines (GT) have been used for electricity generation in most countries around the world. In the past, their use has been generally limited to generating electricity in periods of peak electricity demand. Gas turbines are ideal for this application as they can be started and stopped quickly enabling them to be brought into service as required to meet energy demand peaks.

However, due to availability of natural gas at relatively cheap prices compared to distillate fuels, many countries around the world, e.g. Jordan, use large conventional GTs as base load units, while small ones to meet any shortages in available electricity supplies occurring during an emergency or during the peak load demand periods. Such systems, especially those operating in an open or simple cycle have the disadvantage of being least efficient and so the unit cost of generated electricity is relatively high.

Gas turbines are used widely in power generation, gas transfer stations and petrochemical industries (GE Energy, 2006) [1]. The site ambient conditions, especially the temperature, have great influence on gas turbines performance (Brook, 1998) [2]. Since the air density is decreased during warm days, the mass flow rate through the turbine is decreased. Therefore, it causes a drop in the output power.

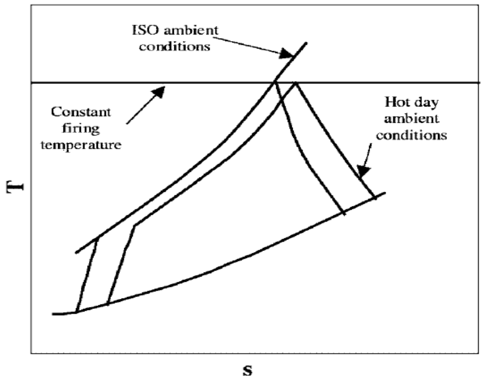


Fig.1. T-S diagram for a hot day

Moreover, the compressor work increases due to the divergence of constant pressure lines in T–S diagram Fig 1. On the other hand, the compressor final pressure decreases. Given the fact that the turbine inlet temperature is constant, it will reduce the turbine work. As a result the net output of gas turbine falls. Moreover, there is a peak demand of electricity in summer. Therefore, the gas turbine inlet air cooling is one of the useful methods which can be applied for the gas turbine power enhancement.

2. State of the Art

Thermal Energy Storage (TES) Systems are becoming a popular demand side management tool for utilities because it helps avoid costly plant expansions and reduces summer-time peak electricity demand. The TES represents a technology that can provide a win-win scenario for both the utility and the customer. In its simplest form, TES provide cooling energy that has been produced during off-peak hours (i.e. during the night when ambient temperature is low) and stored for utilization during on-peak hours when the demand is high.

However since the largest component of on-peak energy use is the creation of cooling, there is plenty of need for the stored cooling. As far as efficiency, again thermal storage comes out on top. Pumped hydro, as described above, uses excess nighttime electricity to create a lake on top of a mountain and then during the day runs it down and through a turbine to re-create the electricity. The round trip “cycle efficiency” of this is about 65% to 70%. Other forms of large scale energy storage have similar numbers. Thermal storage at a building has a cycle efficiency of anywhere from 85% to 99%. So in energy terms thermal storage is a clear winner.

However, with the incorporation of ice thermal storage, the turbine inlet air temperature can be reduced to 5.5°C, which yields a turbine power output of 108% of design and a gas turbine heat rate of 98% of design a 33% increase in the turbine’s output and a 7% reduction in the gas turbine’s heat rate over that attainable when using 43°C ambient air without conditioning. Due to these reasons, TES systems charged during off-peak periods and incorporated with the gas turbine are emerging as a viable, cost effective means of increasing combustion turbine capacity as it provides at least up to 30% more generator output 10% lower turbine heat rate at a fraction of the cost to install additional capacity for power generation [3].

According to Ameri et al. the gas turbine can take advantage of off-peak and mid-peak energy cost by using mechanical chillers and thermal energy storage systems. Thermal energy storage, TES, may be defined as temporary storage of energy at high or low temperature for use when it is needed [4].

Kakaras et al., Thermal storage could be accomplished as sensible heat storage or as latent heat storage. Sensible heat storage media includes water, sand, oil, etc. In latent heat storage, storage is accomplished by change in the physical state of the storage medium with or without change in its temperature. Latent storage media can store relatively large amounts of energy per unit mass compared to sensible heat storage media and hence result in smaller and lighter storage devices with lower storage losses and high efficiency [5].

3. Selection of inlet air cooling systems

Various techniques can be used to enhance the performance and the output power of gas turbines. The gas turbine inlet air cooling technologies are as follows:

1. Evaporative cooling.
2. Absorption chiller cooling
3. Mechanical refrigeration cooling
4. Thermal energy storage System

3.1 Evaporative cooling

These systems use the vaporization latent heat of water in an adiabatic air saturation process to reduce the dry bulb temperature to the wet bulb temperature. Therefore, their success in reducing the high air temperature depends on the relative humidity of the ambient air. Although, these types of systems are economical, they are suitable for hot and dry climates rather than the hot and humid ones.

3.2. Absorption chiller cooling

In this system, the hot flue gas from the gas turbine exhaust is used to generate the steam in a heat recovery steam generator (HRSG). The steam is usually used in a double-effect lithium-bromide absorption chiller to produce the chilled water. A compact heat exchanger should be designed for installation at the compressor inlet duct.

The chilled water from the absorption chiller flows through the heat exchanger and cools the inlet air. Mohanty et al. [6] studied this system for a 100 MW gas turbine in Bankok. The increase in the power output was 11%. Also, this system has been analysed in detail by Bies et al. [7].

Toshiba Corporation has installed a hybrid inlet air cooling system for a 5.42 MW gas turbine. This system includes an absorption chiller and a thermal energy storage system. It cools the inlet air to the gas turbine from 38 to 15 ^{o}C. The capacity of the storage system is 35% of the total system capacity. This system cools the inlet air for 5 hours during the on-peak hours.

3.3 Mechanical refrigeration cooling

The mechanical refrigeration cooling system involves the use of the vapor compression refrigeration equipment, which is commonly, employed in the commercial air-conditioning or industrial refrigeration systems. The inlet air to the gas turbine is cooled in a heat exchanger using the chilled water or the refrigeration fluid itself. The equipment is simpler and has less O&M costs than the absorption chiller. However, its capital cost is still relatively high. The parasitic power needed for the operation of the refrigeration system is typically 25–30% of the incremental power obtained from the gas turbine [8].

3.4 Thermal energy storage (TES)

Two methods can be used for TES system, chilled water storage and ice storage.

The components in these systems are as follows:

(a) Mechanical chiller;
(b) Ice maker only for ice storage system;
(c) Inlet air cooling coil and structure (heat exchanger);
(d) Condenser;
(e) Pumps.

Chilled water storage systems use the conventional chilling equipment to provide the appropriate chilled water supply temperature to the gas turbine inlet air cooling system. Chilled water storage is most practical in applications with relatively high loads and this system typically uses centrifugal chillers. It generally uses R-134a or R-132 [9].

Also mechanical chillers are used in ice energy storage system to produce cooling energy. The favored tank shape for this system is a flat bottomed vertical cylinder. A cylindrical tank has a lower surface-to-volume ratio than a rectangular tank of the same volume. A tank with a low surface-to-volume ratio has a lower degree of thermal loss and a lower construction cost per ton-hour of stored cooling.

The cooling coil could be different typically and costly. The environment at the project location allows less expensive copper tube with the aluminum fins to be used. Depending on the operating hours and the location, more expensive coils such as stainless steel have been used on the other TES projects. There are some specifications for each system that will be described as the following.

3.4.1 Chilled water storage

Fig. 2 shows the TES system that uses chilled water storage. Water is cooled by a chiller and stored in a tank for later use to meet the cooling needs. The amount of stored cooling energy depends on the temperature difference between the chilled water stored in the tank and the warm return water from the heat exchanger. Maximizing the return water temperature and minimizing the storage temperature, maximize the temperature difference, and prevent the mixing of warm return water with the stored chilled water. The chilled water storage is based on maintaining the state of thermal separation between cool charged water and warm return water.

Storage systems achieve this separation by the following methods.

1. Stratification;
2. Multiple tanks;
3. Membrane or diaphragm;
4. Labyrinth and baffle.

Stratified chilled water storage is generally acknowledged as the simplest, most efficient, and most cost-effective method of chilled water storage. This method is emphasized in this paper [10].

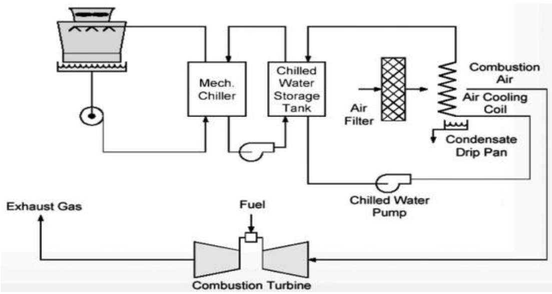


Fig.2. Simplified chilled water energy storage system for inlet air cooling

3.4.2 Ice storage

Fig. 3 shows a simplified TES system that uses ice storage. The produced ice is stored in a storage tank in off-peak hours. There are several methods to produce ice like as:

(a) Ice harvesting;
(b) External melt ice;
(c) Internal melt ice on coil;
(d) Encapsulated ice storage.

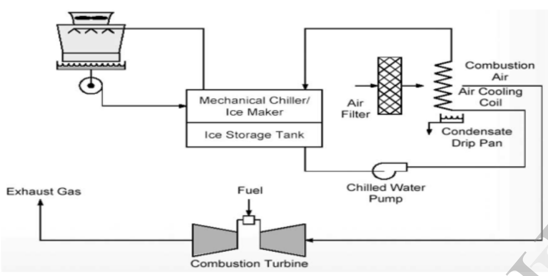
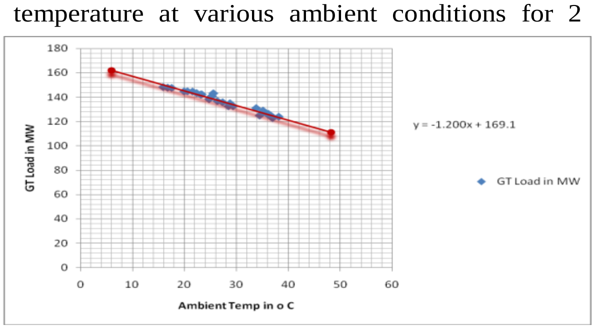


Fig. 3. Simplified ice energy storage system for inlet air cooling

Generally ice harvesting system is used for air cooling, because it has high capacity to store ice [11].

4. Studies on K.G.P.L Gas Turbine

A Study has been conducted on 140 MW Gas Turbine at different loads and inlet air temperature at various ambient conditions for 2



years data from 2010 to 2012

Fig.4. Graph of GT output vs various inlet air temperature

4.1 Model calculations is done for installing TES system in existing both Gas Turbines in M/s.Konaseema Gas Power Ltd., as follows.

Cooling the inlet air of 2 turbines to 15^{0}C when the ambient temperature is 45^{0}C (30% RH), in continuous mode for a minimum of 5 hours per day, 7 days per week during summer period considering 3 months.

The system will include a thermal energy storage system which will be discharged during 5 hours and charged back during the other 19 hours of the day. This means 5 continuous hours with an ambient condition of 45^{0}C & 30% RH.

Fig 4 shows the Single Gas Turbine output at 45^{0}C will be 115.16 MW from Graph and Load calculations.

Y=m X + C.
Whereas Y = GT Output
M = Slope of straight line,
X = Ambient temperature at ^{0}C,
C = Constant Value.

Y = -1.2007 X + 169.19
GT Output at 45^{0}C = -1.2007(45) +169.19 = 115.16 MW
GT Output at 15^{0}C = -1.2007(15) +169.19 = 151.18 MW

Enhancement in output for single GT is 151.18-115.16 =**36 MW**

Enhancement in output for Two GTs is 2 x 36 = **72 MW**

Enhancement in output for Combined Cycle Operation is 2 x 36 + 38.88 (STG load 54% of GTs load)
= 110.88MW

If TES system kept in Operation during peak hours for 5 hours Operation Total Load will be 110.88 X 5 hours = **554.4 MW/day**

Energy Consumption for TES system during off peak hours for 19 hours/day = 19×appox.2.95 MW/hr
= **56.05 MW/day**

Net Effective Power Generation /day = 554.4 – 56.05 = **498.35 MW/day**

Total Net additional Power output during summer period for 3 months
= 90 days × 498.35 MW/day
= **44851.5 MW**

Total amount returns for entire summer is 44851.5 × 1000 × Rs 3.00

= Rs.13, 45, 54,5
= Rs.13.45 Cr

Total expected investment for installation of TES system for both Gas Turbines
Approx. **Rs.60, 00, 00,000**
= **Rs. 60 Cr.**

Total Payback Period = Total Investment / (Total returns/year – O&M Co
=60 / (13.45- 2% of Total Investment)
= 60/ (13.45 – 1.2)
= **4.89 years**

5. Equipment Summary

5.1 – Study Project Guarantee:

Ambient air temperature	:	45.0^{0}C
Relative humidity	:	30.0%
Cooled air temperature	:	15.0^{0}C
Number of cooling hours per day	:	5 hours
Number of cooling days per week	:	7 days

5.2 – Heat load basis:

Ambient air temperature	:	45.0^{0}C
Relative humidity	:	30.0%
Cooled air temperature	:	15.0^{0}C
Inlet air mass flow (ISO)	:	510.0 kg/s
Altitude	:	10 m a.s.l.
Atmospheric pressure	:	1012 mbar
Number of turbines	:	2 units
Inlet air cooling time	:	5 hours

5.3 – Thermal Storage:

Type of storage	:	Water / Stratified
Method of stratification	:	Natural / Concentric Diff.
Figure of Merit	:	0.95

5.4 – Refrigeration Plant:

Refrigerant	:	R717 (ammonia).
Compressors	:	Twin rotary screw type
Evaporators	:	Semi-welded plate heat exchangers, flooded design.
Condensers	:	Evaporative condensers.

6. K.G.P.L correction factor curves

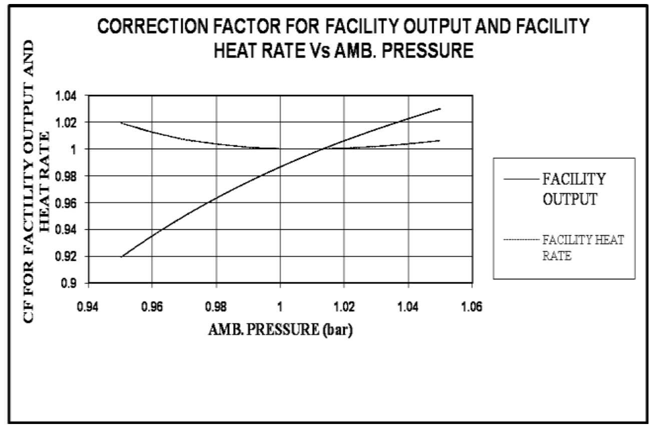


Fig.5. Correction factor for facility output and facility heat rate Vs Ambient pressure

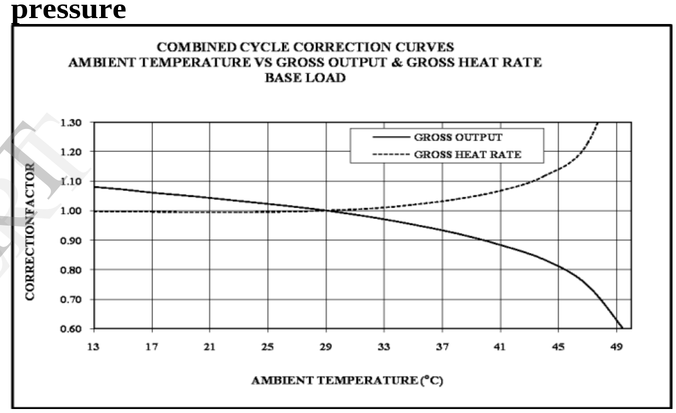


Fig.6. CORRECTION CURVE FOR RELATIVE HUMIDITY V/S FACILITY OUTPUT FOR 15, 30 AND 40 Deg C

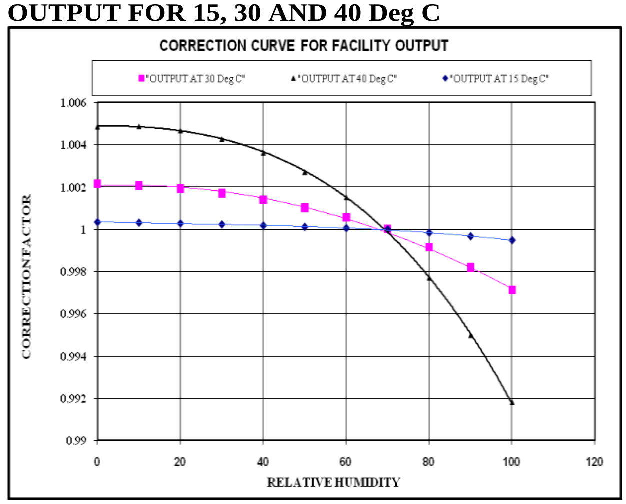


Fig.7. CORRECTION CURVE FOR RELATIVE HUMIDITY V/S FACILITY HEAT RATE FOR 15, 30 AND 40 Deg C

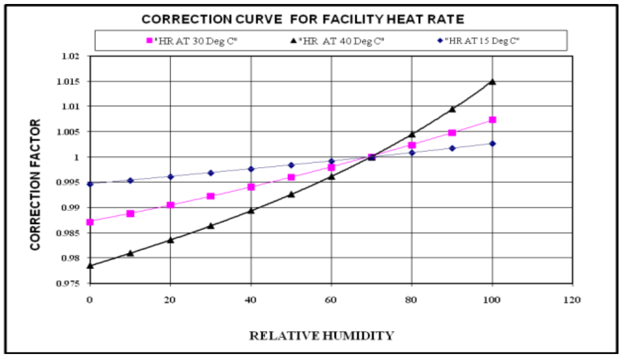


Fig.8. CORRECTION CURVE FOR SPEED V/S FACILITY OUTPUT AT 15, 30 AND 45 Deg C

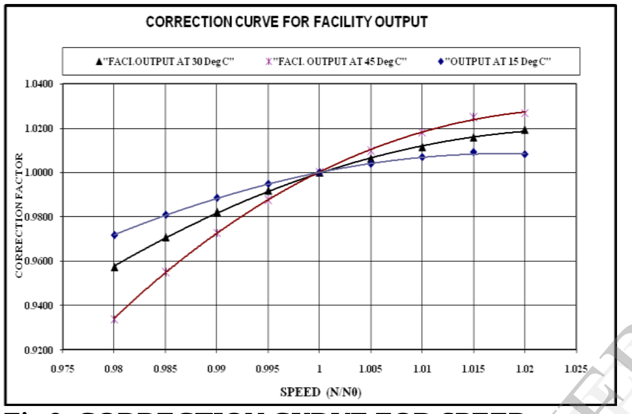


Fig.9. CORRECTION CURVE FOR SPEED V/S FACILITY HEATRATE AT 15, 30 AND 45 Deg C

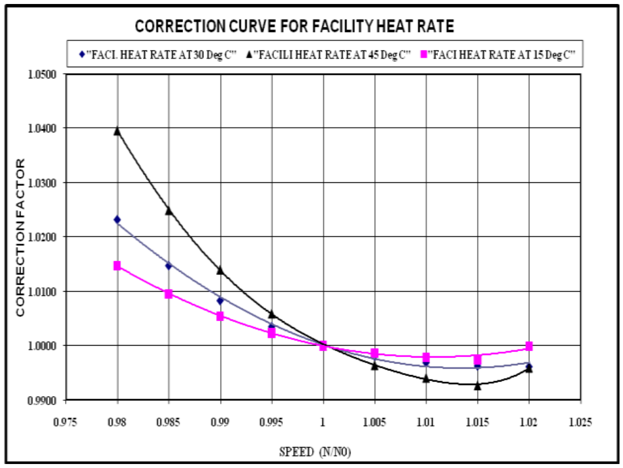
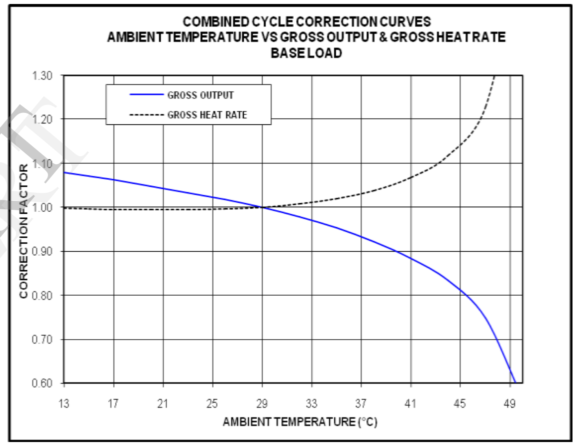
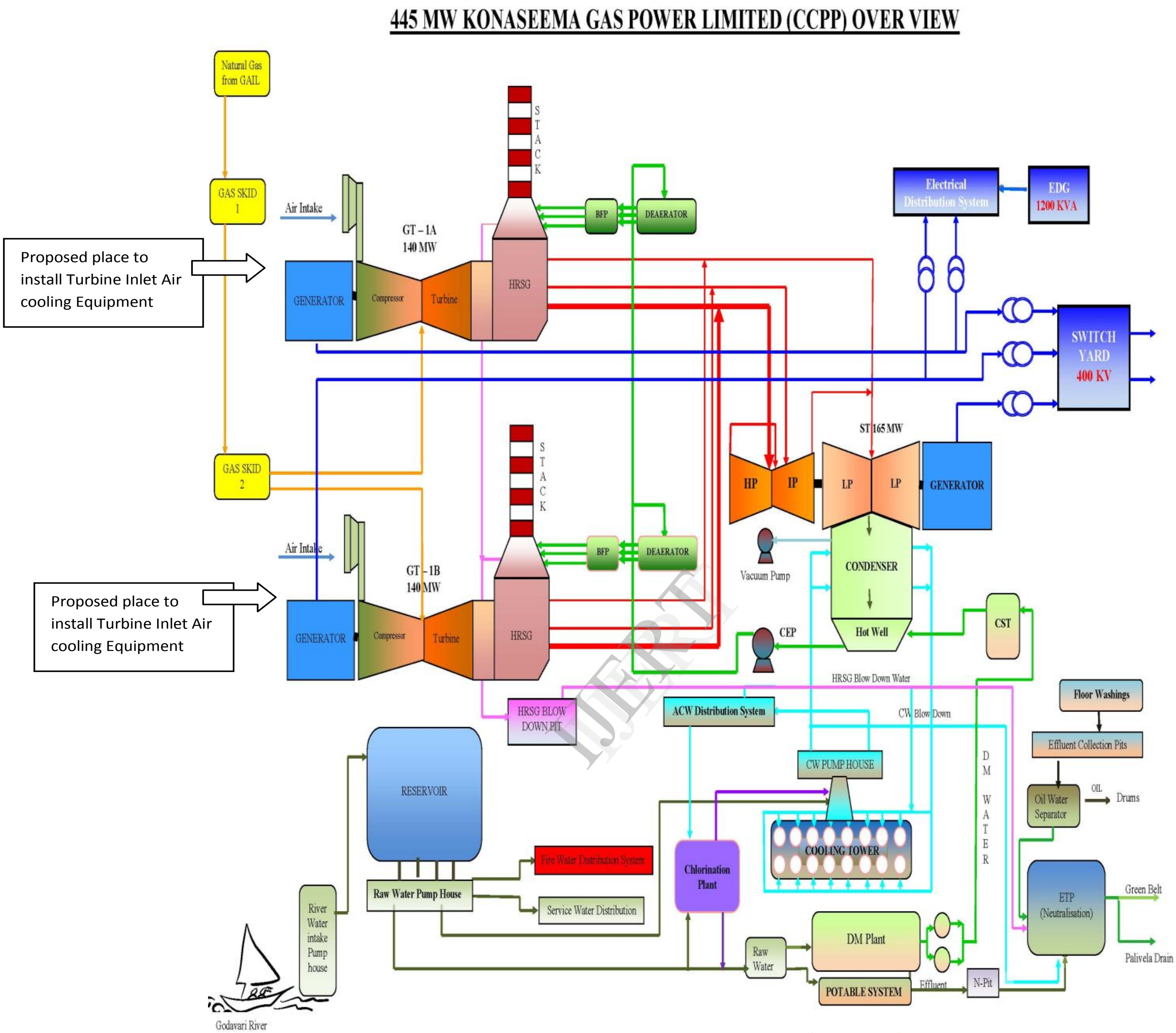


Fig.10. COMBINED CYCLE CORRECTION CURVES AMBIENT TEMPERATURE VS GROSS OUTPUT & GROSS HEAT RATE BASE LOAD



7. Fig.11.shows proposed place to install turbine Inlet air cooling equipment



8. Proposal for Installing TES System in KGPL Plant.

The power output enhancement through thermal energy storage & cooling of gas turbine inlet air for Siemens v 94.2 gas turbines will be studied:

Cooling the inlet air of 2 turbines model Siemens v 94.2, study to installed at Konaseema Gas Power Plant in Devarapalli, East Godavari District, A.P., India down to 15^{0}C when the ambient temperature is 45^{0}C (30% RH), in continuous mode for a minimum of 5 hours per day, 7 days per week. The system will include a thermal energy storage system which will be discharged during 5 hours and charged back during the other 19 hours of the day.

The System is designed and guaranteed to cool the inlet air down to 15^{0}C for a minimum of 5 hours per day, 7 days per week during the hottest days of the year. This means 5 continuous hours with an ambient condition of 45^{0}C & 30% RH.
In practice there will only be a few days a year with 5 hours at such hot ambient conditions and during most days the same system would be able to cool

the inlet air down to 15^0C for approximately 8 hours or more per day, 7 days per week. The system is totally flexible and to cool the inlet air down to 15^0C for an amount of hours per day, 7 days per week, depending on the ambient conditions.

There will be one “emergency condition mode” for the air cooling period where the system will be able to cool the inlet air of the 2 turbines down to 10^0C, during reduced periods of time.

A part from the turbine air inlet cooling, also the generators will be cooled in order to be able to generate the extra power required at high temperature ambient conditions. Assumed is that all the other turbines auxiliary systems have already been prepared for the Turbine Inlet Air Cooling operation and seized for the extra power output and no extra cooling is required for these systems. This will have to be verified in detail design stage.

9. Economic considerations

The cost of an inlet cooling system is often evaluated in terms of MW. This can be misleading because the output power enhancement as the result of the inlet air cooling method varies with the ambient temperature. A better way for the evaluation of the economic feasibility of a cooling system is through the cost-benefit analysis.

In this method the additional revenues are calculated as a result of additional electricity production during summer period is 498.35MW/day. The net electricity production increase for summer period for 3 months is around 44851.5 MW/90days.The benefit of this electricity production is calculated to be 13.45 Crores only in summer season based on the current electricity price in India. For the economical calculation we have considered 17% for the domestic interest rate, 7% for the foreign interest rate and 20 years for the equipment life.

10. Results and Discussions

This study, the (Thermal Energy Storage Inlet Air Cooling) TESTIAC has been selected to cool the inlet air to the KGPL power plant gas turbines and to enhance their output. Inlet air chilling method is a viable means to enhance the gas turbine performance, provided that the revenues associated with the incremental output are cost-effective. The maximum power augmentation is around 72 MW. The economical analysis has shown that the capital cost of the system is estimated to be around 60 Crores compared to the gas turbine installation costs in India. The payback period is calculated to be 4.8 years.

11. Conclusion

Inlet air cooling is a valuable method to enhance the gas turbine power output. Hot and humid climates are the best condition for indirect air cooling. The optimum cooling load should be defined by economical analysis. This study shows that using the chilled water thermal energy storage for KGPL gas turbine inlet air-cooling increases the peaking capacity of the gas turbines during the hot ambient operation only in Summer Season.

This method uses inexpensive off-peak power at night to generate the stored energy in the chilled water for inlet air-cooling during peak demand periods. Therefore it would be useful to use the off-peak power to provide the peak demand. TES installations that, in addition to providing peak power demand reductions, are also providing on-site energy use reductions and reductions in fuel use and emissions at the “source” power plants, and finally TES installations that provide the owners with large net savings in capital cost, when executed at times of new construction, or facility expansions, or rehabilitations of chiller plants.

Case studies in TES are quite widespread geographically, climatically, and in terms of end-use type.

12. Nomenclature

GT = Gas Turbine
TESTIAC = Thermal Energy Storage Inlet Air Cooling)
TES = Thermal Energy Storage
P = output w.r.t. ISO conditions (%MW)
Q = cooling load (kW)
Cp = constant pressure specific heat (kJ/kg K)
h = specific enthalpy (kJ/kg)
m = mass flow rate (kg/s)
P = pressure (Mbar)
RH = relative humidity
T_{amb}= temperature (K or °C)

References

[1] GE Energy. 2006. Library of Standard Gas Turbine. http://www.gepower.com

[2]Brook FJ. 1998. GE gas turbine performance characteristic. Report NO. GER-356H, GE power system.

[3] Hasnain, S M. (1998). ‘A review on sustainable thermal energy storage technologies part II: cool

thermal storage', Energy Conversion Management – An Int. j., 39(11), 1127-1138.

[4] Ameri M, Hejazi SH (2004). The study of capacity enhancement of the Chabahar gas turbine installation using an absorption chiller. Appl. Ther. Eng., 24: 59-68.

[5] Kakaras E, Doukelis A, Prelipceanu A, Karellas S (2006). Inlet air cooling methods for gas turbine based power plants. Trans. ASME., 128: 312-317.

[6] B. Mohanty, J. Paloso, Enhancing gas turbine performance by intake air cooling using an absorption chiller, Heat Recovery Syst. CHP J. 15 (1) (1995) 41–50.

[7] D. Bies, U. Johantgen, J. Scharfe, Optimised cooling of the compressor intake air: a new way for the improvement of power and efficiency in gas turbine plants, Proceedings of the International Gas Turbine Congress, Kobe, 1999.

[8] John S. Andrepont, Combustion turbine inlet air cooling (CTIAC): benefits, technology options and applications for district energy, in: International District Energy Association (IDEA) 91st Annual Conference, Montreal, Quebec, 2000.

[9] B. Omidvar, Gas turbine inlet air cooling system, The 3rd Annual Australian Gas Turbine Conference, Melbourne, Australia, 2001.

[10] D.R. Brown, Thermal energy storage space cooling technology for reducing on-peak electricity demand and cost, Federal Technology Alert, US-DOE, 2000.

[11] W.E. Stewart, Design guide: combustion turbine inlet air cooling systems, ASHRAE J. (1999).