SOME STUDIES ON PERFORMANCE IMPROVEMENTS OF COMBINED CYCLE POWER PLANTS

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Some Studies on Performance Improvements of Combined Cycle Power Plants

Abstract

Worldwide power industry structure is changing to market economy to ensure commercial availability. The resource are allocated for operation and maintenance from commercial consideration rather than technical alone, necessitating introduction of a commercial approach for the analysis of reliability, efficiency, installation and operating cost for thermal power plants. These requirements suggest the need for development of mathematical model for monitoring the performance of system in the form of a single numerical composite index capable of incorporating all design and operating parameters affecting the plant performance.

In the present work a simple, numerically efficient model based on Graph Theoretic Analysis (GTA) is used to develop a single composite performance index on the basis of **efficiency** and **reliability** for **combined** and **cogeneration cycle power plants**. For Graph Theoretic Analysis (GTA), combined and cogeneration cycle power plant are divided into sub-systems and various interconnections between sub-systems and parameters affecting them are presented in System Structure Graph (SSG). The developed SSG for performance, reliability and efficiency, represented by a matrix is used for detailed evaluation and analysis of the both combined and cogeneration cycle power plants using computational tool.

Reliability of different subsystems is used to develop a real-time reliability index (RTRI) for the power plants. Similarly, using operating efficiency data of various sub-systems, real-time efficiency index (RTEI) is also developed. With the help of RTRI and RTEI, a composite index for efficiency and reliability (CIER) has been calculated which is helpful in decision making for system selection and monitoring the performance of the power plant in real time.

Design parameters and their interdependencies are quantified iteratively for calculating RTRI and RTEI and results obtained are found to be in good agreement with industrial data. Initial guess for the quantification is obtained from the thermodynamic inference. Exergy analysis of cogeneration cycle power plant has also been carried out for the identification and quantification of

design parameters for efficiency at sub-system level.

Practical implementation of the proposed methodology in a systematic manner is helpful for power generation industry to identify, categorize, analyse and evaluate parameters responsible for plant reliability and efficiency.

CERTIFICATE

This is to certify that the thesis entitled "**Some Studies on Performance Improvements of Combined Cycle Power Plants**" which is being submitted by **Mr. Nikhil Dev** (Enrolment Number - Ph.D-105/09) to the Faculty of Technology, University of Delhi, Delhi, for the award of the degree of **Doctor of Philosophy** is a record of the original bonafide research work carried out by him under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. The thesis, in our opinion, has attained a standard required for a Ph.D. degree of this University. The results contained in this thesis have not been submitted in part or full to any other university or institution for the award of any other degree or diploma.

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ABSTRACT

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In the present work a simple, numerically efficient model based on Graph Theoretic Analysis (GTA) is used to develop a single composite performance index on the basis of **efficiency** and **reliability** for **combined** and **cogeneration cycle power plants**. For Graph Theoretic Analysis (GTA), combined and cogeneration cycle power plant are divided into sub-systems and various interconnections between sub-systems and parameters affecting them are presented in System Structure Graph (SSG). The developed SSG for performance, reliability and efficiency, represented by a matrix is used for detailed evaluation and analysis of the both combined and cogeneration cycle power plants using computational tool.

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Practical implementation of the proposed methodology in a systematic manner is helpful for power generation industry to identify, categorize, analyse and evaluate parameters responsible for plant reliability and efficiency.

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NOTATIONS AND ABBREVIATIONS

Nomenclatures

c_p = Specific heat at constant pressure (kJ/kg K)

c_v = Specific heat at constant pressure (kJ/kg K)

e = Specific exergy (kJ/kg (dry air))

$\dot{E}$ = Exergy rate (kJ/s)

e_P = Specific exergy associated with process heat (kJ/kg (dry air))

H_f = Heat supplied by fuel (kJ/kg (dry air))

ΔH_r = Heat of reaction of fuel (kJ/kg of fuel)

h = Enthalpy (kJ/kg (dry air))

h_g = Enthalpy of saturated vapor at process steam pressure (kJ/kg)

m = Mass (kg)

n = Number of moles

p = Pressure (bar)

Q_p = Process heat (kJ/kg (dry air))

R = Gas constant (kJ/kg K)

r_e = Expansion ratio

r_p = Pressure ratio

s = Entropy (kJ/kg K)

T = Absolute temperature (K)

T = Temperature (°C)

TP = Process heat temperature (K)

v = Specific volume (m^3/kg)

W = Work (kJ/kg (dry air))

x = Mole fraction of component

Greek Symbols

ω = Humidity ratio (kilogram of water vapor per kilogram of dry air)

φ = Relative humidity (%)

ε = Effectiveness (%)

η = Efficiency (%)

γ = Specific heat ratio

λ = Fuel- air ratio on molar basis

Subscripts

AC = Air Compressor

CC = Combustion chamber

C = Condenser

D = Destruction

HRSG = Heat recovery steam generator

P = Product

PH = Process heater

Q = Heat

R = Reactant

GT = Gas Turbine

W = Work

a = Ambient air

av = Average

f = Fuel

g = Gas

i = Inlet

l = Liquid

o = Outlet

r = Regenerator

s = Isentropic

ST = Steam Turbine

v = Water vapor

w = Water

1,2,3…9 = State points in the cycle

Acronyms

BCM- Billion Cubic Meters

BFP- Boiler Feed Pump

CAGR- Compound Annual Growth Rate

CC- Combined Cycle

CCPP- Combined Cycle Power Plant

CEP – Condensate Extraction Pump

CGCPP- Co-Generation Cycle Power Plant

CIER **-** Composite Index for Efficiency and Reliability

CNG – Compressed Natural Gas

CSSM – Characteristic System Structure Matrix

CV – Calorific Value

CW – Circulating Water

DM – Deminiralized

EES – Engineering Equation Solver

FOD - Foreign Object Damage

FUE - Fuel Utilization Efficiency

GA- Genetic Algorithm

GT- Gas Turbine

GTA – Graph Theoretic Analysis

HPH – High Pressure Heater

HPT – High Pressure Turbine

HRSG – Heat Recovery Steam Generator

HRSG- Heat Recovery Steam Generator

IAT – Inlet Air Temperature

IPH – Intermediate Pressure Heater

IPT - Intermediate Pressure Turbine

ISO – International Standard Organisation

LPH – Low Pressure Heater

LPT – Low Pressure Turbine

MADM – Multi Attribute Decision Making

MT- Million Tonnes

MTBF – Mean Time Between Failures

MTTR – Mean Time To Repair

MW – Mega Watt

O & M – Operation and Maintenance

PPD - Process Performance Digraph

RAM – Reliability Availability Maintainability

RTEI- Real Time Efficiency Index

RTRI- Real Time Reliability Index

SCF - Structural Characteristic Feature

SED - System Efficiency Digraph

SRD - Systems Reliability Digraph

SSG - System Structure Graph

ST- Steam Turbine

TG – Turbo Generator

TIT – Turbine Inlet Temperature

TOT – Turbine Outlet Temperature

VCSSM - Variable Characteristic System Structure Matrix

VPF - Variable Permanent Function

VPSEM - Variable Permanent System Efficiency Matrix

VPSRM - Variable Permanent System Reliability Matrix

VPSSM - Variable Permanent System Structure Matrix

CHAPTER-I

INTRODUCTION

1.1. BACKGROUND

The broad vision behind the Indian energy policy is “To consistently meet the demand for energy services of all sectors including the lifeline energy needs of vulnerable households, in all parts of the country, with safe and convenient energy at the least cost in a technically efficient, economically viable and sustainable manner” [India energy book, 2012]. Data of installed electricity generation capacity and capacity utilization stresses the need to improve efficiency of the technology used in electricity generation. In recent years Compound Annual Growth Rate (CAGR) of production of energy in India by primary sources is largest for the natural gas viz. 9.13% [Energy statistics, 2012].

India’s energy-mix comprises both non-renewable and renewable energy sources. Information on reserves of non-renewable sources of energy like coal, lignite, petroleum, natural gas and the potential for generation of renewable energy sources is a pre- requisite for assessing the country’s potential for meeting its future energy needs.

As on March, 2011 the estimated reserves of coal was around 286 billion tonnes, crude oil and natural gas 757 Million Tonnes (MT) and 1241 Billion Cubic Meters (BCM), respectively. The total potential for renewable power generation in the country as on March, 2011 is estimated at 89,760 MW. This includes an estimated potential of wind power of 49,132 MW (55%), small-hydro power (SHP) 15,385 MW (17%), biomass power 17,538 MW (20%) and 5,000 MW (6%) from bagasse-based cogeneration. Capital costs of generating plants vary according to the type of fuel used; typically for Coal-based plant it is about Rs. 3.8 to 4 crore, Gas-based plant: Rs. 3.5 crore, Hydro: Rs. 5 crore, Wind: Rs. 5-6 crore and Nuclear: Rs. 6 crore per MW in year 2007.

The Combined and Cogeneration Cycle Power Plants are promising mode of energy recovery and conservation, and is an economically interesting proposition. Up to now, there have been four generations of CCPP's. The early versions were basically repowered steam plants with fired steam generator. These steam generators had bare tubes, heat exchange being ensured by the high process temperatures. They had a single or two pressure levels with no reheating. The last of these first generation plants were installed as late as 1968.

In 1958, with the advent of an economically feasible technology for welding continuous fins to tubes, the second generation of combined cycles began to take shape. Improved heat exchange made it possible to recover heat from the gas turbine exhaust, which was then used for feed water heating. The first applications in the 1960s were for power and heat generation. By the 1970s and 1980s, the technology had matured in the utility sector for medium range loads. Two or three pressure level steam generators were employed but still with no reheating. Nitrogen oxide control techniques were also introduced in this period, basically by water or steam injection in the combustion chamber. These second generation plants were still being installed at the end of the 20th Century. The gas turbine of these plants was not specifically designed for use in a combined cycle configuration. Therefore, it was usually characterized by a rather high compression ratio in order to achieve relatively good efficiency in an open cycle configuration.

The third generation plants entered into commercial operation in 1990. The Heat Recovery Steam Generator (HRSG) usually has three pressure levels and reheats. NOx emission control was mandatory, and the plants were equipped with dry low NOx combustion systems for use with natural gas, while a selective catalytic reactor (SCR) was also required to comply with emission regulations.

The latest advance in combined cycle technology consists in the introduction of closed loop refrigeration of the first stage nozzle, the fourth generation, currently being introduced into the market. These plants are designed to reach a 60% efficiency target, as results of further increase in firing temperature, the reduction of temperature drop across the first stage nozzle and the elimination or reduction of the loss of compressed air achieved by open loop refrigeration.

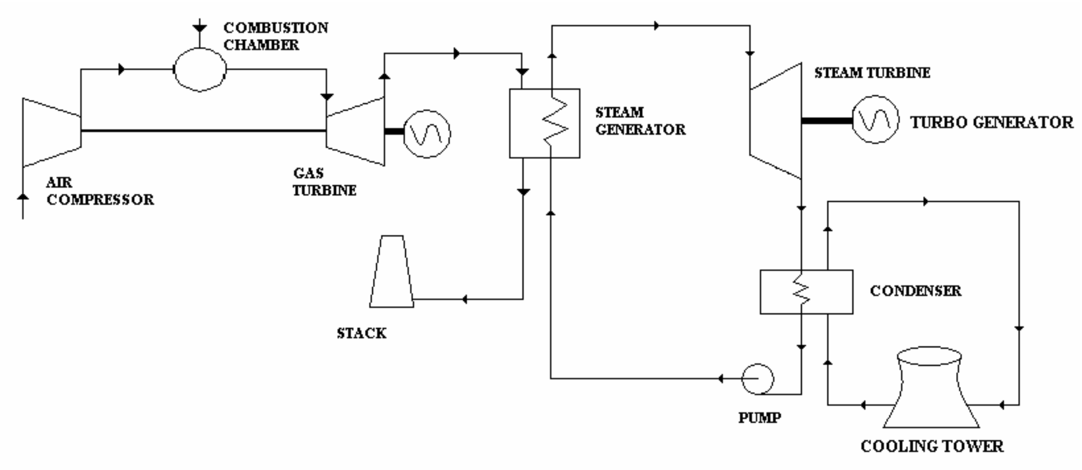
Gas turbines are increasingly used in combination with steam cycle, either to generate electricity alone, as in combined cycles, or to cogenerate both electrical power and heat for industrial processes or district heating. So in a cogeneration cycle power plant, HRSG and steam turbine are replaced with process heater. Waste heat of gas turbine is recovered in process heater and supplied for further use.

At present combined and cogeneration cycle generation system features high thermal efficiency, low installed cost, fuel flexibility with a wide range of gas and liquid fuels, low operation and maintenance costs, operating flexibility, high reliability and availability, short installation times and high efficiency in small capacity increments.

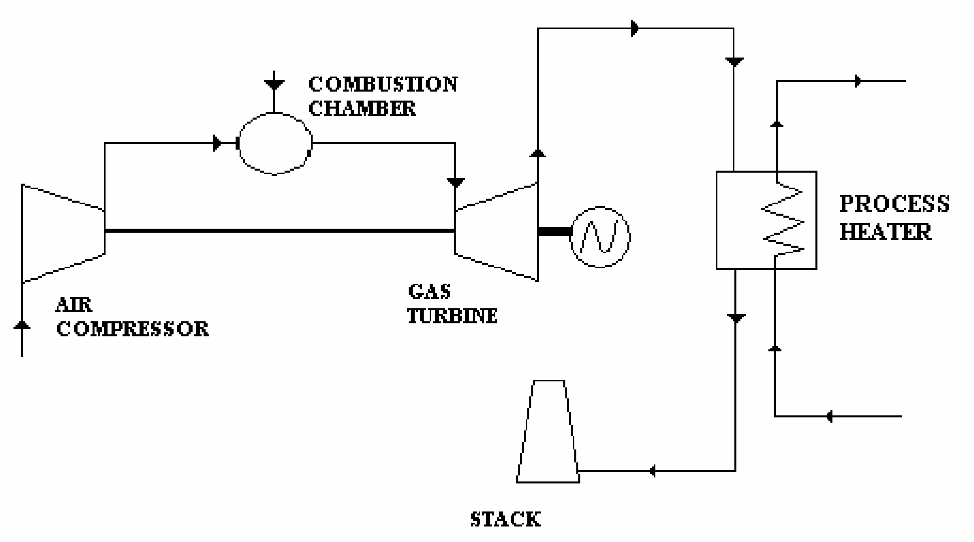
It may be concluded that according to the availability of fuel and technology, at present India can rely on the combined and cogeneration cycle power plants. In the next section basic configuration of combined and cogeneration cycle power plant is described.

1.2. DESCRIPTION OF COMBINED AND COGENERATION CYCLE POWER PLANT

CCPP technology combines two or more thermodynamic cycles, making higher thermal efficiency possible and providing a considerable reduction in pollutant emissions. In general, these plants combine the operation of a gas turbine cycle (Brayton cycle) with that of a HRSG and a steam turbine (Rankine cycle). In a CCPP (Figure 1.1a), a part of the exhaust gas energy generated by the Gas Turbine (GT) is recovered by the HRSG. The recovered thermal energy is used to produce steam at high pressure and high temperature. The steam is then expanded in the Steam Turbine (ST) to generate additional power. Natural gas and air at ambient conditions are the fuel and the oxidant respectively for gas turbine cycle. Each turbine is linked to an electric generator, which transforms the mechanical energy produced by the gas and steam turbines into electrical energy. If the waste heat of gas turbine cycle is used only to produce process steam then the cycle is called as cogeneration cycle (Figure 1.1b).



(a) Combined Cycle Power Plant



(b) Cogeneration Cycle Power Plant

Figure 1.1 Schematic diagrams of a Combined and Cogeneration Cycle Power Plants

1.3. LIMITATIONS OF PRESENT SYSTEM MODELING

A number of alternative designs of power plant sub-systems are available and there is continual upgrading in their design. From the economical, environmental and practical point of view, the combination of a simple gas turbine cycle coupled to a Rankine steam bottoming cycle (which may be with dual/triple pressure and reheat) without supplementary firing is the most common type of power plants.

Most of the thermodynamic analysis and parametric studies are based on step by step calculation of cycle processes of different combined cycle configurations. The basis of comparison has mostly been the energy and exergy analysis. But, the new market environment demands introduction of a new approach for developing a composite single index for performance monitoring based on product and process performance parameters, and RAMS (Reliability Availability Maintainability and Serviceability). At managerial level it may also be difficult to analyze the efficiency of power plant by energy or exergy analysis as it requires the solution of a large number of non-linear equations with sophisticated computer programming tools. Further there is an urgent need to integrate efficiency analysis with reliability, maintainability and other operating parameters of power plant so that its performance can be expressed by a single composite index.

In the study of CCPP and CGCPP, there are large number of systems and sub-systems affecting each other at system or sub-system level. The performance of any system is a function of its structure. Therefore, performance (e.g. efficiency and reliability etc.) of a complete power plant depends upon the efficiency or availability of all individual systems and their interconnections in an integrated manner. At present, there is no effective mathematical model for studying these aspects in association with each other or independently by considering the effect of design and operating parameters.

1.4. MOTIVATION

A logical mathematical modeling, capable of handling performance parameter (efficiency or reliability) that may be either tangible or intangible, interaction or interdependency of subsystems and design and operating parameters affecting these subsystems, is obligatory for complete analysis of thermal power plants. In case of combined and cogeneration cycle power plant, the system structure is very large and complex; having large number of sub-systems interacting with each other and these sub-systems are affected by large number of design and operating parameters. Therefore, their analysis through visual inspection is difficult and computational techniques can be helpful only if real life problem is converted into a logical mathematical modeling.

The performance of a real life operating power plant cannot be measured by single parameter and also measuring scales for different performance parameters are different. In view of this, there is a need to develop a simplified and accurate methodology for decision making which is capable of simultaneously measuring all performance parameters contained by one scale and results in the form of single numerical index.

Graph Theory and matrix approach is found to be suitable to develop a single composite performance index applicable for combined and cogeneration cycle power plant. The index have potential to be used for system selection or monitoring the performance of the power plant in real time in the new emerging competitive market.

For identification, quantification and validation of design parameters, mathematical modeling of cogeneration cycle is carried out for energy and exergy analysis. Model is solved with the help of Engineering Equation Solver (EES). EES is chosen for the analysis because fluid and gases thermodynamic properties are the inbuilt function of the software. Coding of the same is enclosed in appendix-VI.

1.5. OUTLINE OF THESIS

The thesis is organized into five chapters and objectives of these chapters are discussed below.

Chapter 1 describes working of CCPP and CGCPP and limitations of the present system performance monitoring methodology followed by motivation for the present work.

Chapter 2 summaries the literature survey on suitable techniques for CCPP and CGCPP analysis for different operating parameters. Some of the latest trends in the field of combined and cogeneration cycle power plant available in open literature has been studied. In the literature, graph theoretic technique is found useful for developing the methodology for power plant performance analysis as it takes care of inheritance and interdependency of sub-system. The objective of present research work is to develop the methodology using GTA for evaluation of reliability and efficiency of CCPP and CGCPP.

In Chapter 3, combined and cogeneration cycle power plant with their subsystems are described. Using the proposed methodology, real life operating CCPP and CGCPP are converted into graph theoretic representation. Variable Permanent Function (VPF), obtained from the equivalent matrix, of CCPP and CGCPP systems at a particular level of hierarchy represents all possible combinations of its subsystems. These combinations provide an expression for structural analysis and evaluation. A concept of Real Time Reliability Index (RTRI) and Real Time Efficiency Index (RTEI) of the combined and cogeneration cycle power plant analysis is also proposed in this chapter. Design and performance parameters are identified and their quantification is done based on the mathematical modeling and available industrial data. Mathematical modeling of cogeneration is carried out for energy and exergy analysis for different design and operating parameters. Model is solved with the help of computer programming using Engineering Equation Solver (EES).

In Chapter 4, results obtained from GTA are also presented with their possible uses. Effect of various design parameters on exergy destruction in cogeneration cycle components is studied for identification and quantification of design parameters in Graph Theoretic Analysis.

Conclusions and scope for future work are given in Chapter 5. Scope for future work in the area of development of similar indices includes the economy, safety, ergonomics, maintainability and environment concerns has also been presented in this chapter.

CHAPTER-II

LITERATURE REVIEW

The interest in the combined and cogeneration cycle operation was aroused through the world in mid 1970's. During the last two decades a number of alternative combined and cogeneration cycle concepts have been developed. The stress is on the improvement of efficiency and reliability of power plant. In this chapter, a review of literature on combined and cogeneration cycle power plant is undertaken, which evaluates various gas/steam combined and cogeneration cycle arrangements consisting of a gas turbine coupled to an alternative bottoming cycles. In addition the methods of thermodynamic analysis and simulation of these power plants available in the literature have been briefly reviewed.

First part of this chapter is dealing with thermodynamics and reliability of combined and cogeneration power plants. Second part is dealing with the Graph Theoretic Analysis (GTA) of mechanical and thermal power plant systems, analyzed by different researchers.

2.1. DEVELOPMENTS IN COMBINED AND COGENERATION CYCLE POWER PLANTS

A large number of researches are going on in the area of CCPP and CGCPP efficiency and reliability improvement. A summary of recent developments for the efficiency improvements and reliability analysis are given below.

2.1.1. EFFICIENCY IMPROVEMENT

Rao and Francuz (2013) investigated improvement techniques such as gas turbine firing temperature, pressure ratio, combustion techniques, intercooling, enhanced blade cooling schemes and supercritical steam cycles related to combined cycle and studied their effects on performance improvements in coal based Integrated Gasification Combined Cycle (IGCC) plant utilizing an H class gas turbine technology with steam cooling.

Herfeh and Eslami (2013) presented a probabilistic Price Based Unit Commitment (PBUC) approach using Point Estimate Method (PEM) to model the uncertainty in market price and generation sources, for optimal bidding of a Virtual Power Plant (VPP) in a day-ahead electricity market.

Morosuk and Tsatsaronis (2012) presented a way for combining exergoeconomic and the exergoenvironmental analysis and for formulating common conclusions for further improvement of an energy conversion system by taking into account simultaneously the minimization of cost and of environmental impact.

Vallianou and Frangopoulos (2012) studied a trigeneration system consisting of a gas engine with heat recovery, an absorption chiller driven by thermal energy, electrically driven compression chillers and two thermal storage tanks (one with hot and one with cold water). Gaggioli (2012) discussed about the selection of the dead state for exergy analysis of energy-conversion and materials processing plant, and to ecology.

Triple-pressure reheat combined cycle with two different types of gas turbines, GE Stage 107H and Mitsubishi M501H, were analyzed and optimized relative to their operating parameters using software Engineering Equation Solver (EES) by Bassily (2012). Sha and Hurme (2012) presented an environmental accounting method based on the embodied solar energy (emergy) principle for evaluating biomass and coal-based combined heat and power (CHP) cogeneration processes. The method analyzed sustainability from the point of view of the biosphere.

Chacartegui et al. (2012a) studied the effects of using a set of syngas fuels on the components of a combined cycle. It was found that cross sectional area of the nozzle guide vanes increase with respect to the standard engine to prevent the compressor from surging. This increase depends on the heating value of the fuel. Chacartegui et al. (2012b) studied the use of gasified fuels in the gas turbine and combined cycle technologies and aimed at analysing the effects of syngas fuels on the performance of a particular component within the power plant or at assessing the impact of fuel composition at a particular level (from component level through system level and up to plant level).

Anozie and Odejobi (2011) developed computer program codes in Microsoft Excel macros for simulation of a thermal plant at various circulation water flow rate, to determine the optimum condenser cooling water flow rate for the process. Ahmadi and Dincer (2011) used a modified version of evolutionary algorithm (non-dominated sorting genetic algorithm) for multi objective optimization of a Gas Turbine power plant.

Godoy et al. (2011) proposed a strategy for simplifying the resolution of the rigorous economic optimization problem of power plants based on the economic optima distinctive characteristics which describe the behavior of the decision variables of the power plant on its optima. Franco (2011) compared three different supercritical HRSG configurations with single (SC1RH) and double reheaters (SC2RH) with simple HRSG single pressure configurations and advanced double and triple pressure HRSG structures.

Woudstra et al. (2010) measured the difference between the actual exergy losses with the ones of the corresponding ideal reversible case. Results showed that more than 35% of the fuel exergy entering the combined cycle plant was lost due to combustion and friction in the gas turbine cycle. Ameri et al. (2008) studied the exergy analysis of a 420MW CCPP with objective to evaluate irreversibility of each part.

Polyzakis et al. (2008) carried out optimization analysis of four potential GT cycles, namely single cycle (SC), intercooled cycle (IC), reheated cycle (RH) and intercooled and reheated cycle (IC/RH). The optimum GT cycle to operate in a CCPP came out to be the reheated cycle. Srinivas et al. (2008) carried out thermodynamic evaluation for a combined cycle with Steam Injected Gas Turbine (STIG) and dual pressure heat recovery steam generator (HRSG).

Khaliq and Choudhary (2007) have studied the combined first and second-law analysis of gas turbine cogeneration system with inlet air cooling and evaporative aftercooling of the compressor discharge. Butcher and Reddy (2007) have studied Second law analysis of a waste heat recovery based power generation system for various operating conditions. The temperature profiles across the heat recovery steam generator (HRSG), network output, second law efficiency and entropy generation number were simulated for various operating conditions. The variation in specific heat with exhaust gas composition, pinch point and temperature were accounted in the analysis and results.

Ertesvag et al. (2005) carried out exergy analysis of a CCPP with precombustion CO_2 capture for a natural-gas (NG) fired power plant. NG was reformed in an Auto-Thermal Reformer (ATR), and CO_2 was separated before the hydrogen-rich fuel was used in a conventional combined-cycle process. Korakianitis et al. (2005) studied design-point performance characteristics of a wide variety of CCPP and CGCPP, with different amounts of supplementary firing, different amounts steam injection (or no steam injection), different amounts of exhaust gas condensation, etc.

Yadav (2005) analyzed simple CCPP for different type of coolants for gas turbine stage cooling. Steam coolant is bled from heat recovery steam generator. Influence of different type of coolant upon the performance of topping, bottoming, combined cycle and HRSG has been presented and analyzed. Khaliq and Kaushik (2004a) carried an improved second-law analysis of the combined power-cycle with reheat and showed that gains are substantial for one and two reheats, but progressively smaller for subsequent stages. Khaliq and Kaushik (2004b) presented first and second law analyses for gas turbine cogeneration system with reheat.

Alhazmy and Najjar (2004) studied the performance enhancement of gas turbine power plants by cooling the air at plant intake. A comparison between two different types of air coolers, namely water spraying system and cooling coil has also been carried out. Kim (2004) examined the effect of power control strategy on the part load performance of the combined cycle. It was observed that gas turbines with higher design performances exhibit superior part load performance.

Franco and Casarosa (2002) have shown that the application of the thermo economic optimization (obtained with increase of the heat surface and a decrease of the pinch-points) leads to a meaningful increase of the thermal efficiency of the plant that approaches to 60%. Alessandro and Alessandro (2002) proposed an analysis of some possibilities to increase the CCPP efficiency to values higher than the 60% without resorting to a new gas turbine technology.

Pilavachi (2000) gave an overview of power generation with gas turbine and combined heat and power (CHP) systems and discussed various methods to improve the performance of the several types of gas turbine cycles. Heppenstall (1998) described and compared several power generation cycles which have been developed to take advantage of the gas turbine's thermodynamic characteristics.

Horlock (1995) outlined developments of 1970s, 1980s and future prospects of combined-cycle power plants. Lugand and Parietti (1991) studied combined cycle of 200 MW using combinations of GEC Alstom MS9001E and F gas turbine with a single shaft VEGA 209E and VEGA209F steam turbine.

Bolland (1991) studied various measures used to improve the efficiency of CCPP. A typical modern dual pressure cycle was chosen as reference and alternative arrangements such as dual pressure with reheat, triple-pressure cycle, triple pressure with reheat and dual/triple pressure supercritical reheat cycles were considered. Bejan et al. (1996) has established a design methodology for the gas turbine cogeneration system. This simple system is integrated with regenerator and HRSG to utilize the waste heat. A 30 MW Gas turbine is designed on the basis of analysis of enthalpy and entropy of air and gas.

2.1.2. RELIABILITY ANALYSIS

The performance of any power plant is generally expressed in terms of its Reliability, Efficiency, Availability and Maintainability (REAM) parameters. These reflect the fixed and operating part of cost or capital cost required for setting up, running and maintaining the plant.

Unavailability of a component doesn’t necessarily mean that whole plant will be tripped but, nonetheless, it will affect the availability of other components or systems. Combined or cogeneration cycle power plant is a multifarious organisation. A method for reliability analysis of a power plant refers to the reliability evaluation (quantitative or qualitative) based on the reliability of its components or systems.

In literature, both qualitative and quantitative methods are available for reliability analysis of complex systems.

Ji et al. (2013) used a staircase function to approximate the aging failure rate curve, and a renewal-process-based model was introduced to calculate time-varying failure probabilities. The proposed time-varying outage model was to reflect the effects of component aging and repair activities on the failure rate. The model yielded an analytical solution without Monte Carlo simulation to simplify the calculations.

Carpaneto et al. (2011a) carried out Monte Carlo simulation for identifying long, medium and short term time frames by incorporating uncertainty at large-scale and small-scale for cogeneration system. Availability coefficient assumed to be independent of year, scenario and control strategy was defined for unavailability of the CHP (combined heat and power) units, due to scheduled maintenance and reliability aspects, taking into account. Large-scale uncertainty referred to the evolution of energy prices and loads and relevant to the long-term time frame was addressed within multi-year scenario analysis. Small-scale uncertainty relevant to both short-term and medium-term time frames was addressed through probabilistic models and Monte Carlo simulations (Carpaneto et al., 2011b).

Haghifam and Manbachi (2011) modeled three CHP subsystems: Electricity-generation subsystem, Fuel-distribution subsystem and Heat-generation subsystem and found that reliability analysis is essential in economic and technical feasibility studies, operating expenses and optimal maintenance scheduling of these systems.

A comparison between single-shaft and multi-shaft CCPP of 800 MW_{el} was carried out by Edris (2010). Single-shaft configuration was found more suitable with regards to performance, NOx specific emissions, CO_2 specific emissions, start-up and extension possibilities. The multi-shaft configuration was more suitable with regards to space limitations, steam turbine shaft power, availability, and reliability.

Eti et al. (2007) integrated reliability and risk analysis for maintenance policies of a thermal power plant. Need to integrate RAMS (reliability, availability, maintainability and supportability) centered maintenance along with risk analysis was stressed. Although results expected or obtained with the application of those concepts were not explained.

Zigmund et al. (2005) have introduced Bouncing Failure Analysis (BFA) – an innovative combination of two traditional and widely used Failure Analysis (FA) techniques: Failure Mode and Effect Analysis (FMEA) Fault Tree Analysis (FTA). The authors have also presented the methodology and the procedure to maximize the advantages and at the same time to minimize the shortcomings of both known methodologies.

Jian-Ping and Thompson (2005) have proposed a method by which material inhomogeneity may be taken into account in reliability calculations. The method employed Monte Carlo simulation; and introduced a material strength index, and a standard deviation of material strength to model the variation in the strength of a component throughout its volume.

Wenyuan (2002) indicates that failures due to aging have significant impacts on system reliability, particularly for an “aged” system. Ignoring aging failures in reliability evaluation of an aged power system will result in over or under estimation of system risk and most likely to a misleading conclusion for system planning.

Jon et al. (1999) suggested strategic models to assist power generating plants to improve their work control processes by continually keeping the process up to date. Work control process include elements for system cost/performance analysis, life-cycle maintenance planning, on-line scheduling and look-ahead techniques, and schedule implementation to conduct work on the asset.

The paper also discussed how risk management associated with work control issues affecting the safety and reliability. Operation and Maintenance (O and M) costs were also integrated into this strategy.

Reliability is an innate aspect of combined cycle power plant design and plays significant role during the operation of the plant in terms of operating and maintenance expenses and optimal maintenance scheduling of its equipments, components and systems. Reliability is the ability of an equipment, component, product, system, etc., to function under designated operating state of affairs for a specified period or number of cycles (De Souza, 2012).

The attempts reported in literature are in general concerned with the development of methodology taking into account one aspect at a time. However in respect of a power plant more than one aspect would need to be considered simultaneously. Thus, a methodology is required which simultaneously take care of proper peer group selection for comparison purposes and interaction amongst different sub-systems and operating parameters of a power plant. The new indices should also consider component’s contribution and the effect of failure rate of the sub-systems or components to reliability of the system.

2.2. GRAPH THEORY ANALYSIS

Combined and cogeneration cycle power plants are a very large and complex system. Performance of its components and systems are closely intertwined and insuperable without taking the effect of others. Therefore, reliability and efficiency of the combined-cycle thermal power plants depends on the perfect operation of all its systems (e.g. gas turbine, heat recovery steam generator, steam turbine and cooling system) (Kehlhofer et al., 1999). Energy and exergy analysis are the methods available in literature for calculating thermal power plant efficiency.

The most commonly used qualitative methods for reliability estimation are Fault Tree Analysis (FTA), Failure Modes, Effects and Criticality Analysis (FMECA), Failure Modes and

Effects Analysis (FMEA), Root Cause Analysis (RCA), Root Cause Failure Analysis (RCFA), Fish Bone Analysis (FBA), Event Tree Analysis (ETA), and Predictive Failure Analysis (PFA). Block diagram analysis, Markov chain, and Monte Carlo simulation are some of the quantitative methods of reliability analysis available in literature.

So far researchers evaluated combined cycle power plant system reliability only at system level without making an allowance for the interactions of systems, and subsystems. Therefore, there is need for extending the compass of reliability analysis for combined and cogeneration cycle power plants to take care of interaction among different systems and subsystems.

Therefore, design of combined cycle power plant, improvement in existing plant and comparison of two real life operating power plants need a Multi Attribute Decision Making (MADM) technique to analyze the effect of one system/design parameter on the other systems/design parameters. Some of the MADM techniques are discussed below.

Delphi method (Linstone, 1975) is a structural equation modeling technique which follows a series of steps to develop consensus among a group of experts and used for forecasting purpose in different areas. Problem associated with Delphi method is poor internal consistency and reliability of judgments among experts. Structural equation models (SEM) are mathematical relationships which represents the structure among variables. Moreover, it requires a large sample size that is generally several hundred observations, as the precision of the estimates is affected by sample size (Anbanandam et al., 2011). Therefore, it is not found suitable for the present analysis.

Pair-wise comparison and Analytic Hierarchy Process (AHP) do not capture the interdependence of variables while Analytic Network Process (ANP) captures the interrelationship, but not the hierarchical relationships among variables (Raj and Attri, 2010; Muduli et al., 2012).

Besides these techniques, El-Saadany and El-Kharbotly (2004) recommended that multi-period stochastic programming is appropriate tool to solve network design problems. El-Sayed et al. (2010) extended the work of El-Saadany and El-Kharbotly (2004) to a multi-period multi-echelon stochastic model. Taha et al. (2011) developed Genetic Algorithm (GA) to solve the two-sided assembly line balancing problem. Tao et al. (1999) proposed a distributed networked-manufacturing prototype system on the basis the concept of distributed networked-manufacturing system. Shuzi et al. (2000) discussed the effect of competition due to globalization, technical progress, and demand for customized product on the manufacturing environment.

In the current work, the main purpose is to quantify the parameters affecting the CCPP and CGCPP performance. It depends upon the degree of inheritance of the parameters and amount of interactions between them. Quantification of inheritance and interactions is not possible by using the above mentioned techniques. One approach having such a capability for development of mathematical model as reported in literature is Graph Theory and matrix method (Harary, 1985; Deo, 2007; Balakrishnan, 2005; and Rao, 2007). With the use of graph theoretic approach, interaction among the factors can be easily visualized by using the digraph. Digraph can be transformed into mathematical form with the help of incidence matrix which is suitable for computer processing.

2.2.1. GTA FOR MECHANICAL SYSTEMS

Graph Theory has been extensively used in the field of mechanical engineering for mechanisms and machine theory, computer aided design and manufacturing (Laperriere and Elmaraghy, 1996; Freudenstein and Maki, 1979; Agrawal and Rao, 1987). The applications include representation and identification of kinematic structure and for enumeration of kinematic chains and mechanisms in a relatively simpler and systematic manner. Matrix representation has proved to be useful in identification of known, as well as unknown chains. Representations and analysis of design variants was found to be more efficient using graph theory and digraph models and in particular during the conceptual design stage of a system (Salomons, 1994). Graph theory has been used for generation of disassembly sequences of an assembly (Laperriere and Elmaraghy, 1996). In the recent past the graph theory has been used in the field of Tribology (Gandhi and Agrawal, 1990, 1992, 1994). Graph and digraph representation of Tribology systems have proved to be useful for carrying out wear evaluations and analysis and lubrication selection. This modeling approach has been used by some researchers for analysis and evaluation of hydraulic systems (Gandhi et al., 1991), Failure cause Analysis (Gandhi and Agrawal, 1996), Reliability Evaluation and Selection of rolling element bearings (Sehgal et al., 2000), maintainability index (Wani and Gandhi, 1999). However, the performance of a complex system such as a CCPP, which comprises of many systems and sub-systems, has not been attempted.

Tang (2001) proposed a new method based on graph theory and Boolean function for assessing reliability of mechanical systems. The proposed methodology incorporates the graph theory for system level reliability and Boolean analysis for interactions. The combination of graph theory and Boolean function provides an effective way to evaluate the reliability of a large and complex mechanical system.

Reliability of combined cycle power plant is the probability of generating electricity under operational conditions encountered in a specific period of time. Reliability is a function of maintenance (scheduled or forced) cost, which in turns depends upon the Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) of equipment or system, and which is further dependent on complexity in design, state, age of the equipment or system and to some extent on the availability of spare parts. Wani and Gandhi (2002) suggested a GTA based procedure for maintainability design and evaluation of mechanical systems based on tribology. They identified tribological features of mechanical systems which can be used to characterize maintainability and modeled the relationships between them by using digraphs. Afterwards permanent function based indexes were derived in order to be able to compare alternative systems design in terms of maintainability.

Grover et al. (2004) developed a TQM index by utilizing GTA approach. In their approach five characteristics namely human factors, behavioral factors, use of tools/techniques, non behavioral factors and functional areas and their interactions are modeled by using digraphs. Afterwards a permanent index is proposed which can be used to quantify degree of TQM concepts implementation in an industry.

Kulkarni (2005) proposed a TQM index by utilizing GTA approach. In their approach five characteristics namely infrastructure, top management support, strategic planning, employee empowerment, customer satisfaction and their interactions are modeled by using digraphs. Afterwards a permanent index is proposed which can be used to quantify success of implementation of TQM in an industry.

Grover et al. (2005, 2006) presented two papers on the development of TQM indexes by utilizing GTA approach. In these studies the focus was on the evaluation of human factors on TQM implementation success. They identified various factors and sub-factors related to human issues from different perspectives and their interaction in deriving permanent indexes to quantify TQM success.

Rao and Padmanabhan (2006) employed GTA approach for developing a procedure for robot selection for manufacturing applications. They actually used an example from the literature and presented how GTA approach can be used to solve the same example. Six factors namely, purchase cost, load capacity, velocity, repeatability, number of degrees of freedom, and man-machine interface were used to rank/evaluate robot alternatives for a specific manufacturing application.

Zhong et al. (2006) proposed a systematic procedure by using GTA approach for machinability evaluation of ceramic materials. In their approach three criteria namely hardness, fracture toughness and elastic modules and their interactions were used to develop a material selection index.

Kaur et al. (2006) proposed a supply chain coordination index by using GTA which can be used to evaluate several coordination mechanisms like coordination by contracts, coordination by information sharing, coordination by using information technology and coordination by collaboration and their interaction.

Ionica and Edelhauser (2006) used GTA for evaluating customer supplier relationships within a total quality management context. They considered, “improving external communication”, “increasing the accessible market segment”, “consolidating the relations with the main clients” and “improving the relations with the main suppliers” as the main criteria. Criteria interactions are modeled via digraph and permanent index is used to evaluate alternative policies.

Rao and Padmanabhan (2007) presented a methodology for rapid prototyping process selection for a given product by using GTA approach. They actually modified one of the previous approaches from the literature and presented how this problem can be handled by GTA. In their study, six main criteria namely; accuracy, surface roughness, tensile strength, elongation, cost of part and build time and their interaction were considered in developing a selection index.

Faisal et al. (2007b) developed an information risk index by using GTA approach. This index can be used to quantify information risk factors in supply chains. In developing this index they used for main criteria and their interactions namely, information security/breakdown risk, forecast risk, intellectual property rights risk, IS/IT outsourcing risks.

Upadhyay and Agrawal (2007) proposed a systematic approach in order to model, evaluate and analyze intelligent mobile learning environments by making use of GTA approach. They identified five main systems like; “intelligent tutoring system”, “multi-agent intelligent system”, “mobile dimension system”, “environment and human aspect system”, “mobile agent system” and their sub-system along with interaction between these sub-systems in evaluating alternative mobile learning environments.

Thakkar et al. (2008) proposed an extensive methodology for evaluating buyer-supplier relationships in supply chains by making use of GTA approach. The proposed approach can also be used to compare supply chain relationships of SMEs. In developing their model many factors (like; business growth-long term perspective, mutual understanding and closeness, meeting customer/market requirement, role in decision making, risk/profit sharing) and sub-factors along with their interrelationships were considered and modeled with digraphs.

Wagner and Neshat (2010) developed a vulnerability index for supply chains by making use of GTA approach. They classified supply chain vulnerability factors under three category such as “demand side”, “supply side” and “supply chain structure characteristic” factors in developing their index and compared supply chain vulnerability characteristics of different industries.

In this section some of the applications of the GTA in mechanical engineering are presented. In the next section analysis of literature on the graph theoretic analysis of thermal plants have been discussed.

2.2.2. GTA FOR THERMAL POWER PLANT SYSTEMS

Mohan et al. (2003) developed a mathematical model using graph theory and matrix method to evaluate the performance of a steam power plant. Detailed methodology for developing a system structure graph (SSG), various system structure matrices, and their permanent functions were described for the boiler of an SPP. Structural interconnections between six systems of boiler were considered for developing an SSG of a boiler. To carry out complete structural modelling and analyses of the boiler, system structure graphs of its six systems and their subsystems were presented. A top–down approach for complete analysis of any system was also given. But in this work no quantitative data was reported for the analysis.

Mohan et al. (2004) applied Graph Theoretic Approach (GTA) to develop a mathematical model for determining the maintenance criticality index for the equipment of a coal-based steam power plant. Using this model, an appropriate maintenance strategy for any type of coal based power plant can be recommended.

Mohan et al. (2006) applied Graph Theoretic Approach (GTA) to calculate real-time efficiency index (RTEI) for a steam power plant which is the ratio of the values of variable permanent system structure function (VPF) in real-time (RT) situation to its achievable design value. The proposed methodology was explained with the help of two examples. With the value of

RTRI, plant manager can calculate the probability of failure of different systems and subsystems on real-time basis, thus enabling him to decide reliable level of process performance, i.e. restricted load operation. This knowledge of RTRI could be helpful to take commercial decision on real-time basis.

Garg et al. (2006) developed a deterministic quantitative model based on graph theoretical methodology to compare various technical and economical features of wind, hydro and thermal power plants. Suitability factor for three plants a) Thermal Power Plant b) Hydro Power Plant c) Wind Power Plant, were calculated on the basis of installation cost, cost of electricity generation and Plant Load Factor (PLF). Thermal power plant was found to be most suitable and after that was Hydro power plant followed by Wind power plant.

Mohan et al. (2008) proposed a graph model in conjunction with the matrix method to obtain real time reliability index (RTRI) for a steam power plant (SPP). This model enables incorporation of any number of systems and subsystems of the SPP as also the interaction among them in the study of performance of a SPP. Further it was pointed out that the methodology developed can be applied for obtaining other RAMS (Reliability, Availability, Maintainability, Serviceability) indices: availability and maintainability; including optimum selection, bench marking, and sensitivity analysis of a SPP.

Simple model, easy to implement, lesser computational cost and flexible with changing environment is required to evaluate the combined and cogeneration cycle power plant reliability and efficiency on design or analysis basis. From the literature, it is clear that graph theory and matrix approach as a decision making method offers a generic, simple, easy, convenient and indigenous way of decision making that involves less computational efforts.

2.3. SUMMARY OF LITERATURE REVIEW AND GAPS

The review shows that a number of alternative designs of combined and cogeneration cycle power plant sub-systems are available and there is continual upgrading in their design. From the economical, environmental and practical point of view, the combination of a simple gas turbine cycle coupled to a Rankine steam bottoming cycle (which may be with dual/triple pressure and reheat) without supplementary firing is the most common type of CCPP. In a CGCPP process heater is used in place of HRSG and heated water or low pressure steam is generated.

Most of the thermodynamic analysis and parametric studies are based on step by step calculation of cycle processes of different combined and cogeneration cycle configurations. The basis of comparison has mostly been the energy or exergy analysis.

A number of qualitative and quantitative methods of reliability analysis are also available in literature.

The attempts reported in literature are in general concerning the development of new methods taking into account one aspect, either efficiency or reliability, at a time. However, in respect of a power plant more than one aspect would need to be considered simultaneously. Thus, new statistics are required to simultaneously take care of interaction amongst different systems and design parameters of a CCPP or CGCPP. The new indices should also consider sub-system's contribution and the effect of failure rate of the sub-system to reliability of the system.

During literature survey it is found that Graph Theoretic Approach has not been used for performance analysis of combined and cogeneration cycle power plant.

2.4. OBJECTIVE OF COMBINED AND COGENERATION CYCLE POWER PLANT ANALYSIS

Performance analysis of a power plant and improvement in the existing one is dependent on many parameters such as efficiency, reliability, environmental impact; availability of fuel etc. and other issues such as ergonomics etc. also can't be neglected. Thermodynamic analysis capable of analyzing efficiency cannot be used for reliability analysis and vice-versa. Keeping the above requirements of upcoming electricity markets in view, the efforts are required to develop a single composite index to monitor the overall performance of power plant. Thus, present work aims to fulfill the following objectives:

(a) To develop methodology for Multi Attribute Decision Making (MADM) technique, using Graph theoretic approach, capable of studying interdependency of design parameters and sub-systems.

(b) To analyze the plant performance on efficiency and reliability basis by taking into account the interactions amongst the various sub-systems, effect of design parameters on sub-systems and interdependencies of design parameters using GTA.

(c) To determine the indices in the form of a ratio (RTEI and RTRI) to eliminate the shortcomings of graph theoretic analysis available in literature due to variance in the type, design and configuration of power plants.

(d) To carry out exergy analysis of cogeneration cycle for quantification of inheritance for different design parameters and validation of graph theoretic model.

To fulfill these objectives, a methodology based graph theory for the analysis of combined and cogeneration cycle is presented in the next chapter.

CHAPTER-III

METHODOLOGY FOR GRAPH THEORETIC AND EXERGETIC ANALYSIS

Literature review, as discussed in the previous chapter, bestows the overview of graph theoretic and exergetic analysis of some of the thermal power plant systems. Research in engineering analysis usually starts with an understanding of the physical system, then the adoption of suitable mathematical model for the system. In this chapter, system modeling of a combined and cogeneration cycle power plant and its analysis using graph theory and matrix method is described followed by thermodynamic modeling of CGCPP.

3.1. GRAPH THEORETIC ANALYSIS (GTA)

Graph theory is a logical and systematic approach useful for modeling and analyzing various kinds of systems and problems in numerous fields of science and technology. If the graph/digraph is complex, it becomes difficult to analyze it visually. Quick analysis may be carried out by logical and systematic computer programming tool through the use of the matrix method. It is a three stage unified systems approach.

1. Modeling of system and subsystem in terms of nodes and edges for structural representation in the form of directed graph (digraph) which is suitable for visual analysis and gives a better understanding of interrelationships among system and subsystems.

2. Digraph representation is converted to matrix form, which is suitable for computational analysis. Value of each element in the matrix is assigned based upon inheritance of system or subsystem and their interdependency.
3. Matrix model is solved and results in the expression form called as permanent function. After quantification of each term of permanent function, result is represented in term of a single numerical index which is the indication of system performance.

Digraph representation, matrix representation and permanent function can be developed for the quality, cost, reliability, environmental and efficiency characteristics of combined or cogeneration cycle power plant. Design and operating parameters affecting efficiency, reliability, cost etc. may be identified either with the help of thermodynamic model of power plant or with the help of experts in this area. Graph theoretic model of combined cycle power plant is explained in the following section. With the help of this model performance of CCPP evaluated. Further, this model is used for the evaluation of real time reliability and efficiency index for CCPP. In the similar manner analysis of CGCPP is also carried out afterwards.

3.1.1. GTA FOR COMBINED CYCLE POWER PLANT

CCPP, considered for the present analysis, is shown in Figure 3.1. The air at the ambient temperature and pressure enters the air compressor after being filtered by air filters. Mechanical energy of compressor is used to compress the air so that higher quantity of fuel may be added in air at lesser volume in combustion chamber. After compression air comes to combustion chamber and mixes with the Compressed Natural Gas (CNG) from the fuel supply system. Activation energy for the reaction between air and fuel is being provided by spark between two electrodes and reaction is at constant pressure. After this, hot combustion gases enter the gas turbine where thermal energy of flue gases is converted into mechanical power of gas turbines. HRSG is the link between the gas turbine and the steam turbine process, whose function is to transfer heat energy from exhaust gases to pressurized water and produces superheated steam. The steam is separated in the boiler drum and supplied to the super heater section. The super heated steam produced in the super heater then enters into the steam turbine through the turbine stop valve. After expansion in steam turbine the exhaust steam is condensed in the condenser. In the cooling water system, heat of steam turbine exhaust is carried away by the circulating water, which is finally rejected to the atmosphere with the help of cooling towers. Because of this direct path to the atmosphere, surrounding water bodies typically do not suffer adverse thermal effects (Sanjay et al., 2008). The power plant is a series of systems except for the cooling tower that is modeled as K out of N systems, meaning that it is necessary to have a given number of cooling towers working (K) out of total N to allow the plant to

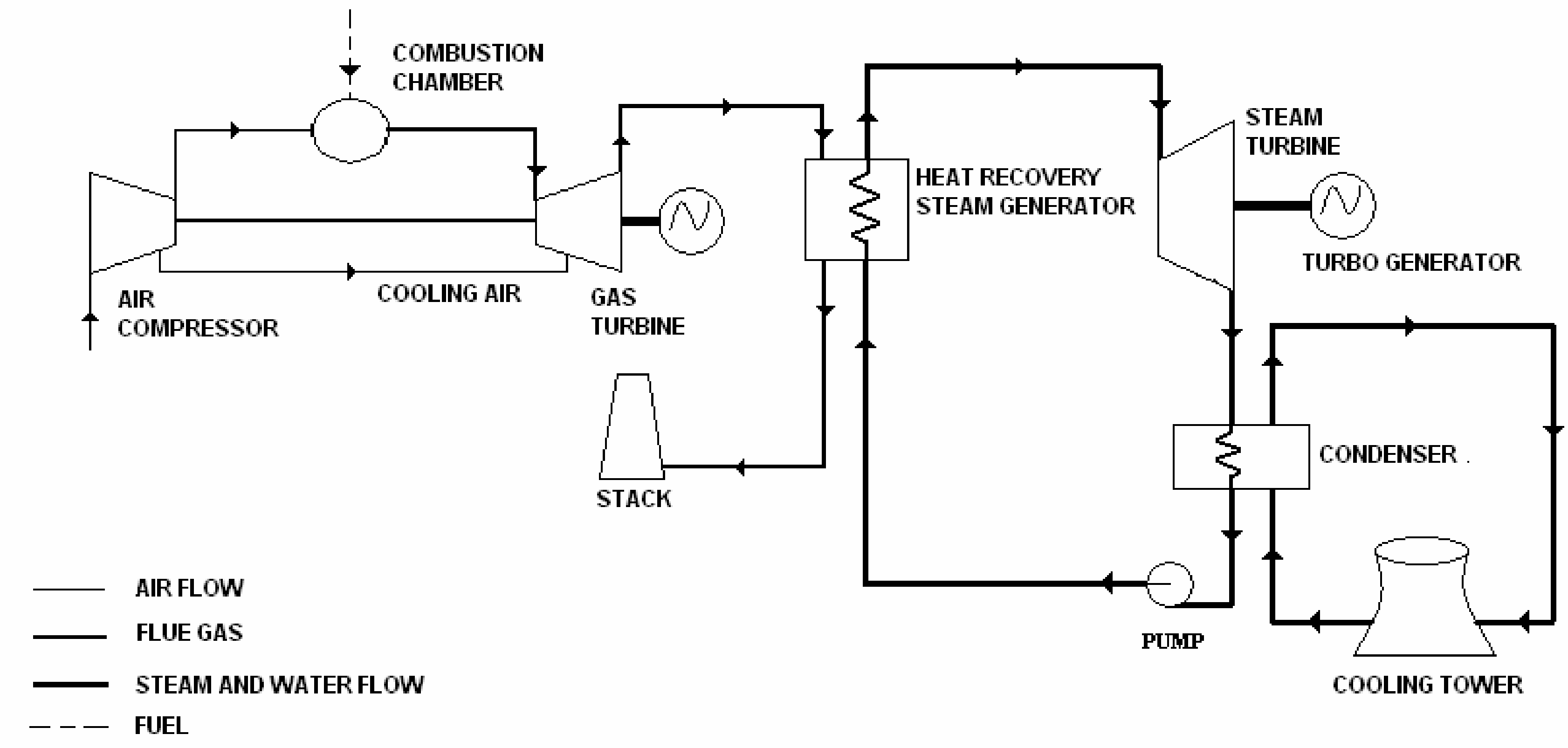


Figure 3.1 Schematic flow diagram of Combined Cycle Power Plant

achieve nominal output (De Souza, 2012). The abridged model as explained above is easy to analyse with GTA.

3.1.1.1. SYSTEM STRUCTURE GRAPH OF CCPP

Structure is the key for deliberation and analysis of system performance or failure analysis (Yoshikawa, 1982). Structure or topology may be physical or abstract. The physical structure of a system implies subsystems, assemblies, components and their interconnections, while an abstract structure involves performance or failure contributing events.

A real life CCPP system is highly complex in nature. In present analysis it is being found appropriate to divide combined cycle power plant into following six subsystems:

1. Air Compressor System (S_1)
2. Combustion Chamber System (S_2)
3. Gas Turbine System (S_3)
4. Heat Recovery Steam Generator System (S_4)
5. Steam Turbine System (S_5)
6. Water System (S_6)

Here, air system is considered a part of air compressor system and fuel system is a part of combustion chamber system. In a CCPP, gas turbine and steam turbine may be installed either on same shaft or separate shaft. In the present analysis turbo-generators are attached with gas and steam turbine and considered to be a part of them.

Division of combined cycle power plant in these subsystems is based on the working of different components and it may be divided further into sub-subsystems. As these subsystems are also very big, so hereafter they will be referred as systems. Let each of the six systems of plant be represented by vertices S_i's (i=1,2,3,4,5,6) and interconnection between two systems (S_i, S_j) is represented by edges c_{ij}'s (i,j=1,2,3,4,5,6 and $i \neq j$) connecting the two vertices S_i and S_j. In the combined cycle power plant all these six systems are connected by flow of air, flue gases, water, steam, heat and work. This flow is shown in Figure 3.2 with the help of vertex and edges.

This representation is called as System Structure Graph (SSG). This is based upon the functioning of combined cycle power plant as per the following:

1. The ambient air comes to the compressor after being filtered by air filters. Compressor and turbine are attached with a shaft. Therefore, the power to compress the air comes to the compressor from the turbine. This is represented by the edge c_{31}. S_1 and S_3 are the compressor system and gas turbine system respectively.
2. After compression, air goes to the combustion chamber. This is represented by edge c_{12}. Fuel is added in the combustion chamber.
3. A blade is cooled by being made hollow so that a coolant air can circulate through it. Coolant air is obtained directly from the compressor, thus, bypassing the combustion chamber. Edge c_{13} represents the bypassing of cooling air.
4. Fuel supplied to the combustion chamber is generally CNG. Fuel supply is taken as a part of combustion chamber system. Outlet temperature of combustion chamber system [S_2] depends upon thermal stress limit of gas turbine blade material. Highest temperature of flue gas coming out from combustion chamber is controlled by changing air-fuel (A/F) ratio. Combustion product flows to gas turbine as shown by edge c_{23}.
5. Depending upon the temperature of flue gas, HRSG [S_4] may be used for (i) partial heating (regeneration) of the compressed air leaving the compressor (c_{42}), (ii) feed water heating of the steam cycle in a closed type feed water heater (c_{46}), or (iii) generating steam in a dual or multipressure steam cycle.
6. Flue gases coming out of combustion chamber and entering to HRSG system [S_4] are shown by

the edge c_{34}.

7. Due to HRSG [S_4] heat transfer surfaces fouling, back-pressure is increased and the gas turbine [S_3] does not work at its design point condition because of the inherent problems which accompanies the increase of back-pressure, e.g., high torque on the shaft, coupling forces on thrust bearing, and vibration (Zwebek and Pilidis 2003). It is shown by the edge c_{43}.
8. High temperature and high pressure steam flows from HRSG system to steam turbine system [S_5] shown by edge c_{45}.
9. Single stage reheating is employed between High Pressure Turbine (HPT) and Intermediate Pressure Turbine (IPT). For this steam coming out from HPT [S_5] is sent to HRSG [S_4] shown by edge c_{54}.
10. From steam turbine, low pressure and temperature steam comes to the cooling tower (c_{56}) and after condensation it goes to HRSG after passing the pump.
11. De-mineralized (DM) feed water is injected to control the temperature of superheated and reheated steam as an attemperation spray (c_{65}).
12. DM water from the water circuit [S_6] is fed to HRSG as feed water represented by edge c_{64}.

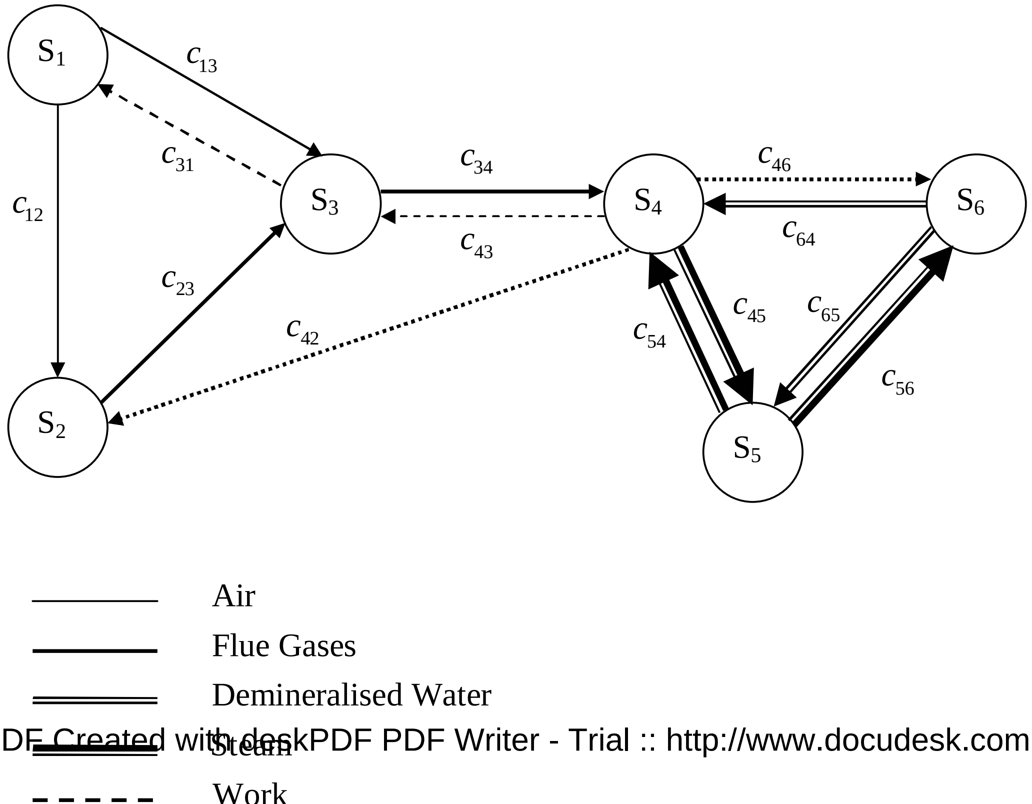


Figure 3.2 System structural graph of CCPP with material and energy interaction

The SSG of Figure 3.2 represents the internal structure of the CCPP at system level. It clearly shows different systems and their interconnections in the CCPP as discussed above. This graph theoretic representation permits the incorporation or deletion of any interconnection or system in order to make it closer to a real life combined cycle power plant based on different design and principles in any given situation.

A graph with directed edges is called as digraph. The digraph permits to analyse CCPP performance and gives a feeling of interactions between the systems. Simplified diagraph corresponding to SSG of CCPP (Figure 3.2) is shown in Figure 3.3.

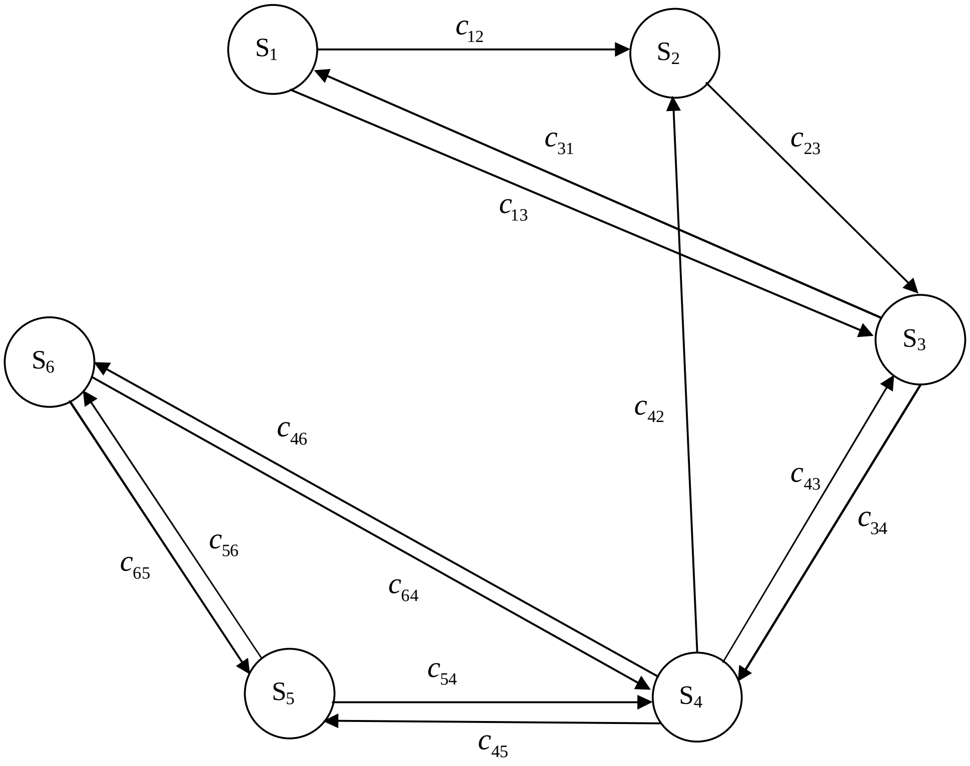


Figure 3.3 Digraph showing six systems (S_i) of CCPP and their interdependencies (c_{ij})

Digraph representation is suitable for visual analysis but not for computer processing. Moreover, if the system is large, its corresponding graph is complex and this complicates its understanding visually. In view of this, it is necessary to develop a representation of the CCPP that can be understood, stored, retrieved and processed by the computer in an efficient manner. The SSG can be retrieved and processed by converting it into suitable matrix form as discussed in the next section.

3.1.1.2. MATRIX REPRESENTATION

Firstly graphical model of the system is developed using graph theory which is named as attribute graph and after that graphical model is converted into matrix model called as attribute matrix. Finally this matrix is expressed in the form of a function called ‘Variable Permanent Function (VPF)’. Matrix representation of the CCPP attribute digraph gives one-to-one representation. Finally selected matrix should be flexible enough to incorporate the structural information of systems and interconnections between them.

Many matrix representations, for example, adjacency and incidence matrix are available in literature (Deo, 2000; Harary, 1985). The adjacency matrix is a square matrix and is selected for this purpose. An adjacency matrix is a means of representing vertices (or node) of a graph adjacent to other vertices.

Specifically, the adjacency matrix, of a finite graph S on N vertices, is the NXN matrix where the non-diagonal entry c_{ij} is the number of edge from vortex i to vortex j, and the diagonal entry c_{ii}, represents the connectivity of the system with itself. Using this, the SSG of CCPP is represented in the matrix form. The structural expansion, a characteristic of the CCPP system is obtained by solving the matrix and is useful for its exhaustive analysis.

(a). System Structural Adjacency Matrix

Let a general case of a system, for example, a CCPP having N systems be considered leading to adjacency matrix (0, 1) of order NXN and c_{ij} representing the connectivity between system i and j such as $c_{ij} =1$, if system i is connected to the system j, (in the graph, this is represented by an edge (c_{ij}) between node i and j) and is equal to zero, otherwise. Thus $c_{ii} = 0$ for all i, as no system is connected to itself in case of combined cycle power plant.

Each row of the system structure adjacency matrix corresponds to a system. The off diagonal matrix elements, c_{ij} represent connection between system i and j. In this matrix $c_{ij} \neq c_{ji,}$ as directional consideration is taken into account. The possible interconnections between six systems of CCPP have been discussed in the last section. The adjacency matrix A_c for the SSG of CCPP shown in Figure 3.3 is as represented in expression (3.1).

$$A_c = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \tag{3.1}$$

This (0, 1) adjacency matrix only shows interconnection between different systems. This matrix also does not contain any information about the six systems as diagonal terms are zeros. Secondly, interdependency of systems is common for each case but in real life operating plant it is not so. Adjacency matrix simply represents connectivity amongst six systems of CCPP. As this matrix considers only the connections between the systems and the characteristic features of the system do not come in the picture, a new matrix called 'Characteristic System Structure Matrix' is defined as discussed in next sub-section.

(b). Characteristic System Structure Matrix

The presence of different systems of the CCPP is realized by defining a characteristic system structure matrix that is

$$B_c = \{SI - A_c\} \tag{3.2}$$

Where I is the identity matrix and S is the characteristic of systems, representing its characteristic structural features. This matrix for system structural graph of CCPP is expressed as:

$$B_c = \{SI - A_c\} = \begin{bmatrix} S & -1 & -1 & 0 & 0 & 0 \\ 0 & S & -1 & 0 & 0 & 0 \\ -1 & 0 & S & -1 & 0 & 0 \\ 0 & -1 & -1 & S & -1 & -1 \\ 0 & 0 & 0 & -1 & S & -1 \\ 0 & 0 & 0 & -1 & -1 & S \end{bmatrix} \tag{3.3}$$

This matrix is analogous to characteristic matrix in graph theory (Deo, 2000; Harary, 1985). The characteristics features of systems could be efficiency, reliability, availability, cost and so on. It can be seen that characteristic matrix contains information about the presence of system and their interconnections. It does not include information about attributes of the connections among different systems. The determinant of characteristic system structure matrix is also called as characteristic system structure polynomial and written as:

$$\det\{B_c\} = S^6 + 5S^4 - 4S^3 + 4S^2 - 6S + 2 \tag{3.4}$$

The characteristic system structure polynomial which is derived above is known as the invariant of the system and its value does not change by altering the labeling of systems. It is characteristic of the system structure. However, the characteristic system structure matrix is not an invariant of the system, because a new matrix is obtained by changing the labeling of the systems. However, one matrix can be obtained from the other by proper permutation of rows and columns. From the above matrix, it is noted that a value of S is taken to be same for all the diagonal elements i.e. all the systems are considered to be identical. This is one of the reasons that make the characteristic polynomial inappropriate for the present analysis. In practice, a CCPP having all the six systems do not possess the same structural features. Inheritance of each system is different and interdependency of systems is also dissimilar. To incorporate distinct information of different systems and interconnections between them, a matrix called ‘variable characteristic system structure matrix' is proposed.

(c). Variable Characteristic System Structure Matrix (VCSSM) of CCPP

A variable characteristic system structure matrix T_c is defined taking into account the distinct characteristic of systems and their interconnection defined in the system structure graph. Let the off diagonal elements of a matrix, F_c, representing the connection between systems be denoted by c_{ij} instead of 1, whenever system i is connected to system j with i, j = 1,2,3,4,5,6 ($i \neq j$) and 0 otherwise. Let us also define a diagonal matrix D_c, with its variable diagonal elements S_i (i=1,2,3,4,5,6) representing the characteristic structural feature of six distinct systems. For system structural graph of CCPP (Figure 3.3) the VCSSM $T_c = [D_c - F_c]$ is written as

$$T_c = [D_c - F_c] = \begin{bmatrix} S_1 & -c_{12} & -c_{13} & 0 & 0 & 0 \\ 0 & S_2 & -c_{23} & 0 & 0 & 0 \\ -c_{31} & 0 & S_3 & -c_{34} & 0 & 0 \\ 0 & -c_{42} & -c_{43} & S_4 & -c_{45} & -c_{46} \\ 0 & 0 & 0 & -c_{54} & S_5 & -c_{56} \\ 0 & 0 & 0 & -c_{64} & -c_{65} & S_6 \end{bmatrix} \tag{3.5}$$

The determinant of VCSSM is variable characteristic system structural multinomial (VCM-s) and is written as

$$\begin{aligned}Per\left[T_c\right] = {} & [S_1S_2S_3S_4S_5S_6 - \left(c_{13}c_{31}\right)\left(S_2S_4S_5S_6\right) - \left(c_{46}c_{64}\right)\left(S_1S_2S_3S_5\right) \\ & - \left(c_{56}c_{65}\right)\left(S_1S_2S_3S_4\right) - \left(c_{34}c_{43}\right)\left(S_1S_2S_5S_6\right) - \left(c_{45}c_{54}\right)\left(S_1S_2S_3S_6\right) \\ & - S_1S_2S_3\left(c_{45}c_{56}c_{64}\right) - S_1S_2S_3\left(c_{46}c_{65}c_{54}\right) - S_1S_5S_6\left(c_{23}c_{34}c_{42}\right) \\ & - S_4S_5S_6\left(c_{12}c_{23}c_{31}\right) + S_1S_2\left(c_{34}c_{43}\right)\left(c_{56}c_{65}\right) + S_2S_6\left(c_{13}c_{31}\right)\left(c_{45}c_{54}\right) \\ & + S_2S_4\left(c_{13}c_{31}\right)\left(c_{56}c_{65}\right) + S_2S_5\left(c_{13}c_{31}\right)\left(c_{46}c_{64}\right) + S_1\left(c_{56}c_{65}\right)\left(c_{23}c_{34}c_{42}\right) \\ & + S_2\left(c_{13}c_{31}\right)\left(c_{46}c_{65}c_{54}\right) + S_2\left(c_{13}c_{31}\right)\left(c_{45}c_{56}c_{64}\right) + S_4\left(c_{56}c_{65}\right)\left(c_{12}c_{23}c_{31}\right) \\ & + S_5\left(c_{46}c_{64}\right)\left(c_{12}c_{23}c_{31}\right) + S_6\left(c_{12}c_{23}c_{31}\right)\left(c_{45}c_{54}\right) + \left(c_{12}c_{23}c_{31}\right)\left(c_{45}c_{56}c_{64}\right) \\ & + \left(c_{12}c_{23}c_{31}\right)\left(c_{46}c_{65}c_{54}\right)]\end{aligned}$$

(3.6)

Every term in the Per [Tc] is representing the part of the system and interlink. For example the $S_1S_2S_3S_4S_5S_6$ shows that all six systems are linked to each other. Any of the system cannot be omitted. The multinomial (3.6), consist of variable structural components such as S_i, c_{ij}, $c_{ij}c_{jk}$, $c_{ij}c_{jk}c_{kl}$ and so on. Here S_i is the Structural Characteristic Feature (SCF) of the system that is S_1 represents the SCF of the compressor system, S_2 represents the SCF of the combustion chamber system, S_3 represents the SCF of gas turbine system and so on. By associating proper physical meaning to these structural components, appropriate information about the system and interlink is obtained. To read the expression (3.6) in a systematic manner, the terms are arranged in N+1 grouping (with N = 6 in the present case).

The first grouping contains only one term and is $S_1S_2S_3S_4S_5S_6$ signifying that for the CCPP system to work or to exist all its systems must be in place. The second grouping is absent in the absence of self loop in the graph. This means, this grouping in the expression will appear if a system is connected to itself. The third grouping consists of number of terms and each is collection of two- system structural dyad and four system characteristics structural features. The absence of the term containing dyads such as $c_{24,}$ c_{25} signifies absence of direct interaction of combustion chamber system and HRSG and steam turbine system. The fourth grouping consists of a term which is a set of three system structural loop and three system characteristic structural features. The absence of interactions e.g. $c_{14,}$ $c_{15,}$ c_{16} etc. show that there is no direct interlink of air compressor system with HRSG system, steam turbine system and water system. Each term of the fifth grouping is a collection of two two-system structural dyad and two-system characteristic structural features. The terms of sixth grouping are a set of three-system structural loop, two systems structural dyad and a system characteristic structural feature. The term of seventh grouping is a set of two 3-system structural loops.

From the subject discussion, it is obvious that, in general, the *i*th grouping contains (N +1 - i) S*i*'s and the remaining structural components (for example c_{ij}, $c_{ij}c_{jk}$, $c_{ij}c_{jk}c_{kl}$ etc.). The terms of the expression are arranged in decreasing number of S*i*s for better interpretation of the system. Because of the arrangement of the terms of system structure in the same grouping, the complete multinomial can be written by visual inspection of the graph. For finding the value of the diagonal attributes, i.e., S_1, . . . , S_6, a SSG for these systems considering their subsystems and elements can be developed and the determinant value of the corresponding VCM-s can be calculated.

In a matrix, change in the value of any entity, changes the value of the determinant. In expression (3.6) some of the terms are with negative sign and some of the information regarding loops and systems is subtracted. Due to this reason, researchers have used the permanent function of a matrix, which does not contain any negative terms, and thus provides the complete information without any loss (Gandhi et al., 1991; Gandhi and Agrawal, 1992, 1994; Rao and Gandhi, 2001, 2002a, 2002b; Rao, 2004, 2006a, 2006b, 2006c, 2006d; Grover et al., 2004; Rao and Padmanabhan, 2006). Therefore, a 'variable permanent system structure matrix' is explained below which is appropriate for present analysis.

(d). Variable Permanent System Structure Matrix (VPSSM) for a CCPP

The negative signs in equation (3.6) indicate subtraction of information about dyads, loops of systems, or system attributes such as reliability, efficiency, and so on, which will not project a true picture of the CCPP under analysis. For realistic understanding and characterization, a permanent function is proposed and no negative sign will appear in the expression. Application of the permanent concept will thus lead to a better appreciation of the complete structure, in general. The variable permanent system structure matrix (VPSSM) T_a for the combined cycle power plant is as represented by the expression (3.7). All the terms of the expressions (3.6) and (3.7) are same and differ in their signs. The determinant of the VPSSM will be with the positive and negative signs. Therefore, Variable Permanent System Structure Function (VPSSF) is used in place of determinant for the evaluation of VPSSM. Evaluation and formulation of VPSSF is explained in the next section.

$$T_a = [D_c + F_c] = \begin{bmatrix} S_1 & c_{12} & c_{13} & 0 & 0 & 0 \\ 0 & S_2 & c_{23} & 0 & 0 & 0 \\ c_{31} & 0 & S_3 & c_{34} & 0 & 0 \\ 0 & c_{42} & c_{43} & S_4 & c_{45} & c_{46} \\ 0 & 0 & 0 & c_{54} & S_5 & c_{56} \\ 0 & 0 & 0 & c_{64} & c_{65} & S_6 \end{bmatrix} \tag{3.7}$$

Where the meaning of S_is, c_{ij}, D_c, and F_c is same as in the expression (3.6).

3.1.1.3. EVALUATION OF VPSSF

The permanent of VPSSM is called as the variable permanent system structure function and is abbreviated as VPF-s. It may be mentioned that the permanent is a standard matrix function, and is used in combinatorial mathematics (Marcus and Minc, 1965; Jurkat and Ryser, 1966; Nijenhuis and Wilf, 1975).

The only difference between matrices (3.5) and (3.7) is in the signs of the off-diagonal elements. In the VCSSM, expression (3.5), the off-diagonal elements c_{ij} have negative signs, while these are positive in the VPSSM of expression (3.7). VPF-s for matrix (3.7) is written as:

$$
\begin{aligned}
Per\left[T_c\right] = {} & [S_1S_2S_3S_4S_5S_6 \; + \; (c_{13}c_{31})(S_2S_4S_5S_6) + \; (c_{46}c_{64})(S_1S_2S_3S_5) \\
& + \; (c_{56}c_{65})(S_1S_2S_3S_4) + (c_{34}c_{43})(S_1S_2S_5S_6) \; + \; (c_{45}c_{54})(S_1S_2S_3S_6) \\
& + \; S_1S_2S_3\left(c_{45}c_{56}c_{64}\right) \; + \; S_1S_2S_3\left(c_{46}c_{65}c_{54}\right) + \; S_1S_5S_6\left(c_{23}c_{34}c_{42}\right) \\
& + S_4S_5S_6\left(c_{12}c_{23}c_{31}\right) + \; S_1S_2\left(c_{34}c_{43}\right)\left(c_{56}c_{65}\right) \; + \; S_2S_6\left(c_{13}c_{31}\right)\left(c_{45}c_{54}\right) \\
& + S_2S_4\left(c_{13}c_{31}\right)\left(c_{56}c_{65}\right) \; + \; S_2S_5\left(c_{13}c_{31}\right)\left(c_{46}c_{64}\right) + \; S_1\left(c_{56}c_{65}\right)\left(c_{23}c_{34}c_{42}\right) \\
& + S_2\left(c_{13}c_{31}\right)\left(c_{46}c_{65}c_{54}\right) + \; S_6\left(c_{12}c_{23}c_{31}\right)\left(c_{45}c_{54}\right) \; + \; S_2\left(c_{13}c_{31}\right)\left(c_{45}c_{56}c_{64}\right) \\
& + S_4\left(c_{56}c_{65}\right)\left(c_{12}c_{23}c_{31}\right) \; + \; S_5\left(c_{46}c_{64}\right)\left(c_{12}c_{23}c_{31}\right) + \; \left(c_{12}c_{23}c_{31}\right)\left(c_{45}c_{56}c_{64}\right) \\
& + \; \left(c_{12}c_{23}c_{31}\right)\left(c_{46}c_{65}c_{54}\right)]
\end{aligned}
$$

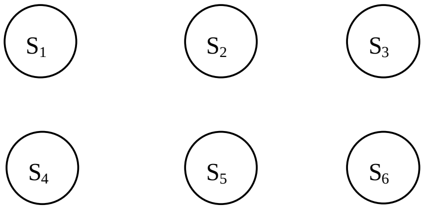
(3.8)

The quantified values of S_i and c_{ij} in the expression (3.8), explained later in this section, results in the form of an index called as CCPP Performance Index in the present case. The main features of CCPP Performance Index (CPI) are as follows:

1. This index is quantitative representation of CCPP performance and a mean to evaluate the affect of six systems on combined cycle power plant performance.
2. By changing the value of inheritance (S_i) and interdependency (c_{ij}), index value is changed. A comparison in between the index values for different S_i and c_{ij} is helpful to study the effect or importance of different systems.
3. Index value may be used for the comparison of combined cycle power plant performance under varying sets of inheritance of systems.
4. Performance of two or more power plants may be compared on design or performance basis and it may help in deciding selection criteria for the new plant.

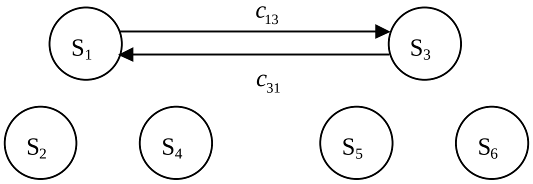
Every term of the multinomial (3.8) represents a physical subset of the system. It is possible to write these equations simply by visual inspection of the SSG of Figure 3.3. To achieve this objective, the permanent function of equation (3.8) is written in standard form in (N +1) groups. All these distinct combinations of systems of the macro system are shown graphically in Figure 3.4.

The multinomial, that is, the permanent function when written down in $N + 1$ groups, present an exhaustive way of structural analysis of CCPP performance and interdependencies of systems. It helps in identifying critical components and links to improve reliability, efficiency, and cost of the system.



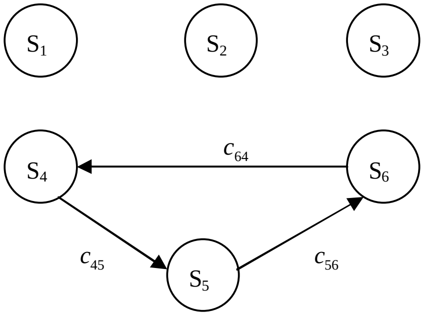
1 Term

(a) Group 1



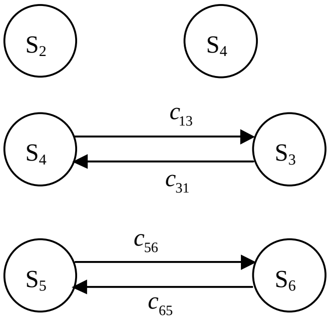
+ 4 Other Terms

(b) Group 3



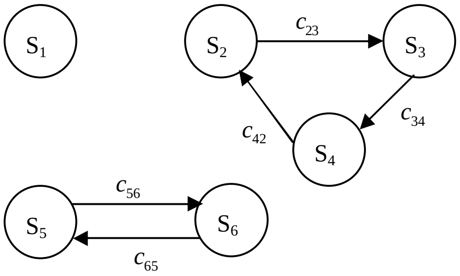
+3 Other Terms

(c) Group 4



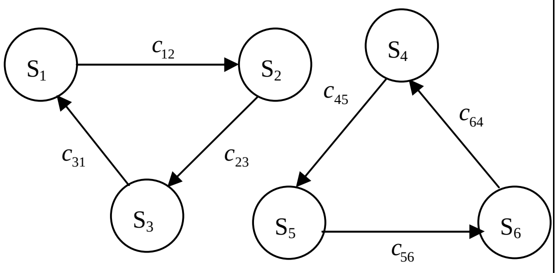
+3 Other Terms

(d) Group 5



+5 Other Terms

(e) Group 6



+1 Term

(f) Group 7

Figure 3.4 Graphical representation of permanent function (Equation 3.8)
corresponds to digraph (Figure 3.3)

To calculate this index, the values of S_i and c_{ij} are required to be replaced in equation (3.8). Faisal et al. (2007a) explained that if data regarding the variables from some previous research or field study is available then, it can be used to determine the index. But in case no quantitative values are available and in order to avoid complexity at system or subsystem level, then values of S_i called as inheritance can be assigned from 1-9 based on the level of real life performance of the sub-systems as shown in Table 3.1. Similarly, the value of c_{ij} (interdependency) between the two systems or parameters can be assigned a value on a scale of 1-5 as mentioned in Table 3.2 based on the strength of interdependency expected in the real life situation. From literature it has been found that Wani and Gandhi (1999) have used data from previous research for selecting the values of the variables while Kulkarni (2005) used a questionnaire to measure each attribute in quantitative terms.

Table 3.1 Quantification of factors affecting combined cycle power plant performance

S. No.	Qualitative measure of parameters affecting performance	Assigned value of parameter (inheritance)
1	Exceptionally low	1
2	Very Low	2
3	Low	3
4	Below average	4
5	Average	5
6	Above Average	6
7	High	7
8	Very High	8
9	Exceptionally High	9

Table 3.2 Quantification of interdependencies/ off diagonal elements

S. No.	Qualitative measure of interdependencies	Assigned value of interdependencies
1	Very Strong	5
2	Strong	4
3	Medium	3
4	Weak	2
5	Very weak	1

It may be mentioned that one can choose any scale for S_i or c_{ij} (Faisal et al. 2007b, Wani and Gandhi, 1999). The user may select an appropriate scale, for example, 0–5, 0–10, 0–50 or 0–100 for S_i's and c_{ij}'s, but the final ranking will not be affected as these are relative values. However, lower scale value is desirable to obtain a manageable value of performance index and also to reduce partisanship.

3.1.1.4. STEP BY STEP PROCEDURE FOR PERFORMANCE ANALYSIS

A methodology based on Graph Theory and matrix method is developed for evaluating performance of combined cycle power plant. Digraph representation, Matrix representation and Permanent function representation are the three steps of this methodology. The main steps of methodology developed for the evaluation of CCPP performance index are as follows:

1. Identify the various systems affecting the CCPP performance.
2. Develop the CCPP system structural graph.
3. Develop the system structural digraph corresponding to SSG of CCPP. This is the digraph at the system level.
4. Develop the CCPP system structure matrix for the CCPP system structure digraph. This will be M x M matrix with diagonal elements of S_i (inheritance) and off-diagonal elements of c_{ij} (interdependency). For avoiding the complexity, the numerical values of inheritance and

interactions are used. The values of inheritance (diagonal elements) and interaction among these systems (off-diagonal elements) are to be decided by the experts on the basis of scale of 1-9 and 1-5 respectively as stated in Table 3.1 and 3.2.

5. Calculate the permanent function of the system structure matrix developed in step 4. A computer program is developed using C^{++} language for calculating the value of permanent function.

The computer program developed for calculating the value of permanent function is capable of solving a matrix of 50 X 50. The program developed is given in appendix-III.

The value of permanent function is the value of performance index for CCPP. With the help of the methodology developed above, complete multinomial of VPF-s for the combined cycle power plant can be calculated. The above proposed methodology is extended in next section for the evaluation of real time reliability index and real time efficiency index for a CCPP reliability and efficiency analysis respectively.

3.1.2. RELIABILITY ANALYSIS OF CCPP

In general terms reliability is the ability of a system to perform the required function under given conditions for a given period of time. Combined cycle power plant is a very large and complex system comprised of air compressor, combustion chamber, gas turbine, HRSG, steam turbine and water system. Reliability of CCPP depends upon the reliability of these systems and their interconnections. The reliable availability of a power plant is strongly associated with reliability of systems and their components and requisite premeditated maintenance policy. Maintenance policy influences recurring failures, repair time, availability, reliability and degradation of the system (Smith and Hinchcliffe, 2004).

Recurring failures that lead to complete power plant outage need repair and proactive maintenance to invigorate power plant performance. Downtime losses and maintenance cost of a CCPP can be reduced by adopting a proper mix of maintenance and repair strategies based on attributes such as maintenance efforts, loss of production, safety/reliability and efficiency. In the worst situation, unavailability of an equipment or system affects all these attributes and has maximum criticality. The power plant will trip in this case. But in general, the failure of an equipment or system may not affect all the attributes and therefore its criticality will have some intermediate value. In that case reliability of system will come down and it may affect reliability of other systems also. The criticality level decides the importance of the equipment or system and choice of appropriate maintenance and repair strategy so that reliability may be maintained upto a mark. In this section, a systems approach of graph theory in conjunction with matrix method for assessing the reliability of CCPP is developed.

3.1.2.1. CCPP SYSTEM RELIABILITY DIGRAPH (SRD)

Graph theoretic models have adaptability to model any of the efficiency, cost, reliability, availability and maintenance characteristics by associating suitable attributes and interdependencies to the nodes and edges of the systems structural graph (SSG) (Gandhi et al. 1991). For example, if the node R_i represents the reliability of *i*th system and r_{ij} represents the reliability of the interconnection between *i*th and *j*th systems (nodes) of CCPP; then, Systems Reliability graph or Digraph (SRD) shown in Figure 3.5 can be obtained from the SSG of a CCPP (Figure 3.2 or 3.3).

The SRD provides the system structure reliability unequivocally. Reliability of the connection between two systems is considered if the systems are connected either by rigid or non-rigid links such as connection between turbine and generator rotors through a mechanical shaft or between combustion chamber system and water system

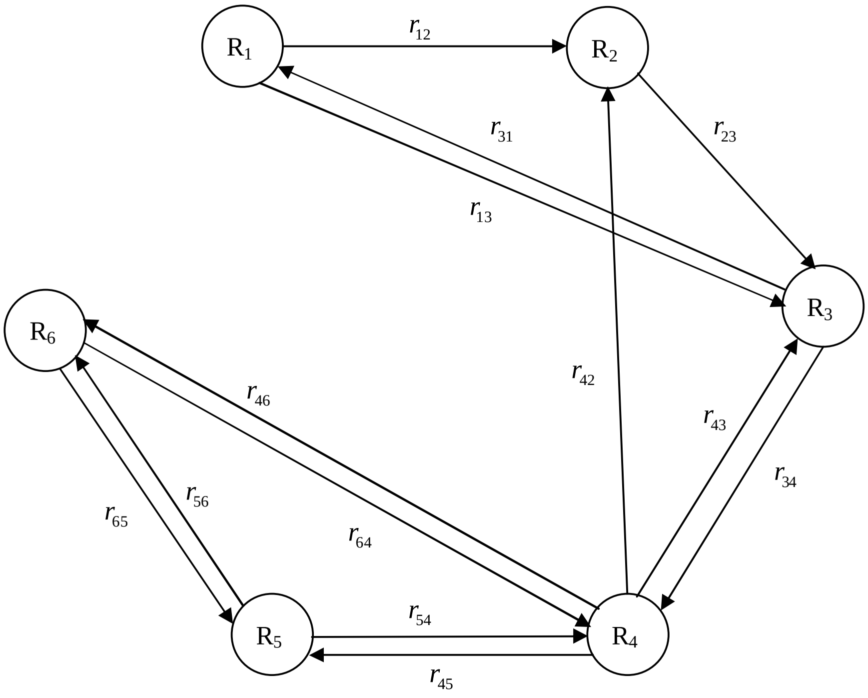


Figure 3.5 System reliability digraph for combined cycle power plant

of boiler, through flue gases. Once the SRD of the CCPP is obtained from SSG, reliability analysis is carried out using matrix representation and development of permanent function as outlined below.

3.1.2.2. VARIABLE PERMANENT SYSTEM RELIABILITY MATRIX (VPSRM)

A variable permanent system reliability matrix (VPSRM) Q_c abbreviated as VPM-r for the combined cycle power plant is written as:

$$Q_c = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\ \begin{bmatrix} R_1 & r_{12} & r_{13} & 0 & 0 & 0 \\ 0 & R_2 & r_{23} & 0 & 0 & 0 \\ r_{31} & 0 & R_3 & r_{34} & 0 & 0 \\ 0 & r_{42} & r_{43} & R_4 & r_{45} & r_{46} \\ 0 & 0 & 0 & r_{54} & R_5 & r_{56} \\ 0 & 0 & 0 & r_{64} & r_{65} & R_6 \end{bmatrix} \end{array} \begin{array}{c} Systems \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \qquad (3.9)$$

The method to develop the VPM-r is same as explained in section (3.1.1.2) of this chapter for the development of VPM-s for the performance evaluation of CCPP.

3.1.2.3. VARIABLE PERMANENT SYSTEM RELIABILITY FUNCTION

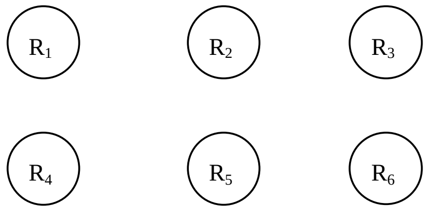
The permanent of VPSRM is called the variable permanent system reliability function and is abbreviated as VPF-r. VPF-r for expression (3.9) is as represented by the expression (3.10). This multinomial (equation 3.10) represents the reliability of CCPP system of Figure 3.2 and includes all the information regarding various constituents as systems and interactions amongst them. A physical meaning is associated with each term of permanent function (Prabhakaran et al. 2006). Permanent function for SRG in Figure 3.5 is written as equation (3.10) and graphical representation of different terms is shown in Figure 3.6. In the expression (3.10) all the terms are arranged in the decreasing number of system reliability attribute. As there are six systems, the number of groups is seven and second group is absent due to self looping.

$$
\begin{aligned}
Per\left[Q_c\right] = [&R_1R_2R_3R_4R_5R_6 + \left(r_{13}r_{31}\right)\left(R_2R_4R_5R_6\right) + \left(r_{34}r_{43}\right)\left(R_1R_2R_5R_6\right) \\
&+\left(r_{45}r_{54}\right)\left(R_1R_2R_3R_6\right) + \left(r_{46}r_{64}\right)\left(R_1R_2R_3R_5\right) + \left(r_{56}r_{65}\right)\left(R_1R_2R_3R_4\right) \\
&+R_1R_2R_3\left(r_{45}r_{56}r_{64}\right) + R_1R_2R_3\left(r_{46}r_{65}r_{54}\right) + R_1R_5R_6\left(r_{23}r_{34}r_{42}\right) \\
&+ R_4R_5R_6\left(r_{12}r_{23}r_{31}\right) + R_1R_2\left(r_{34}r_{43}\right)\left(r_{56}r_{65}\right) + R_2R_4\left(r_{13}r_{31}\right)\left(r_{56}r_{65}\right) \\
&+ R_2R_5\left(r_{13}r_{31}\right)\left(r_{46}r_{64}\right) + R_2R_6\left(r_{13}r_{31}\right)\left(r_{45}r_{54}\right) + R_1\left(r_{56}r_{65}\right)\left(r_{23}r_{34}r_{42}\right) \\
&+ R_2\left(r_{13}r_{31}\right)\left(r_{45}r_{56}r_{64}\right) + R_2\left(r_{13}r_{31}\right)\left(r_{46}r_{65}r_{54}\right) + R_4\left(r_{56}r_{65}\right)\left(r_{12}r_{23}r_{31}\right) \\
&+ R_5\left(r_{46}r_{64}\right)\left(r_{12}r_{23}r_{31}\right) + R_6\left(r_{45}r_{54}\right)\left(r_{12}r_{23}r_{31}\right) + \left(r_{12}r_{23}r_{31}\right)\left(r_{45}r_{56}r_{64}\right) \\
&+ \left(r_{12}r_{23}r_{31}\right)\left(r_{46}r_{65}r_{54}\right)]
\end{aligned}
$$

(3.10)

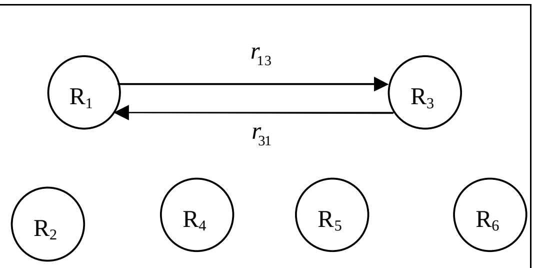
The first group in the permanent function (expression 3.10) is $R_1R_2R_3R_4R_5R_6$ and it signifies that for the reliable availability of CCPP all six systems must be present. It is required to consider the reliability of all the six systems.

First term of third group, $\left(r_{13}r_{31}\right)\left(R_2R_4R_5R_6\right)$, shows the interdependency of systems and signifies that reliable transfer of power from gas turbine to air compressor (r_{31}) and compressed air from air compressor to gas turbine (r_{13}) for



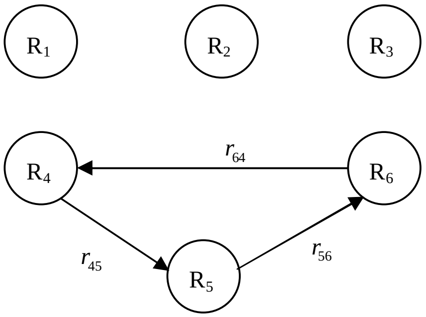
1 Term

(a) Group 1



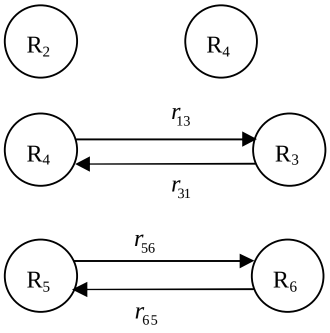
+4 Other Terms

(b) Group 3



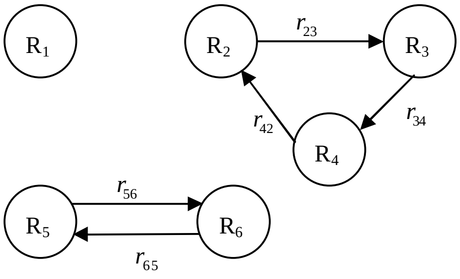
+3 Other Terms

(c) Group 4



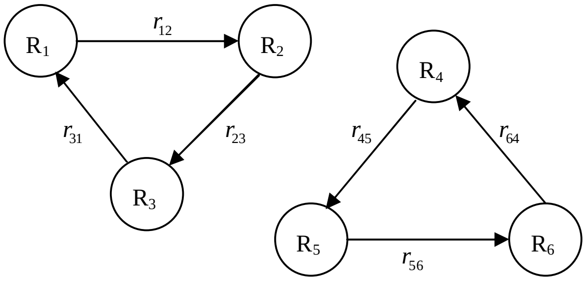
+3 Other Terms

(d) Group 5



+5 Other Terms

(e) Group 6



+1 Term

(f) Group 7

Figure 3.6 Graphical representation of permanent function (Equation 3.10) corresponds to digraph (Figure 3.5)

cooling the gas turbine blades will effect the reliable availability of combustion chamber system

(R_2), HRSG system(R_4), steam turbine system(R_5) and water system (R_6). Second term of third grouping, $(r_{34}r_{43})(R_1R_2R_5R_6)$, interprets that effect of air compressor and combustion chamber system reliability on steam turbine and water system reliability is affected by the loop $r_{34}r_{43}$. In the similar way gas turbine cycle reliability affects water system reliability if loop $r_{45}r_{54}$ is working reliably. It is represented by the term $(r_{45}r_{54})(R_1R_2R_3R_6)$. Fourth term of third group, $(r_{46}r_{64})(R_1R_2R_3R_5)$ interprets that reliability of gas turbine cycle, represented by $R_1R_2R_3$, will effect the reliability of loop $r_{46}r_{64}$ which is further connected to the steam turbine system (R_5). Therefore, steam turbine system is not affected by the gas turbine cycle directly and it will be affected by the reliable availability of HRSG and water system loop.

Fifth term in third group, $(r_{56}r_{65})(R_1R_2R_3R_4)$, represents that reliability of gas turbine cycle and HRSG system will affect the reliability of steam turbine and water system loop. HRSG system is the link between gas turbine cycle and steam turbine cycle due to which loop $r_{56}r_{65}$ is effected by gas turbine cycle. In the Figure 3.5 there are three two system reliability loops ($r_{13}r_{31}$, $r_{46}r_{64}$ and $r_{56}r_{65}$) and all these loops are covered by third grouping.

First and second terms of fourth group, $R_1R_2R_3(r_{45}r_{56}r_{64})$ and $R_1R_2R_3(r_{46}r_{65}r_{54})$, signifies the effect of gas turbine cycle on the loops $r_{45}r_{56}r_{64}$ and $r_{46}r_{65}r_{54}$. Flue gases coming out of the gas turbine cycle give thermal energy to the steam turbine cycle with the help of HRSG. Any effect on the reliable availability of flue gases will affect the reliability of steam cycle loops ($r_{45}r_{56}r_{64}$ and $r_{46}r_{65}r_{54}$). Third term of fourth group is $R_1R_5R_6(r_{23}r_{34}r_{42})$. Air compressor reliability will affect the loop $(r_{23}r_{34}r_{42})$. HRSG, present in the loop, is the system affecting the reliability of steam and water system. Fourth term of fourth group, $R_4R_5R_6(r_{12}r_{23}r_{31})$, signifies that performance of steam turbine cycle is affected by the loop ($r_{12}r_{23}r_{31}$) which is in the gas turbine cycle. The number of three system reliability loop in the Figure 3.5 is four, due to which there are four terms in fourth group.

Fifth group is having four terms $R_1R_2\left(r_{34}r_{43}\right)\left(r_{56}r_{65}\right)$, $R_2R_4\left(r_{13}r_{31}\right)\left(r_{56}r_{65}\right)$, $R_2R_5\left(r_{13}r_{31}\right)\left(r_{46}r_{64}\right)$ and $R_2R_6\left(r_{13}r_{31}\right)\left(r_{45}r_{54}\right)$. First term signifies that air compressor system affects combustion chamber system and reliability of flue gas coming out of combustion chamber affects the loop $\left(r_{34}r_{43}\right)$ and this loop further affects the loop $\left(r_{56}r_{65}\right)$. Reliability of steam turbine and water system is affected by the gas turbine and air compressor system because HRSG (R_4) is the link between them. The second term, $R_2R_4\left(r_{13}r_{31}\right)\left(r_{56}r_{65}\right)$, signifies affect of combustion chamber on air compressor and gas turbine and this effects two system reliability loop $\left(r_{56}r_{65}\right)$ due to the presence of HRSG system in between them. Third term signifies the effect of combustion chamber and steam turbine system on two system reliability loops $\left(r_{13}r_{31}\right)$ and $\left(r_{46}r_{64}\right)$ respectively. In the similar manner forth term represents that combustion chamber and water system affects the loops $\left(r_{13}r_{31}\right)$ and $\left(r_{45}r_{54}\right)$ respectively and these loops are linked due to HRSG.

Sixth group is having six terms. These terms are having one system, one loop of two systems reliability and one loop of three systems reliability. In sixth group also effect of each system is taken into consideration.

Seventh group is having two terms with two loops of three systems reliability.

Permanent function related with any digraph may be developed by visual inspection also. For this purpose all the loops have to be identified and a proper association with system has to be presented in such a way that characteristic of all systems is covered.

From the analysis it is also found that no such combination of loops and systems comes into permanent function which is not able to cover the effects of all systems. For example no group is having the terms like ($\left(r_{12}r_{23}r_{31}\right)$ $\left(r_{42}r_{23}r_{34}\right)$) or ($\left(r_{42}r_{23}r_{34}\right)$ $\left(r_{45}r_{56}r_{64}\right)$) because this combination is not covering the effect of all six systems.

The value of VPF-r gives reliability of the CCPP under the specified conditions. This reliability value can be compared with the reliability of the other similar power plant. In engineering analysis it is more suitable to represent the real time value of performance parameter in terms of percentage or dimensionless number. For this purpose the concept of Real Time Reliability Index (RTRI) is used for reliability analysis of CCPP.

3.1.2.4. CCPP REAL TIME RELIABILITY INDEX (RTRI$_{CCPP}$)

Concept of real-time reliability index (RTRI) was proposed first time for a steam power plant (SPP) by Mohan et al. (2008). It was defined as the ratio of its reliability under real-time conditions to the reliability under its designed conditions. The reliability of a CCPP decreases regularly with time due to various reasons such as non-availability of some of the systems, equipments or due to aging effect, etc. Performance of a combined cycle power plant in any case can not be higher than its designed value. Therefore, for all practical purposes, real-time performance of a CCPP is judged with respect to its designed performance. In view of this, the RTRI for combined cycle power plant is defined as the ratio of real time reliability, i.e. (Reliability)$_{RT}$ to the designed reliability that is (Reliability)$_D$. Mathematical expression is as following:

$$RTRI_{CCPP} = \frac{(\text{Reliability})_{RT}}{(\text{Reliability})_{D}} = \frac{(VPF-r)_{RT}}{(VPF-r)_{D}} \tag{3.11}$$

To calculate this index, the values of R$_i$ and r$_{ij}$ are required to be replaced in equation (3.11). Faisal et al. (2007a) explained that if data regarding the variables from some previous research or field study is available it can be used to determine the index. But in case no quantitative values are available and in order to avoid complexity at system or subsystem level, then values for inheritance and interrelation may be taken from Table 3.3 and 3.4 respectively. As mentioned earlier that one can choose any scale for R_i or r_{ij} (Faisal et al., 2007a; Wani and Gandhi, 1999). The user may select an appropriate scale, for example, 0–5, 0–10, 0–50 or 0–100 for R_i's and r_{ij}'s, but the final ranking will not be affected as these are relative values. However, lower scale value is desirable to obtain a manageable value of $RTRI_{CCPP}$ and also to reduce partisanship.

Index value may differ from plant to plant because every system and interdependency has different values. In this way, different power plants may be arranged in ascending or descending order, according to their reliability index value. The value of RTRI will indicate the probability of complete shut down or operation of the CCPP at partial load or due to degradation of systems or equipments.

Table 3.3 Quantification of factors affecting combined cycle power plant reliability

S. No.	Qualitative measure of parameters affecting combined cycle reliability	Assigned value of parameter (R_i)
1	One failure in every shift	1
2	One failure in one day	2
3	One failure in one week	3
4	One failure in one month	4
5	One failure in three months	5
6	One failure in six months	6
7	One failure in one year	7
8	One failure in two years	8
9	One failure in five years	9

Table 3.4 Quantification of interdependencies/ off diagonal elements

S. No.	Qualitative measure of interdependencies	Assigned value of r_{ij}
1	Very Strong	5
2	Strong	4
3	Medium	3
4	Weak	2
5	Very weak	1

3.1.2.5. STEP-BY-STEP PROCEDURE FOR DETERMINING $RTRI_{CCPP}$

A methodology is the key for the evaluation of $RTRI_{CCPP}$ for different combined cycle power plants. Step by step methodology based on graph theory and matrix method developed in forgoing section is epitomized as following:

Step 1: Consider a combined cycle power plant. If it seems to be very large system then divide it into smaller subsystems (e.g. air compressor system, combustion chamber system, gas turbine system, HRSG system, steam turbine system, and water system). Identify the various system categories affecting the CCPP reliability.

Step 2: Develop system structure graph for the reliability of CCPP system based upon the interaction among different subsystems.

Step 3: Convert the system structure graph of CCPP into corresponding system reliability digraph (SRD) with systems reliability as nodes and edges for the reliability of interconnections.

Step 4: Develop the CCPP system reliability matrix corresponding to the CCPP system reliability digraph. This will be N x N matrix with diagonal elements of R_i and off-diagonal elements of r_{ij}. The value of inheritance R_i (diagonal elements) and reliability of interactions r_{ij} (off-diagonal elements) for each sub-system is decided by data available in literature or from industry.

Step 5: Calculate the permanent function of CCPP system reliability matrix for values of real time reliability $(\text{Reliability})_{RT}$ and designed reliability $(\text{Reliability})_{D}$.

Step 6: Calculate the ratio of real time reliability and designed reliability as in equation (3.11). This is the value of $RTRI_{CCPP}$ which mathematically characterizes the reliability of combined cycle power plant based on the different systems and their interdependencies.

3.1.3. EFFICIENCY ANALYSIS OF CCPP

Due to the inexorable rise of electricity demand, researchers in the power plant area are hankering for best utilization of energy resources. A power plant is considered inefficient if the plant's existing resources or inputs are utilized sub-optimally, as a consequence of which the plant's power generation is less than its potential or maximum possible generation. Efficiency, to effectively utilize the energy supplied, is influenced by the design, manufacturing, construction, operation, and maintenance. Capability and efficiency reflect how well the power plant is designed and constructed (De Souza, 2012). It is the nature of power plants that they do not work at all times at their design point conditions (Zwebek and Pilidis, 2003). Off-design due to normal conditions (change of ambient conditions and part load) and abnormal conditions (change in fluid path component configuration due to degradation) are two main sources which offset the plant from its design point conditions.

This section presents a mathematical model using graph theoretic systems approach that enables the prediction of the efficiency of a CCPP in terms of an index by taking into account various design parameters and interactions between them. The first step for GTA is to develop system attribute digraph for efficiency analysis. It is developed in the next section.

3.1.3.1. SYSTEM EFFICIENCY DIGRAPH (SED)

For the efficiency analysis also CCPP is divided into six systems as explained in section (3.1.1.1) of this chapter. Let efficiency of the six systems of plant be represented by vertices D_i's (i=1,2,3,4,5,6) and interconnection between two systems (D_i, D_j) is represented by edges d_{ij} (i, j =1,2,3,4,5,6 and i≠j) connecting the two vertices D_i and D_j.

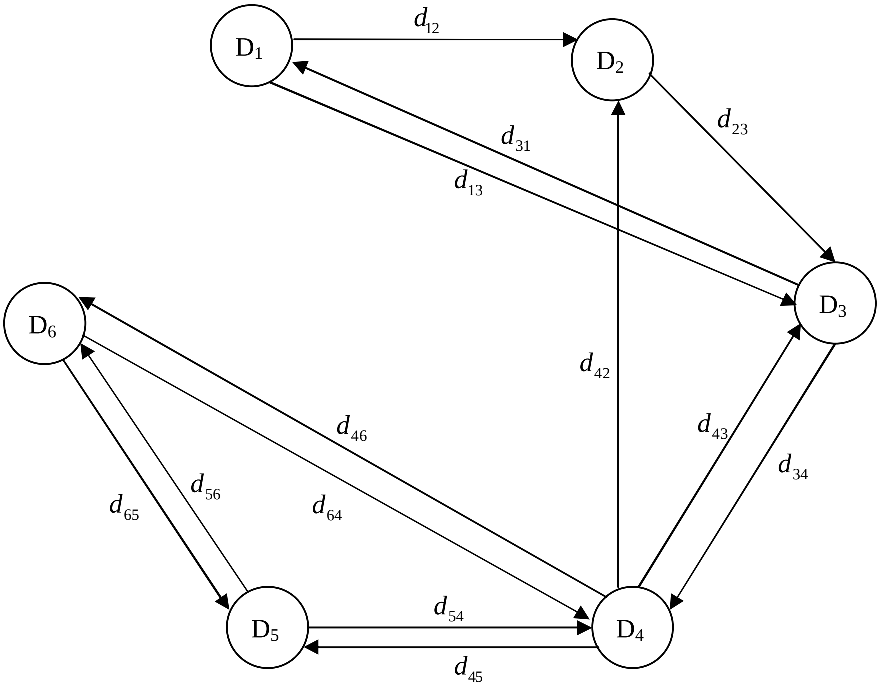


Figure 3.7 Digraph showing six attributes of CCPP and their interdependencies

In actual system all six system doesn't affect each other. The digraph consists of a set of nodes D = {D_i} with i=1, 2, 3, 4, 5, 6 and a set of directed edges d = {d_{ij}} called as System Efficiency Digraph (SED) is shown in Figure 3.7 and is corresponding to the SSG shown in Figure 3.3. SED shows effect of one system efficiency on the other systems without taking interacting media into consideration.

3.1.3.2. VARIABLE PERMANENT SYSTEM EFFICIENCY MATRIX (VPSEM)

The procedure for converting a SED into matrix form is as explained in section 3.1.1.2. The matrix corresponding to the SED of Figure 3.7 is called as Variable Permanent System Efficiency Matrix (VPSEM) Z_c and is written as in expression (3.12). The matrix representation gives an overview of the systems and interdependencies of the systems. The value of the VPSEM can be analyzed using variable permanent system efficiency function as explained in next section.

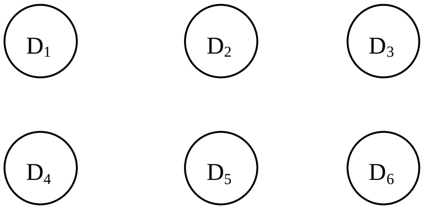
$$Z_c = \begin{bmatrix} D_1 & d_{12} & d_{13} & 0 & 0 & 0 \\ 0 & D_2 & d_{23} & 0 & 0 & 0 \\ d_{31} & 0 & D_3 & d_{34} & 0 & 0 \\ 0 & d_{42} & d_{43} & D_4 & d_{45} & d_{46} \\ 0 & 0 & 0 & d_{54} & D_5 & d_{56} \\ 0 & 0 & 0 & d_{64} & d_{65} & D_6 \end{bmatrix} \tag{3.12}$$

3.1.3.3. VARIABLE PERMANENT SYSTEM EFFICIENCY FUNCTION

The permanent function of VPSEM is called the variable permanent system efficiency function and is abbreviated as VPF-e. VPF-e for matrix (3.12) is written as:

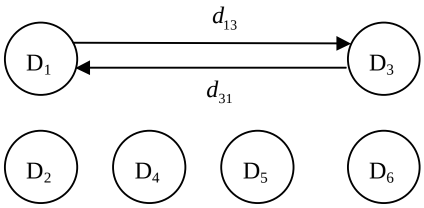
$$\begin{aligned} Det\left[Z_c\right] = [& \left(D_1D_2D_3D_4D_5D_6\right)+(d_{13}d_{31})(D_2D_4D_5D_6)+(d_{34}d_{43})(D_1D_2D_5D_6) \\ & +(d_{45}d_{54})(D_1D_2D_3D_6)+(d_{46}d_{64})(D_1D_2D_3D_5)+(d_{56}d_{65})(D_1D_2D_3D_4) \\ & +(d_{45}d_{56}d_{64})(D_1D_2D_3)+(d_{46}d_{65}d_{54})(D_1D_2D_3)+(d_{23}d_{34}d_{42})(D_1D_5D_6) \\ & +(d_{12}d_{23}d_{31})(D_4D_5D_6)+(d_{34}d_{43})(d_{56}d_{65})(D_1D_2)+(d_{13}d_{31})(d_{56}d_{65})(D_2D_4) \\ & +(d_{13}d_{31})(d_{46}d_{64})(D_2D_5)+(d_{13}d_{31})(d_{45}d_{54})(D_2D_6)+(d_{23}d_{34}d_{42})(d_{56}d_{65})D_1 \\ & +(d_{45}d_{56}d_{64})(d_{13}d_{31})D_2+(d_{46}d_{65}d_{54})(d_{13}d_{31})D_2+(d_{12}d_{23}d_{31})(d_{56}d_{65})D_4 \\ & +(d_{12}d_{23}d_{31})(d_{46}d_{64})D_5+(d_{12}d_{23}d_{31})(d_{45}d_{54})D_6+(d_{12}d_{23}d_{31})(d_{45}d_{56}d_{64}) \\ & +(d_{12}d_{23}d_{31})(d_{46}d_{65}d_{54}) \end{aligned}$$

(3.13)



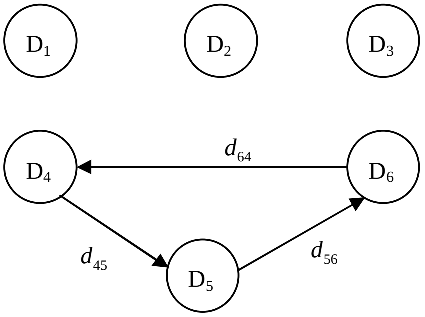
1 Term

(a) Group 1



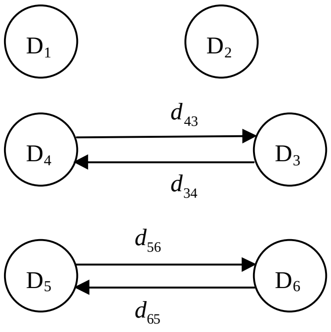
+4 Other Terms

(b) Group 3



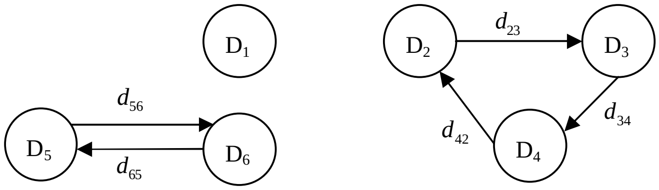
+3 Other Terms

(c) Group 4



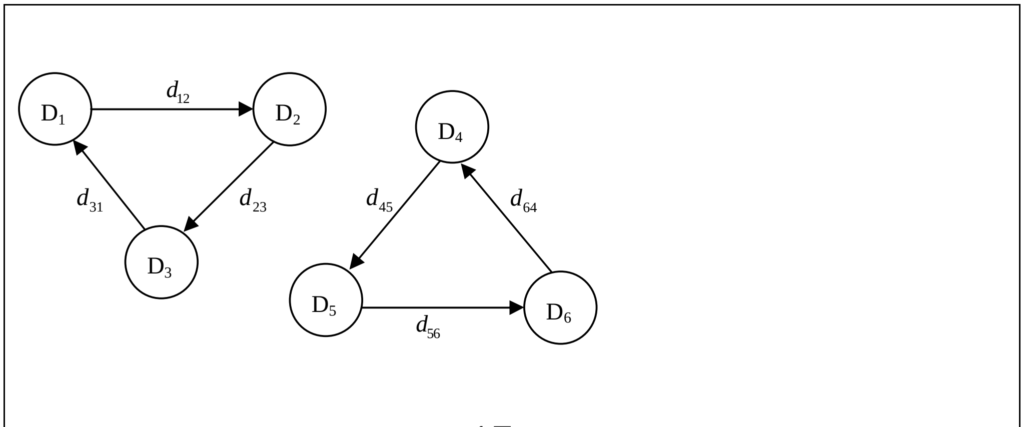
+3 Other Terms

(d) Group 5



+5 Other Terms

(e) Group 6



+1 Terms

(f) Group 7

Figure 3.8 Graphical representation of permanent function (equation 3.13) corresponds to digraph in Figure 3.7

Every term in the permanent function carries information about the physical system of combined cycle power plant. Permanent function developed above for the efficiency index may also be written by visual inspection of SED in Figure 3.7. In SED there are five two system efficiency loops { $(d_{13}d_{31})$, $(d_{34}d_{43})$, $(d_{45}d_{54})$, $(d_{46}d_{64})$ and $(d_{56}d_{65})$ }, four three system efficiency loops { $(d_{12}d_{23}d_{31})$, $(d_{23}d_{34}d_{42})$, $(d_{45}d_{56}d_{64})$ and $(d_{46}d_{65}d_{54})$ }. There is no loop with four, five or six system efficiency. All the possible combinations with these loops covering all the systems are shown in expression (3.13).

The value of the permanent function can be calculated with the help of computer programming tool. For calculation of permanent function, values of the interdependencies (d_{ij}) and inheritance (D_i) have to be quantified in the expression (3.13) and graphical representation is shown in Figure 3.8.

In real life situation inheritance of the systems is further dependent on the design parameters. Design parameters not only affect the efficiency of systems but each other also. This makes the efficiency analysis highly complex. Effect of design parameters on systems efficiency are studied using digraph and matrix method at system level. Performance Parameter Digraph (PPD) is developed at system level which takes care of inheritance and interdependency of design parameters affecting the efficiency of that system. For the simplification of analysis and to obtain the manageable value of efficiency index the concept of Real Time Efficiency Index (RTEI) developed by Mohan et al. (2006) is used. The first step for the efficiency analysis at system level is to identify the design parameters, corresponding to each system, affecting its efficiency.

3.1.3.4. IDENTIFICATION OF DESIGN PARAMETERS FOR CCPP SYSTEMS

The design parameters affecting CCPP performance are very large in number. It is difficult to establish relationship amongst these design parameters without categorizing them in relation to six systems. The design parameters affecting the CCPP efficiency have been identified on the basis of literature survey and industrial data. The digraph at system level, for each system, are developed to

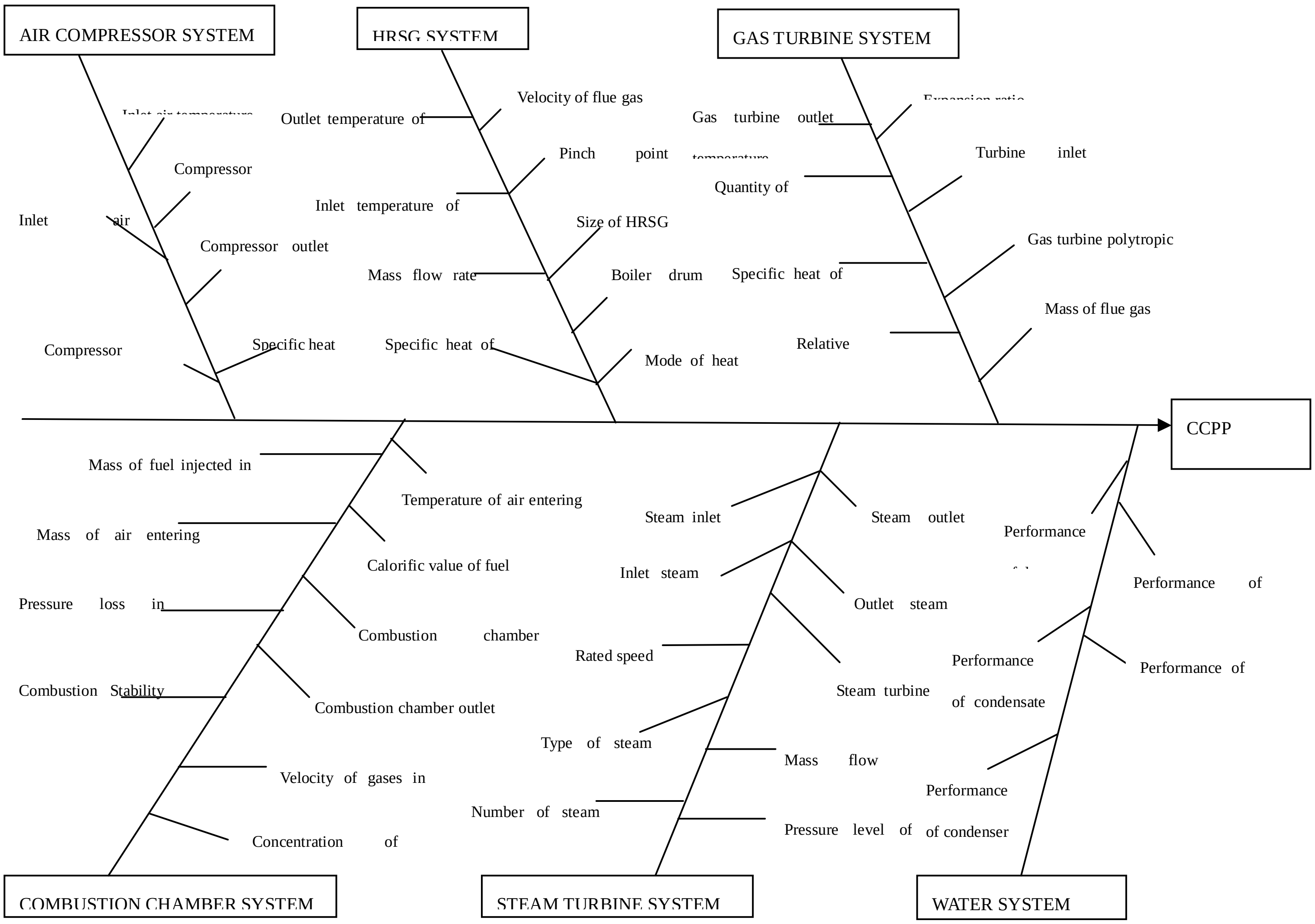

AIR COMPRESSOR SYSTEM
Inlet air temperature
Compressor
Inlet air
Compressor outlet
Compressor
Specific heat
HRSG SYSTEM
Outlet temperature of
Velocity of flue gas
Pinch point
Inlet temperature of
Size of HRSG
Mass flow rate
Boiler drum
Specific heat of
Mode of heat
GAS TURBINE SYSTEM
Gas turbine outlet
temperature
Expansion ratio
Quantity of
Turbine inlet
Gas turbine polytropic
Specific heat of
Mass of flue gas
Relative
CCPP
Mass of fuel injected in
Temperature of air entering
Mass of air entering
Calorific value of fuel
Pressure loss in
Combustion chamber
Combustion Stability
Combustion chamber outlet
Velocity of gases in
Concentration of
COMBUSTION CHAMBER SYSTEM
Steam inlet
Steam outlet
Inlet steam
Outlet steam
Rated speed
Steam turbine
Type of steam
Mass flow
Number of steam
Pressure level of
STEAM TURBINE SYSTEM
Performance
Performance of
Performance
of condensate
Performance of
Performance
of condenser
WATER SYSTEM

Figure 3.9 Diagram showing systems of CCPP and design parameters represent the inheritance and interdependencies of design parameters. The parameters identified are epitomized in Figure 3.9 corresponding to each system. Rationales for selecting the design parameters for air compressor, combustion chamber, gas turbine, HRSG, steam turbine and water system are discussed below.

(i) Compressor System

Axial flow compressor is used to compress filtered air before entering combustion chamber. The thermodynamic losses in compressor are incorporated in the model by considering polytropic efficiency in place of isentropic efficiency. The main gas path components of the gas turbine cycle, namely compressor and turbine, will degrade with engine use, (Diakunchak, 1992; Lakshminarasimha et al., 1994; Tabakoff, 1986; Tabakoff et al., 1990) which then results into engine performance deterioration. Design parameters affecting air compressor system efficiency are as explained below:

1. For compressing the air at a higher temperature; the compressor needs a more significant work. With the increase of the ambient temperature, the compressor work is increased and the net power output is decreased, which affect in decreasing the thermal efficiency (Ashley and Zubaidy, 2011; Yokoyama and Ito, 2006). Output of CCPP is a strong function of the inlet air temperature. When the inlet air temperature drops, cycle power output increases considerably and heat rate varies slightly (Wen and Narula, 2000). Where heat rate is heat input required to produce a unit quantity of power.
2. Enthalpy and specific heats (both at constant pressure and constant volume) for a gas at particular temperature and pressure have different values for humidified air and non-humidified air. This difference depends upon the relative humidity.
3. Compressor efficiency is a function of manufacturing quality. Different gas turbine has different

efficiencies (Bhargava et al., 2004; Bianchi et al., 2005). Compressor erosion is represented by a lower inlet mass flow capacity and a reduction in compressor isentropic efficiency (Lakshminarasimha et al., 1994).

4. Due to fluid friction, pressure ratio across the compressor would be greater than the pressure ratio across the turbine. The thermal efficiency of ideal Brayton Cycle is being given by the following relationship

$$\eta_{TH} = 1 - \frac{1}{r_p^{\frac{(\gamma-1)}{\gamma}}} \tag{3.14}$$

   r_p= compressor pressure ratio

   γ = ratio of specific heats

5. Compressor outlet temperature is the temperature at which compressed air will be entering the combustor. It is affected by the pressure ratio and polytropic efficiency of compressor.

(ii) Combustion Chamber System

Combustion chamber system includes the consideration of losses due to incomplete combustion and pressure loss due to friction. Loss due to incomplete combustion is taken care by the use of the concept of combustion efficiency, while pressure loss is accounted by taking percentage pressure drop of the combustor inlet pressure. Rationales for selecting the combustion chamber design parameters are as given below:

1. If the inlet temperature of air to combustion chamber is higher then lower amount of fuel is required to attain the combustion outlet temperature or Turbine Inlet Temperature (TIT).
2. Type of fuel used in combustion chamber is one of the deciding factors that how much heat is released by burning unit amount of fuel. Ratio of Carbon to Hydrogen (C/H) decides the calorific value of fuel. With the increase in fuel-calorific value the burning velocity increases which

decline the NOx conversion rate slightly (Poullikkas, 2005).

3. Combustion chamber loses energy due to heat transfer, noise and vibration. Fuel utilization efficiency depends upon the design of combustion chamber. Fuel utilization efficiency (FUE) of a plant is the ratio of all useful energy (power and process heat) extracted from the system to the input fuel energy (Sanjay et al., 2008).
4. Overall efficiency of cycle depends upon the amount of fuel injected in combustion chamber being other factors same. There is no other supply of energy to the cycle for a fixed net output power, so mass of fuel injected will be deciding factor for cycle efficiency.
5. If the mass of air entering the combustion chamber gets changed and amount of fuel is unchanged then combustion chamber outlet temperature will depend upon the mass of air. For a lean fuel-air mixture, if amount of fuel remains same and mass of air decreases then temperature of flue gas is increased.
6. Combustion chamber outlet temperature is fixed by thermal stress limit of turbine blade material. As the TIT changes the cycle efficiency also changes.
7. Under high pressure conditions, combustion efficiency improves with increase in pressure in combustion chamber (Saravanamuttoo et al., 2003).

(iii) Gas Turbine System

Each row of the turbine is treated as an expander whose walls continuously extract work. Expansion process in turbine is polytropic and the polytropic efficiency takes care of losses in the expansion process. Performance deterioration in gas turbines is due to fouling, increase in tip clearance, water ingestion and Foreign Object Damage (FOD) (Lakshminarasimha et al., 1994). Design parameters affecting gas turbine system efficiency are based upon the following reasoning:

1. Expansion ratio of gas turbine and compression ratio of compressor are mutually dependent.

Increase in expansion ratio along with turbine inlet temperature decreases specific fuel consumption and in return efficiency is increased (Vogt, 1992; Najjar and Akyurt, 1994; Chiesa et al., 1993).

2. In principle, raising the turbine inlet temperature increases the efficiency and the specific work output of gas turbine cycles (Bolland and Stadaas, 1995).
3. If the efficiency of gas turbine is higher then the utilization of energy in gas turbine is higher. Turbine erosion is represented by an increased flow capacity plus a reduction in the turbine isentropic efficiency (Lakshminarasimha et al., 1994).
4. Flue gases coming out of gas turbine at lower pressure and high temperature are passed through HRSG for waste heat recovery.
5. Cooling air is passed through the blades for cooling (Torbidoni and Horlock, 2006). This air quantity is fixed by air-by-pass ratio.

(iv) Heat Recovery Steam Generator (HRSG) System

In the case of the HRSG and the condenser (heat exchangers), two types of degradation are available, one is the outer tubes surface fouling and corrosion due to flue gas, and another is the inner tubes surface scaling or erosion due to impurities dissolved in water. Even with the latest fuel treatment techniques, the exhaust gases from the gas turbine contain some chemicals in the form of soot which deposits on the outer heat transfer surfaces of the HRSG. The impurities present in circulating water deposit on the inner walls of the heat exchanger pipes and lead to reduction in the heat exchanger performance (effectiveness). Nine design parameters are identified affecting HRSG efficiency based upon the following explanations:

1. It is being found that introducing multipressure steam generation in the HRSG in place of single pressure improves the performance of CCPP. HRSGs are classified into single, dual, and triple pressure types depending on the number of drums in the boiler (Shin et al., 2003).

2. Due to increased velocity of flue gas, convective heat transfer coefficient of flue gas is increased. If the velocity of flue gases coming of gas turbine is high then more heat is transferred to HRSG tubes and steam is produced at high temperature and pressure (Carapellucci and Milazzo, 2007).
3. Heat transfer by conduction mode is more than convection mode for the same temperature difference. Heat transfer by radiation is very less in case of flue gas.
4. If the flue gas is having high specific heat then there will be very less drop in temperature of flue gases while passing through HRSG for a specific amount of heat transfer (Beans, 1990).
5. A large size of HRSG will minimize the heat loss but this will increase the cost of construction (Shin et al., 2003).
6. Temperature of gases coming out from HRSG is being limited by the dew point temperature of flue gases (Nguyen and Otter, 1994; Dechamps, 1998). At lower temperature, water present in flue gas is condensed and leads to the corrosion of stack walls due to reaction in between water and SO_2 present in flue gas. Higher flue gas temperature leads to increased energy lost to the environment and drop in efficiency.
7. The HRSG steam production for a given gas turbine goes down as the steam pressure and temperature goes up (Pasha and Jolly, 1995; Huang, 1990).
8. The amount of steam generated in the HRSG depends on the pinch point of the boiler. (Bouam et al., 2008; Chmielniak and Kosman, 2004; Huang, 1990). Where pinch point is the difference between gas temperature leaving an evaporating section and the temperature at which boiling occurs.

(v) Steam Turbine System

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam and converts it into a useful mechanical work. Steam turbine is attached with the Turbo-Generator (TG) and mechanical energy obtained from steam turbine is used for electricity generation. The high pressure section of a steam turbine is a single stage flow turbine and low pressure section is double flow type. As with the case of gas turbine gas path components, (Zwebek and Pilidis, 2001), the steam turbine cycle steam path components are also subjected to degradation due to fouling, erosion and corrosion. Design parameters selected for steam turbine are due to following reasons:

1. Pressure ratio across steam turbine depends upon water pressure in HRSG. Higher pressure ratio leads to higher efficiency.
2. Steam turbine has some internal losses due to which efficiency of cycle decreases. Higher steam turbine efficiency means higher CCPP efficiency.
3. Turbine work per unit pressure drop is much greater at the low pressure end than at high pressure end of a turbine (Boyce, 2002). In a condenser by lowering the back pressure, steam flow for a given output reduces and thus the plant efficiency increases.
4. Inlet temperature of steam in steam turbine is fixed by thermal stress limit of blade material. Lowering the temperature leads to lower efficiency.
5. Steam turbine exhaust pressure is equal to the saturation pressure corresponding to the condensing steam temperature, which in turn, is a function of cooling water temperature (Nag, 2010).

(vi) Water System

Demineralised water is required for cooling the equipments. A plate heat exchanger is installed between equipment cooling water system and auxiliary cooling water system to exchange heat between demineralised water and auxiliary cooling water. Equipment Cooling Water (ECW) system supplies demineralised cooling water to air compressor cooler, high pressure feed pump cooler, steam turbine lubricating oil cooler, steam turbine generator cooler and condensate extraction pump thrust bearing cooling system. The inefficiency of condenser is due to pressure and heat losses and causes undercooling of the condensate. Inefficiency of water system is associated with its equipment’s inefficiency which is due to the reasons as explained below:

1. Clarification of raw water and preparation of deminiralized (DM) water is accomplished in the DM plant and supplied to the deaerator (Tuzson, 1992).
2. In the CCPP cooling water is utilized to condense the steam discharged from the steam turbine (Bianchi et al., 2005). Steam condensate and DM make-up water passes to the deaerator through low-pressure heaters (LPHs) with the help of Condensate Pumps (CP). Large size of condenser gives better effectiveness but cost of the system increases.
3. Condensed water from the condenser, with the help of the boiler feed pump (BFP), passes through High Pressure Heaters (HPH) and the economizer to boiler drum. Some part of energy is lost in the pumps.
4. Some part of energy is lost in boiler makeup water system.
5. From the cooling towers some part of energy is lost to the environment and this depends upon the back pressure of steam at steam turbine outlet.

For CCPP efficiency analysis at system level, three steps of GTA (digraph representation, matrix representation and permanent representation) developed in section (3.1.1) are explained in the following section in sequence.

3.1.3.5. PERFORMANCE PARAMETER DIGRAPH (PPD) AT SYSTEM LEVEL

Digraphs for each system category are developed considering inheritance and interdependencies of design parameters. Nodes in the digraph represent the design parameters and their mutual interactions are depicted by different edges. PPD for each system category are developed and represented as below.

(a) PPD for Air Compressor System

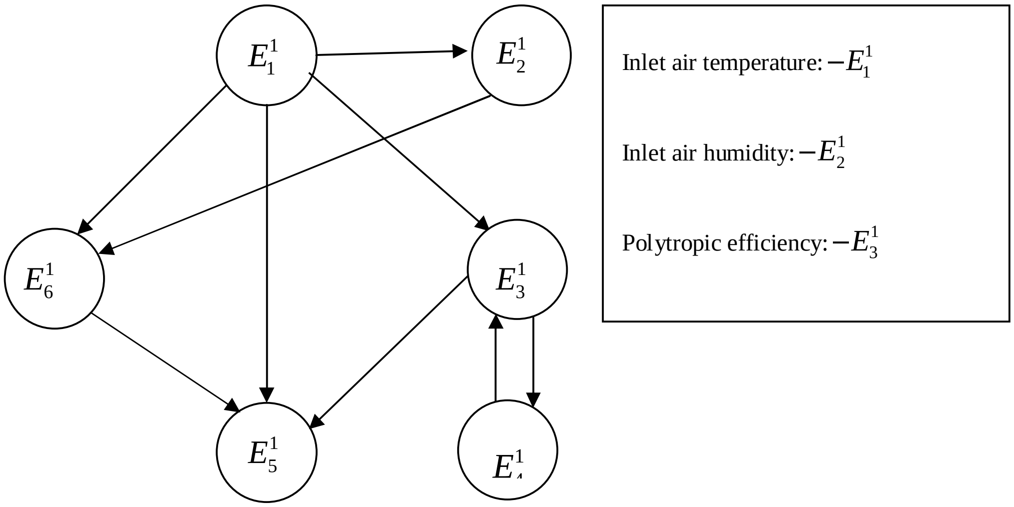


Figure 3.10 Digraph for air compressor system design parameters

(b) PPD for Combustion Chamber System

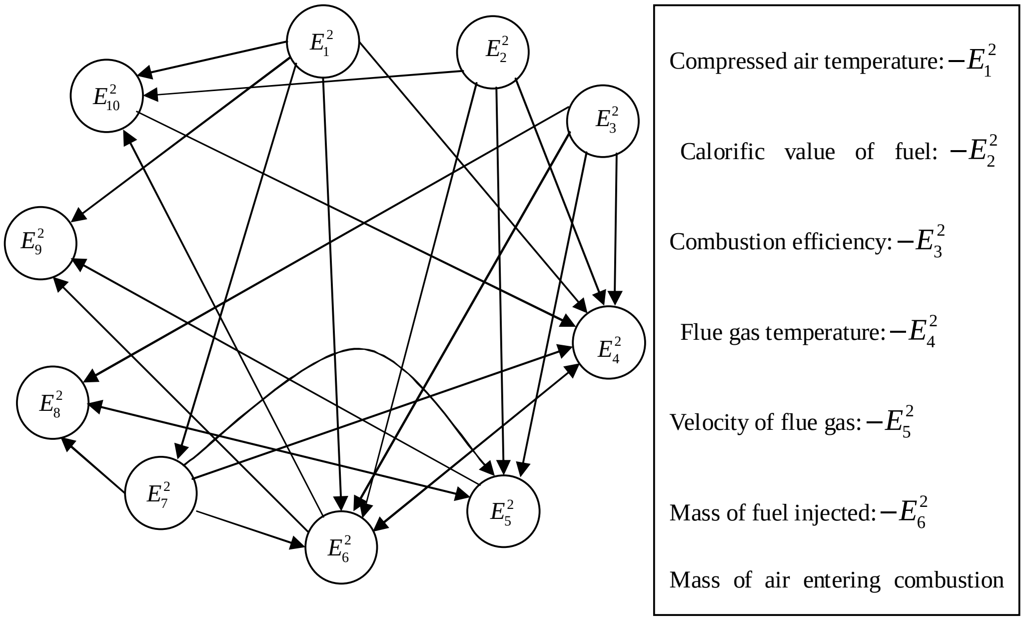
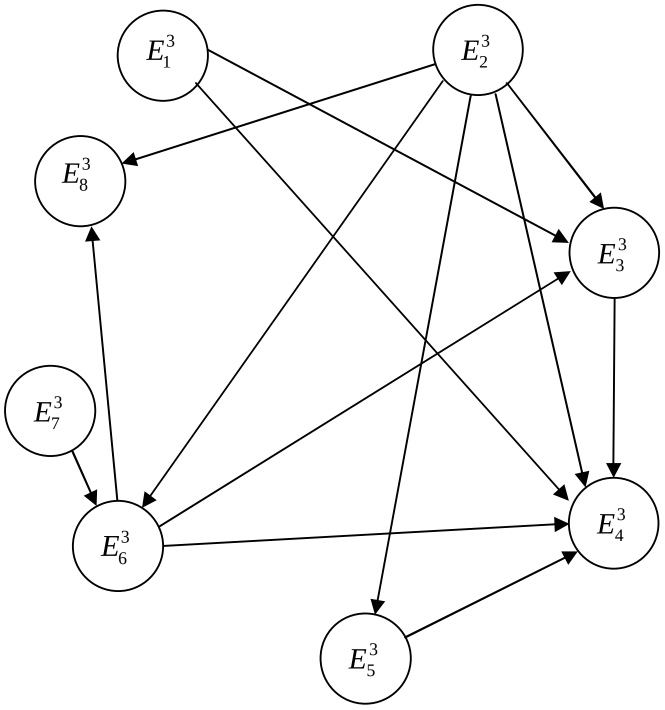


Figure 3.11 Digraph for combustion chamber system design parameters

(c) PPD for Gas Turbine System



Expansion ratio: $-E_1^3$

Turbine inlet temperature: $-E_2^3$

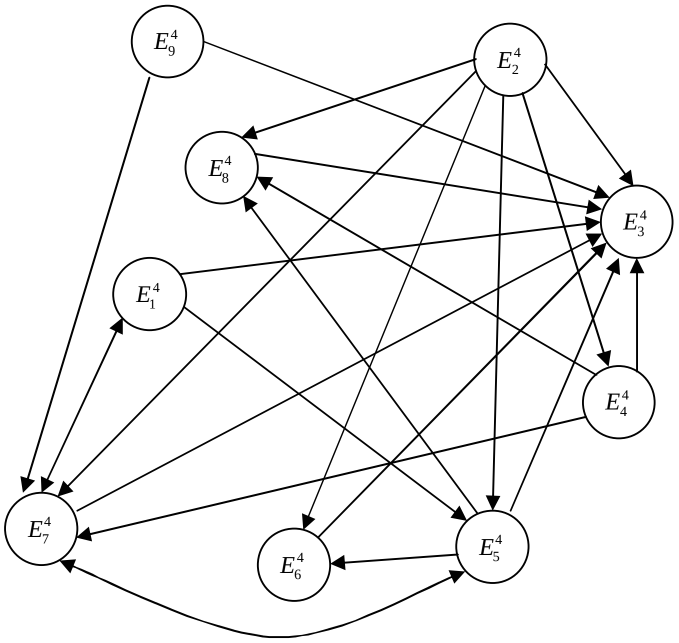
GT polytropic efficiency: $-E_3^3$

GT outlet temperature: $-E_4^3$

Quantity of cooling air: $-E_5^3$

Figure 3.12 Digraph for gas turbine system design parameters

(d) PPD for HRSG System



Mass flow rate of flue gas: $-E_1^4$

Inlet temperature of flue gas: $-E_2^4$

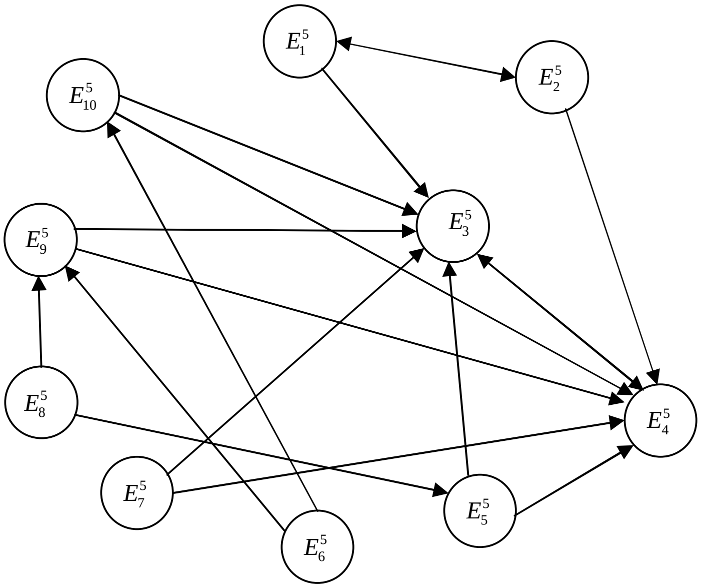
Outlet temperature of flue gas: $-E_3^4$

Specific heat of flue gas: $-E_4^4$

Velocity of flue gas: $-E_5^4$

Figure 3.13 Digraph for HRSG system design parameters

(e) PPD for Steam Turbine System



Steam temperature at ST inlet:- E_1^5

Steam pressure at ST inlet:- E_2^5

Steam temperature at ST outlet:- E_3^5

Steam pressure at ST outlet:- E_4^5

Efficiency of ST:- E_5^5

Figure 3.14 Digraph for steam turbine system design parameters

(f) PPD for Water System

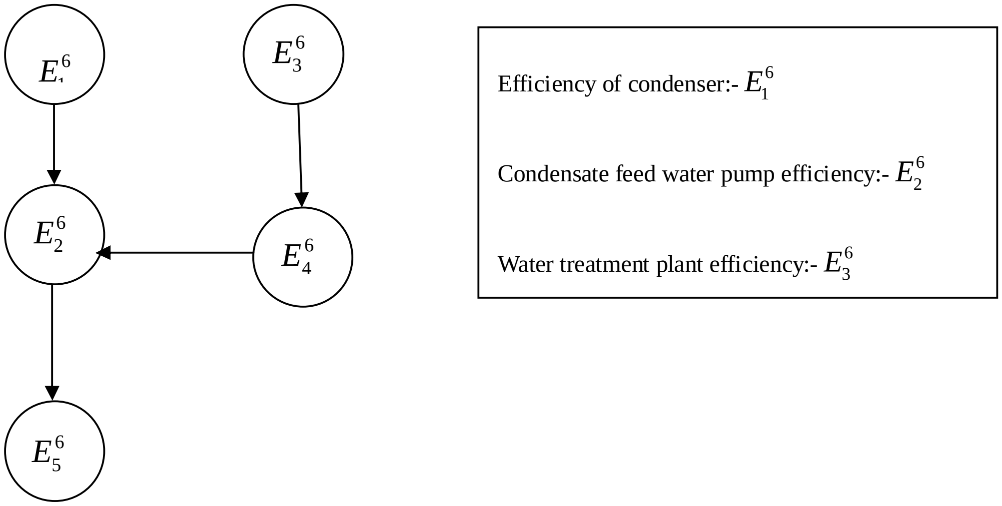


Figure 3.15 Digraph for water system design parameters

3.1.3.6. MATRIX REPRESENTATION OF PPD AT SYSTEM LEVEL

The Variable Permanent System Efficiency Parameter Matrix (VPSEPM) for six systems, for a general case with N design parameters, is represented as:

$$B = \begin{array}{cccccc|c} B_1 & B_2 & B_3 & .... & .... & B_N & Parameters\left(B_i\right) \\ \hline B_1 & b_{12} & b_{13} & .... & .... & b_{1N} & B_1 \\ b_{21} & B_2 & b_{23} & .... & .... & b_{2N} & B_2 \\ b_{31} & b_{32} & B_3 & .... & .... & b_{3N} & B_3 \\ .... & .... & .... & .... & .... & .... & .... \\ .... & .... & .... & .... & .... & .... & .... \\ b_{N1} & b_{N2} & b_{N3} & .... & .... & B_N & B_N \end{array} \tag{3.15}$$

It may be noted that above matrix represents inherent values of the design parameters that is B_i's (i = 1, 2 …, N) and the interaction amongst design parameters is b_{ij}'s (i, j = 1, 2 …, N and i ≠ j). VPSEPM (abbreviated as VPM_{System}) for each system PPD is developed corresponding to the steps explained in section (3.1.1.2). At the system level, corresponding to the digraph for air compressor system (Figure 3.10) in general form is given by:

$$VPM_{AirCompressor} = \begin{array}{cc} \begin{matrix} E_1^1 & E_2^1 & E_3^1 & E_4^1 & E_5^1 & E_6^1 \end{matrix} & Parameter \\ \begin{bmatrix} E_1^1 & E_{12}^1 & E_{13}^1 & 0 & E_{15}^1 & E_{16}^1 \\ 0 & E_2^1 & 0 & 0 & 0 & E_{26}^1 \\ 0 & 0 & E_3^1 & E_{34}^1 & E_{35}^1 & 0 \\ 0 & 0 & E_{43}^1 & E_4^1 & 0 & 0 \\ 0 & 0 & 0 & 0 & E_5^1 & 0 \\ 0 & 0 & 0 & 0 & E_{65}^1 & E_6^1 \end{bmatrix} & \begin{matrix} E_1^1 \\ E_2^1 \\ E_3^1 \\ E_4^1 \\ E_5^1 \\ E_6^1 \end{matrix} \end{array} \tag{3.16}$$

In the similar way, VPSEPM for other systems are written as:

$$VPM_{CombustionChamber} = \begin{array}{cc} \begin{matrix} E_1^2 & E_2^2 & E_3^2 & E_4^2 & E_5^2 & E_6^2 & E_7^2 & E_8^2 & E_9^2 & E_{10}^2 \end{matrix} & Parameter \\ \begin{bmatrix} E_1^2 & 0 & 0 & E_{14}^2 & 0 & E_{16}^2 & E_{17}^2 & 0 & E_{19}^2 & E_{110}^2 \\ 0 & E_2^2 & 0 & E_{24}^2 & E_{25}^2 & E_{26}^2 & 0 & 0 & 0 & E_{210}^2 \\ 0 & 0 & E_3^2 & E_{34}^2 & E_{35}^2 & E_{36}^2 & 0 & E_{38}^2 & 0 & 0 \\ 0 & 0 & 0 & E_4^2 & 0 & E_{46}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & E_5^2 & 0 & 0 & E_{58}^2 & E_{59}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & E_6^2 & 0 & 0 & E_{69}^2 & E_{610}^2 \\ 0 & 0 & 0 & E_{74}^2 & 0 & E_{76}^2 & E_7^2 & E_{78}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & E_{85}^2 & 0 & 0 & E_8^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_9^2 & 0 \\ 0 & 0 & 0 & E_{104}^2 & 0 & 0 & 0 & 0 & 0 & E_{10}^2 \end{bmatrix} & \begin{matrix} E_1^2 \\ E_2^2 \\ E_3^2 \\ E_4^2 \\ E_5^2 \\ E_6^2 \\ E_7^2 \\ E_8^2 \\ E_9^2 \\ E_{10}^2 \end{matrix} \end{array} \tag{3.17}$$

$$
VPM_{GasTurbine} = \begin{array}{cc}
\begin{array}{cccccccc} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 \end{array} & Parameter \\
\begin{bmatrix}
E_1^3 & 0 & E_{13}^3 & E_{14}^3 & 0 & 0 & 0 & 0 \\
0 & E_2^3 & E_{23}^3 & 0 & E_{25}^3 & E_{26}^3 & 0 & E_{28}^3 \\
0 & 0 & E_3^3 & E_{34}^3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & E_4^3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & E_{54}^3 & E_5^3 & 0 & 0 & 0 \\
0 & 0 & E_{63}^3 & 0 & 0 & E_6^3 & 0 & E_{68}^3 \\
0 & 0 & 0 & 0 & 0 & E_{76}^3 & E_7^3 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & E_8^3
\end{bmatrix} &
\begin{array}{c} E_1^3 \\ E_2^3 \\ E_3^3 \\ E_4^3 \\ E_5^3 \\ E_6^3 \\ E_7^3 \\ E_8^3 \end{array}
\end{array} \qquad (3.18)
$$

$$
VPM_{HRSG} = \begin{array}{cc}
\begin{array}{ccccccccc} E_1^4 & E_2^4 & E_3^4 & E_4^4 & E_5^4 & E_6^4 & E_7^4 & E_8^4 & E_9^4 \end{array} & Parameter \\
\begin{bmatrix}
E_1^4 & 0 & E_{13}^4 & 0 & E_{15}^4 & 0 & E_{17}^4 & 0 & 0 \\
0 & E_2^4 & E_{23}^4 & E_{24}^4 & E_{25}^4 & E_{26}^4 & E_{27}^4 & E_{28}^4 & 0 \\
0 & 0 & E_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & E_{43}^4 & E_4^4 & 0 & 0 & E_{47}^4 & E_{48}^4 & 0 \\
0 & 0 & E_{53}^4 & 0 & E_5^4 & E_{56}^4 & E_{57}^4 & E_{58}^4 & 0 \\
0 & 0 & E_{63}^4 & 0 & 0 & E_6^4 & 0 & 0 & 0 \\
E_{71}^4 & 0 & E_{73}^4 & 0 & E_{75}^4 & 0 & E_7^4 & 0 & 0 \\
0 & 0 & 0 & E_{84}^4 & 0 & 0 & 0 & E_8^4 & 0 \\
0 & 0 & E_{93}^4 & 0 & 0 & 0 & E_{97}^4 & 0 & E_9^4
\end{bmatrix} &
\begin{array}{c} E_1^4 \\ E_2^4 \\ E_3^4 \\ E_4^4 \\ E_5^4 \\ E_6^4 \\ E_7^4 \\ E_8^4 \\ E_9^4 \end{array}
\end{array} \qquad (3.19)
$$

$$
VPM_{SteamTurbine} = \begin{array}{cc}
\begin{array}{cccccccccc} E_1^5 & E_2^5 & E_3^5 & E_4^5 & E_5^5 & E_6^5 & E_7^5 & E_8^5 & E_9^5 & E_{10}^5 \end{array} & Parameter \\
\begin{bmatrix}
E_1^5 & E_{12}^5 & E_{13}^5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
E_{21}^5 & E_2^5 & 0 & E_{24}^5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & E_3^5 & E_{34}^5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & E_{43}^5 & E_4^5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & E_{53}^5 & E_{54}^5 & E_5^5 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & E_6^5 & 0 & 0 & E_{69}^5 & E_{610}^5 \\
0 & 0 & E_{73}^5 & E_{74}^5 & 0 & 0 & E_7^5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & E_{85}^5 & 0 & 0 & E_8^5 & E_{89}^5 & 0 \\
0 & 0 & E_{93}^5 & E_{94}^5 & 0 & 0 & 0 & 0 & E_9^5 & 0 \\
0 & 0 & E_{103}^5 & E_{104}^5 & 0 & 0 & 0 & 0 & 0 & E_{10}^5
\end{bmatrix} &
\begin{array}{c} E_1^5 \\ E_2^5 \\ E_3^5 \\ E_4^5 \\ E_5^5 \\ E_6^5 \\ E_7^5 \\ E_8^5 \\ E_9^5 \\ E_{10}^5 \end{array}
\end{array} \qquad (3.20)
$$

$$VPM_{WaterSystem}=\begin{array}{cc} \begin{matrix} E_1^6 & E_2^6 & E_3^6 & E_4^6 & E_5^6 \end{matrix} & Parameter \\ \begin{bmatrix} E_1^6 & E_{12}^6 & 0 & 0 & 0 \\ 0 & E_2^6 & 0 & 0 & E_{25}^6 \\ 0 & 0 & E_3^6 & E_{34}^6 & 0 \\ 0 & E_{42}^6 & 0 & E_4^6 & 0 \\ 0 & 0 & 0 & 0 & E_5^6 \end{bmatrix} & \begin{matrix} E_1^6 \\ E_2^6 \\ E_3^6 \\ E_4^6 \\ E_5^6 \end{matrix} \end{array} \tag{3.21}$$

Inheritance and interaction can be evaluated by developing VPF for each system's VPSEPM explained in next section.

3.1.3.7. PERMANENT FUNCTION OF PPD AT SYSTEM LEVEL

Permanent function of VPSEPM is called Variable Permanent System Efficiency Parameter Function, abbreviated as VPF-ep and for matrix (3.15) is written in sigma form in expression (3.22). Equation (3.22) contains $N!$ terms organized in $N+ 1$ groups, where N is number of elements. The physical implication of various grouping is elucidated as under:

- The first grouping epitomizes the measures of N design parameters.
- The second grouping is absent as there is no self-loop in the digraph.
- The third grouping encompasses 2-design parameters interaction loops and measures of (N-2) design parameters.
- Each term of the fourth grouping exemplifies a set of 3-design parameters interaction loop or its pair and measures of (N-3) design parameters.
- The fifth grouping comprises two subgrouping. The terms of the first subgrouping are a set of two 2-design parameters interaction loops and the measures of (N-4) design parameters. Each term of the second subgrouping is a set of 4- design parameters interaction loop or its pair and the measures of (N-4) design parameters.
- The sixth grouping encompasses two subgrouping. The terms of the first subgrouping is a set of

3-design parameters interaction loop or its pair and 2- design parameters interaction loop and the measures of (*N*-5) design parameters. Each term of the second subgrouping is a set of 5- design parameters interaction loop or its pair and the measures of (*N*-5) design parameters. Correspondingly other terms of the expression are demarcated.

$$
\begin{aligned}
per(B^*) &= \prod_{1}^{N} B_i + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N b_{ij} b_{ji} B_k B_l \ldots\ldots B_N \\
&\quad + \left\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{jk} b_{ki} \right) B_l B_m \ldots\ldots B_N \right. \\
&\quad \left. + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ik} b_{kj} b_{ji} \right) B_l B_m \ldots\ldots B_N + \right\} \\
&\quad + \left[\left\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{ji} \right) \left(b_{kl} b_{lk} \right) B_m B_n \ldots\ldots B_N \right\} \right. \\
&\quad + \left\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{jk} b_{kl} b_{li} \right) B_m B_n \ldots\ldots B_N \right. \\
&\quad \left. \left. + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{il} b_{lk} b_{kj} b_{ji} \right) B_m B_n \ldots\ldots B_N \right\} \right] \\
&\quad + \left[\left\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{ji} \right) \left(b_{kl} b_{lm} b_{mk} \right) B_n B_o \ldots\ldots B_N \right. \right. \\
&\quad \left. + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{ji} \right) \left(b_{km} b_{ml} b_{lk} \right) B_n B_o \ldots\ldots B_N \right\} \\
&\quad + \left\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{ij} b_{jk} b_{kl} b_{lm} b_{mi} \right) B_n B_o \ldots\ldots B_N \right. \\
&\quad \left. \left. + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(b_{im} b_{ml} b_{lk} b_{kj} b_{ji} \right) B_n B_o \ldots\ldots B_N \right\} \right] + \ldots\ldots
\end{aligned}
\tag{3.22}
$$

Quantification of inheritance and interdependencies of design parameters may be established with the help of industrial data or mathematical modeling. If industrial data is not available then quantification of diagonal elements of matrix can be done on a scale of 1-9 as given in Table 3.1, based on the inheritance of each design parameters. Interdependency is decided on the scale of 1-5 as per Table 3.2. The values of permanent functions are used for the calculation of

RTEI for CCPP as explained in the next section.

3.1.3.8. RTEI FOR SYSTEMS

Combined cycle power plant efficiency analysis is highly complex because of interaction among systems and design parameters. For simplification every system is studied individually by considering inheritance and interdependencies of design parameters. In present analysis RTEI for each system is calculated and subsequently used for CCPP efficiency analysis. RTEI for each system is the ratio of real time efficiency ($\text{Efficiency}_{\text{RealTime}}$) to designed efficiency ($\text{Efficiency}_{\text{Design}}$). If system is operating at its best then RTEI is one otherwise it will be lesser than one because no system can perform better than its design performance (efficiency in present case).

If any system is affected by more number of parameters then its VPSEPM is of higher order. After quantification its permanent function is of higher value in comparison to a system being affected by lesser number of parameters. In this case value of permanent is affected by number of parameters and true picture of system efficiency can not be had from the index. By using the concept of RTEI, this problem is resolved. The value of RTEI is between 0 and 1 for each system and it is easy to handle and interpret. For complete analysis of any system it is necessary to develop VPSEPM at system level by taking the inheritance and interdependency of each design parameter in real time and designed conditions. If the VPF-ep for real time and design is represented by $(Efficiency)_{\mathrm{Re}\,alTime}$ and $(Efficiency)_{Design}$ respectively then the value of RTEI for six systems is given by following relations:

$$RTEI_{AirCompressor} = \frac{(Efficiency)_{\mathrm{Re}\,alTimeAirCompressor}}{(Efficiency)_{DesignAirCompressor}} \tag{3.23}$$

$$RTEI_{CombustionChamber} = \frac{(Efficiency)_{\mathrm{Re}alTimeCombustionChamber}}{(Efficiency)_{DesignCombustionChamber}} \tag{3.24}$$

$$RTEI_{GasTurbine} = \frac{(Efficiency)_{\mathrm{Re}alTimeGasTurbine}}{(Efficiency)_{DesignGasTurbine}} \tag{3.25}$$

$$RTEI_{HRSG} = \frac{(Efficiency)_{\mathrm{Re}alTimeHRSG}}{(Efficiency)_{DesignHRSG}} \tag{3.26}$$

$$RTEI_{SteamTurbine} = \frac{(Efficiency)_{\mathrm{Re}alTimeSteamTurbine}}{(Efficiency)_{DesignSteamTurbine}} \tag{3.27}$$

$$RTEI_{WaterSystem} = \frac{(Efficiency)_{\mathrm{Re}alTimeWaterSystem}}{(Efficiency)_{DesignWaterSystem}} \tag{3.28}$$

The values obtained for RTEI of the six systems from the equations mentioned above provide guidance for the quantification of diagonal element (inheritance) in equation (3.13). The value of the permanent function obtained in this way is dependent on inheritance and interdependencies of design parameters and systems. Further values of RTEI and RTRI are dimensionless numbers and composite index for efficiency and reliability can be developed with the help of three steps of graph theoretic methodology.

3.1.3.9. STEP BY STEP FOR PROCEDURE DETERMINING RTEI$_{\mathbf{CCPP}}$

A methodology for the evaluation of RTEI$_{CCPP}$ is proposed on the basis of GTA as discussed above. The main steps of this methodology are as follows:

1. Identify the various systems affecting the CCPP efficiency in such a way that no system should be independent.
2. Develop SED showing all possible interconnections in between systems. This is the digraph at the system level.
3. Identify the various design parameters affecting system’s efficiency for each system.
4. For each system, develop a digraph among the design parameters based on the interactions amongst them. This is the digraph at each system level.
5. Based on the above-mentioned digraphs at system level for design parameters, develop the variable permanent system efficiency parameter matrix for each system.
6. Calculate the variable permanent system efficiency parameter function at each system level. For avoiding the complexity, the numerical values of inheritance and interactions may be used.
7. The value of RTEI at system level is calculated with the help of expressions (3.23) to (3.28) for all six systems.
8. Develop the VPSEPM for the SED developed in step 2. This will be M x M matrix with diagonal elements of D_i and off-diagonal elements of d_{ij}. The value of RTEI calculated at system level in step 7 provides guidance for inheritance (diagonal elements of D_i) for each system category. The values of interaction amongst these systems (i.e. off-diagonal elements of d_{ij}) can be decided by industrial data or mathematical modelling.
9. Calculate the variable permanent system efficiency function for CCPP system. This is the value of CCPP efficiency index based on the different design parameters and their interdependency.
10. Compare different power plants in terms of CCPP efficiency index and list them in descending order of their index values. The power plant having the lowest index value of has the best chance of efficiency improvement.

3.1.4. COMPOSITE INDEX FOR EFFICIENCY AND RELIABILITY (CIER)

None of the power plant system can be understood or analyzed by considering single design parameter or studying all the parameters independently. Analysis of thermal power plant performance on efficiency and reliability basis can be carried out by considering inheritance and interdependency of efficiency and reliability. For this purpose a composite index for efficiency and reliability is proposed in this section. The performance parameter digraph for efficiency and reliability is represented as below:

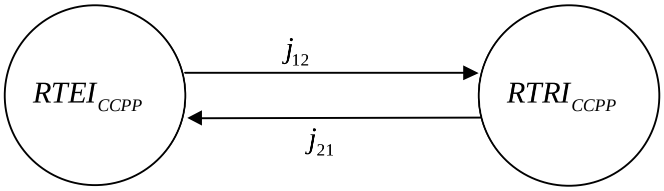


Figure 3.16 Digraph showing attributes of composite index for efficiency and reliability and their interdependencies

The performance parameter permanent matrix corresponding to the performance parameter graph shown in Figure 3.16 is as represented by the following expression

$$J = \begin{bmatrix} RTEI_{CCPP} & j_{12} \\ j_{21} & RTRI_{CCPP} \end{bmatrix} \tag{3.29}$$

The permanent function corresponding to the above expression called as performance parameter permanent function for reliability and efficiency and represented as following

$$J_P = RTEI_{CCPP} RTRI_{CCPP} + j_{12} j_{21} \tag{3.30}$$

The composite index developed above takes care of RTEI, RTRI and their interdependency. This index may be used for the performance evaluation of CCPP on efficiency and reliability basis.

3.1.5. GTA FOR COGENERATION CYCLE POWER PLANT (CGCPP)

Cogeneration is the production of electrical energy and useful thermal energy from the same energy source, due to which it is also called as combined heat and power (CHP) system also. In this section a GTA based methodology is developed for the performance analysis of CGCPP and proposed methodology is based on the methodology developed for CCPP in the section (3.1.1).

CGCPP considered for the present analysis is shown in Figure 3.17. The air at the ambient temperature is compressed by the air compressor and directed to the combustion chamber. The compressed air mixes with the CNG from the fuel supply system to produce hot flue gas in the combustor. The hot flue gas is delivered to the gas turbine where the power is generated. The exhaust gas passes through a process heater where water is converted into heated water or steam. The steam produced is used as process steam. For the GTA, cogeneration cycle power plant is divided into following four systems:

1. Air compressor system (P_1)
2. Combustion chamber system (P_2)
3. Gas turbine system (P_3)
4. Process heater system (P_4)

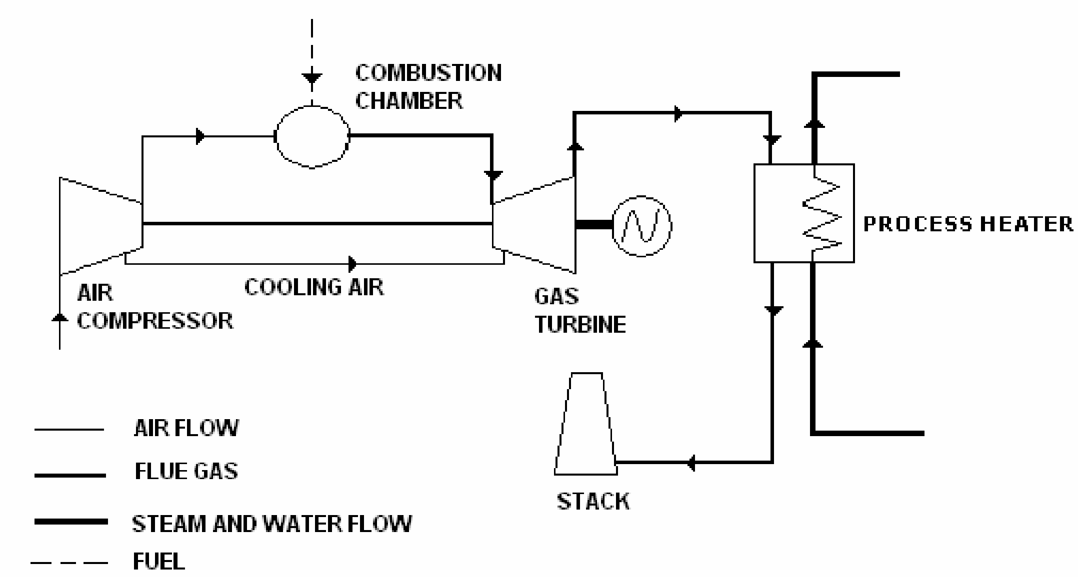


Figure 3.17 Schematic flow diagram of Cogeneration Cycle Power Plant

3.1.5.1. SSG FOR CGCPP

Let each of the four systems of plant be represented by vertices P_i (i=1,2,3,4) and interconnection between two systems is represented by edges g_{ij} (i=1,2,3,4 and $i \neq j$). In actual system all four systems doesn't affect each other. The graph theoretic representation [P, g] of vertex and edge sets of four systems of cogeneration cycle power plant, called system structure graph (SSG), is shown in Figure 3.18. This is based upon the working of cogeneration cycle power plant as per the following:

1. The ambient air comes to the compressor after being filtered by air filters. Compressor and turbine are attached with a shaft. The power to compress the air comes to the compressor from the turbine. This is represented by the edge g_{31}.
2. After compression air goes to the combustion chamber as represented by edge g_{12}.
3. Gas turbine blades are cooled by being made hollow so that a coolant air can circulate through it. Coolant air is obtained directly from the compressor, thus bypassing the combustion chamber.

Edge g_{13} represents the bypassing of cooling air.

4. Combustion product called as flue gas, flows to gas turbine from combustion chamber as shown by edge g_{23}.
5. Depending upon the temperature of flue gas, process heater [P_4] may be used for (i) partial heating (regeneration) of the compressed air leaving the compressor (g_{42}), (ii) generating process steam.
6. Flue gases coming out of combustion chamber and entering to process heater system [P_4] are shown by the edge g_{34}.

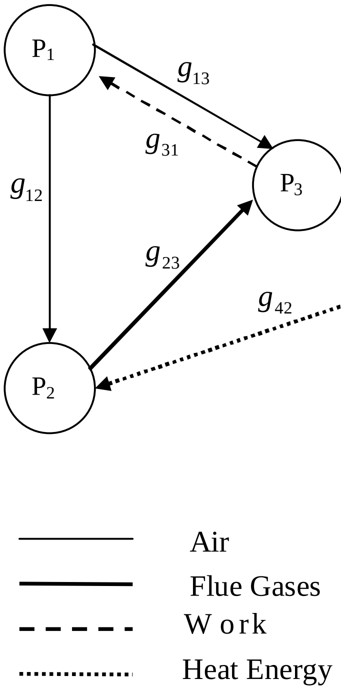


Figure 3.18 System structural graph of cogeneration cycle power plant

The system structure graph (Figure 3.18) represents the internal structure of the CGCPP at system level. It clearly shows different systems and their interconnections in the CGCPP as discussed above.

A CGCPP performance digraph is prepared to represent the effect of one system on the others in terms of nodes and edges as per the methodology developed in section 3.1.1. Diagraph for SSG shown in Figure 3.18 is as shown in Figure 3.19.

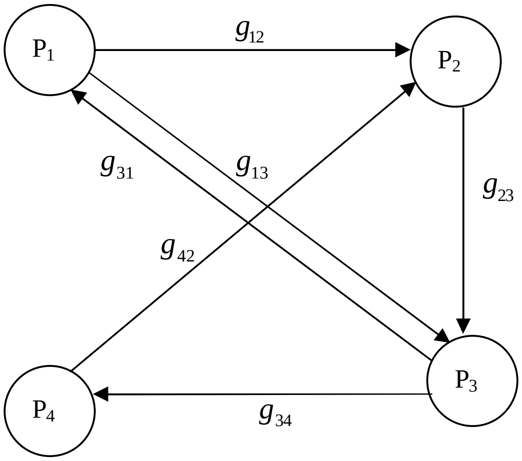


Figure 3.19 Digraph showing four systems of CGCPP and their interdependencies

3.1.5.2. MATRIX REPRESENTATION

In order to obtain proper characterization of CGCPP systems as derived from combinatorial considerations, a variable permanent system structure matrix corresponding to the SSD of Figure 3.19 is developed based on the procedure explained in section (3.1.1.2). Use of this concept in system structure modeling helps in retaining the structural information of the systems and it is converted into mathematical form for computer processing. For the CGCPP system, corresponding to Figure 3.19, variable permanent system structure matrix (V_c) can be written as:

$$\begin{array}{cc} & \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \quad \textit{Systems} \\ V_c = & \left[\begin{array}{cccc} P_1 & g_{12} & g_{13} & 0 \\ 0 & P_2 & g_{23} & 0 \\ g_{31} & 0 & P_3 & g_{34} \\ 0 & g_{42} & 0 & P_4 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \end{array} \tag{3.31}$$

3.1.5.3. EVALUATION OF VARIABLE PERMANENT SYSTEM STRUCTURE FUNCTION (VPSSF)

The permanent of VPSSM is known as variable permanent system structure function and for matrix in expression (3.31) is written as:

$$Per\left[V_c\right] = [P_1P_2P_3P_4 + \left(g_{13}g_{31}\right)\left(P_2P_4\right) + \left(g_{31}g_{23}\right)\left(P_1P_4\right) + P_1\left(g_{23}g_{34}g_{42}\right)] \tag{3.32}$$

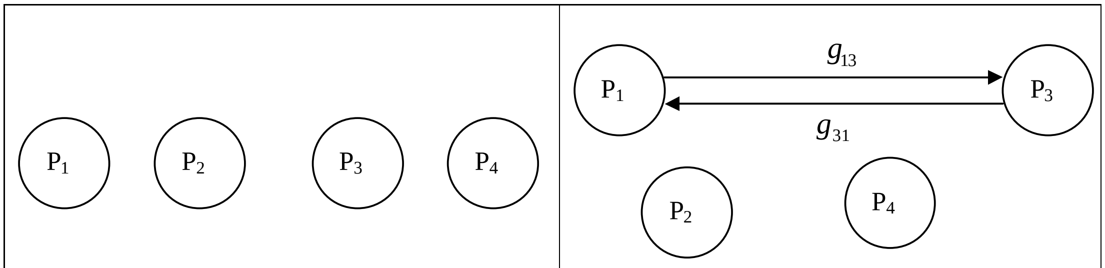
Every term in the Per [V_c] is representing the part of the system and interlink. For example the $P_1P_2P_3P_4$ shows that all four systems are linked to each other. Any of the system cannot be omitted. The term $\left(g_{13}g_{31}\right)\left(P_2P_4\right)$ indicates that if the performance of the link g_{13} and g_{31} is degraded then combustion chamber system and process heater system performance is also affected.

The permanent function of CGCPP system (i.e. equation 3.32) contains all the possible components of CGCPP system and their interdependence. The physical significance of various groupings in equation (3.32) is explained as follows:

- The first group (of the multinomial 3.32) contains only one term and represents the presence of all systems *i.e.*, $P_1P_2P_3P_4$.
- The second grouping is absent since these are no self-loops *i.e.*, this grouping will occur in expression only if a system is connected to itself.
- The third grouping contains a set of two systems, interdependence and inheritance of the remaining two systems.

- Each term of the fourth grouping represents a set of three systems, interdependence and inheritance of the remaining one system.
- Fifth group is absent because there is no loop containing all four systems.

From the above, it is obvious that, in general, the *i*th grouping contains ($N + 1 - i$) P_is and the remaining structural components (for example, g_{ij} , $g_{ij}g_{jk}$, $g_{ij}g_{jk}g_{kl}$, etc.). The terms of the expression are arranged in decreasing number of P_is for better interpretation of the system. Because of the arrangement of the terms of system structure in the same grouping, and distinct structures of different groupings and physical meaning behind each of these, the complete multinomial can be written by visual inspection of the graph and is shown in Figure 3.20. In the following section step by step methodology for CGCPP performance evaluation is given.

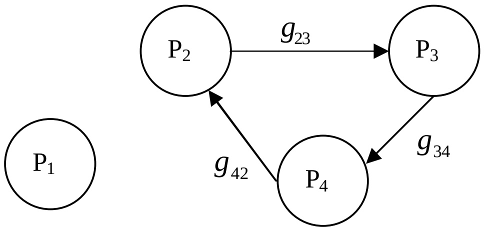


1 Term

(a) Group 1

+1 Other Terms

(b) Group 3



1 Term

(c) Group 4

Absent

(d) Group 5

Figure 3.20 Graphical representation of permanent function (Equation 3.32) corresponds to digraph (Figure 3.19)

3.1.5.4. STEP BY STEP PROCEDURE FOR PERFORMANCE ANALYSIS

1. Identify the various systems affecting the CGCPP performance.
2. Develop the CGCPP system structural graph.
3. Develop the system structural digraph corresponding to SSG of CGCPP. This is the digraph at the system level.
4. Develop the variable permanent system structure matrix for the CGCPP system structure digraph. The values of inheritance (diagonal elements) and interaction among these systems (off-diagonal elements) are to be decided by the experts on the basis of scale of 1-9 and 1-5 respectively as stated in Table 3.1 and 3.2.
5. Calculate variable permanent system structure function for the VPSSM developed in step 4.

In the following sections 3.1.6 and 3.1.7, methodology developed for the reliability and efficiency analysis of CCPP in sections 3.1.2 and 3.1.3, is modified for the reliability and efficiency analysis of CGCPP.

3.1.6. REAL TIME RELIABILITY INDEX FOR COGENERATION CYCLE

Reliability is one of the highest priorities in the design of power plants. It ranks along with cost and efficiency as a measure of successful design. Quantification of reliability is important for successful system design. In this section a methodology based on GTA is developed for CGCPP reliability analysis. The first step is to develop System Reliability Digraph (SRD).

3.1.6.1. CGCPP SYSTEM RELIABILITY DIGRAPH

If the node A_i represents the reliability of *i*th system and a_{ij} represents the reliability of the interconnection between *i*th and *j*th systems (nodes) of CGCPP; then, systems reliability graph or digraph (SRG) can be obtained from the SSG of a CGCPP (Figure 3.18 or 3.19) and is as represented in Figure 3.21.

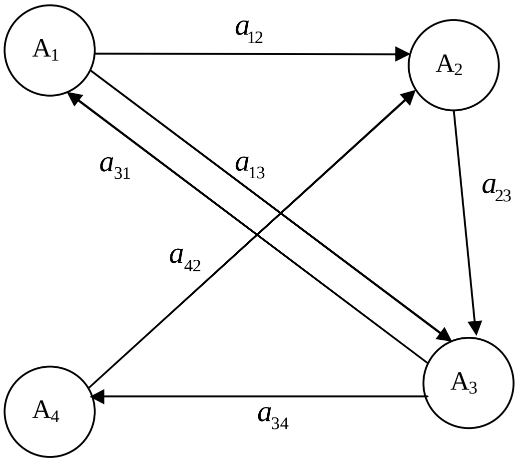


Figure 3.21 System reliability digraph for cogeneration cycle power plant

The digraph model (SRD) provides the system structure reliability unequivocally. Reliability of the connection between two systems is considered if the systems are connected either by rigid or flexible links such as connection between gas turbine and air compressor through a mechanical shaft or between combustion chamber system and water system, through flue gases. Once the SRD of the CGCPP is obtained from SSG, reliability analysis is carried out using matrix representation and development of permanent function as outlined below.

3.1.6.2. VARIABLE PERMANENT SYSTEM RELIABILITY MATRIX

Variable permanent system reliability matrix (VPSRM) B_c abbreviated as VPM-r for the cogeneration cycle power plant corresponding to the digraph of Figure 3.21 is written as:

$$\begin{array}{c|cccc|c} & 1 & 2 & 3 & 4 & Systems \\ \hline & A_1 & a_{12} & a_{13} & 0 & 1 \\ B_c = & 0 & A_2 & a_{23} & 0 & 2 \\ & a_{31} & 0 & A_3 & a_{34} & 3 \\ & 0 & a_{42} & 0 & A_4 & 4 \end{array} \quad (3.33)$$

3.1.6.3. VARIABLE PERMANENT SYSTEM RELIABILITY FUNCTION

The permanent of VPSRM is called as variable permanent system reliability function, abbreviated as VPF-r, and for the expression (3.33) it is written as:

$$Per[B_c] = [A_1A_2A_3A_4 + (a_{13}a_{31})(A_2A_4) + (a_{31}a_{23})(A_1A_4) + A_1(a_{23}a_{34}a_{42})] \quad (3.34)$$

The reliability value of a CGCPP would start gradually decreasing with time due to various reasons such as non-availability of some of the components or due to the aging effect, etc. Some of the plant operators for short duration may be operating the plant at overload conditions. But these short term gains lead to long-term losses like reduction in the life span, or cascading of damage, etc. With the help of expression (3.34), real time reliability and designed reliability for a CGCPP can be evaluated. In the next section $RTRI_{CGCPP}$ is calculated corresponding to the methodology developed in section 3.1.2.4 for the evaluation of $RTRI_{CCPP}$.

3.1.6.4. CGCPP REAL TIME RELIABILITY INDEX

For comparison of actual or real time reliability of CGCPP [$(\text{Reliability})_{RT}$] it is difficult to find a power plant having exactly same design and with same equipments. Secondly the performance any power plant in any case is not expected to be better than its designed value that is

$(\text{Reliability})_{DCGCPP}$. Therefore, it is appropriate to judge real time performance of a CGCPP with respect to its design performance as explained in section (3.1.2). The ratio of real time reliability to the designed reliability is defined as the Real Time Reliability Index (RTRI) for CGCPP and is expressed as:

$$RTRI_{CGCPP} = \frac{\mathrm{Re}\,liability_{RT}}{\mathrm{Re}\,liability_{D}} = \frac{(VPF - r)_{RT}}{(VPF - r)_{D}} \qquad (3.35)$$

Reliability of a CGCPP is further dependent on the maintenance of its equipments/ components. The designed level of the product performance implies that the maintenance has been performed as per the schedule and also the efficiency of operation is at the rated/ designed value that is operating at Maximum Capacity Rating (MCR) or full load conditions. In the real time regime, the process would be performing at the levels restricted by reliability as crossing these restrictions may lead to shut down/ closure of some of the systems.

Reliability of a power plant is not only dependent on component performance but also on the training of operational personnel, human resource policies of management etc. The overload operations also reduces the real time reliability of plant. RTRI for cogeneration cycle power plant will achieve its maximum value of unity when plant is operating at designed condition with satisfactory performance of all of its systems.

3.1.6.5. STEP BY STEP PROCEDURE FOR DETERMINING $\mathbf{RTRI_{CGCPP}}$

The methodology described above for the calculation of RTRI for the cogeneration cycle power plant is reproduced below step by step.

Step 1: Consider a cogeneration cycle power plant. As it is very large system, divide it into smaller subsystems (e.g. air compressor system, combustion chamber system, gas turbine system and process heater).

Step 2: Develop system structure graph for the reliability of CGCPP system based upon the interaction among different systems.

Step 3: Convert the SSG of CGCPP into corresponding system reliability digraph (SRD) with systems reliability as nodes and edges for the reliability of interconnections.

Step 4: Develop the CGCPP system reliability matrix corresponding to the CGCPP system reliability digraph. This will be N x N matrix with diagonal elements of A_i and off-diagonal elements of a_{ij}. The value of inheritance A_i (diagonal elements) for each system and interaction a_{ij} is decided by industrial data or literature survey.

Step 5: Calculate the permanent function of CGCPP system reliability matrix for values of real time reliability and designed reliability.

Step 6: Calculate the ratio of real time reliability and designed reliability as in equation (3.35). This is the value of $RTRI_{CGCPP}$ which mathematically characterizes the reliability of any cogeneration cycle power plant based on the different systems and their interdependencies.

3.1.7. EFFICIENCY ANALYSIS OF CGCPP

The procedure for the evaluation of efficiency is developed using SSG developed in section 3.1.5. Then its corresponding System Efficiency Digraph (SED) is developed by associating attribute efficiency to the systems and interconnections amongst the systems. SED is converted into matrix form and permanent function is developed corresponding to the efficiency matrix. Procedure of efficiency analysis for CGCPP is same as developed for CCPP in section 3.1.3.

3.1.7.1 SYSTEM EFFICIENCY DIGRAPH (SED)

For the development of CGCPP system efficiency digraph, the four systems are represented by four nodes as shown in Figure 3.22. In this figure E_1, E_2, E_3 and E_4 represents the inheritance of air compressor system, combustion chamber system, gas turbine system and process heater system respectively. e_{ij} represents the interdependency of efficiency of *i*th system on *j*th system. SED shown in Figure 3.22 is corresponding to SSG shown in Figure 3.19. The directed edges are drawn according to the interdependence of these systems as developed in section (3.1.5).

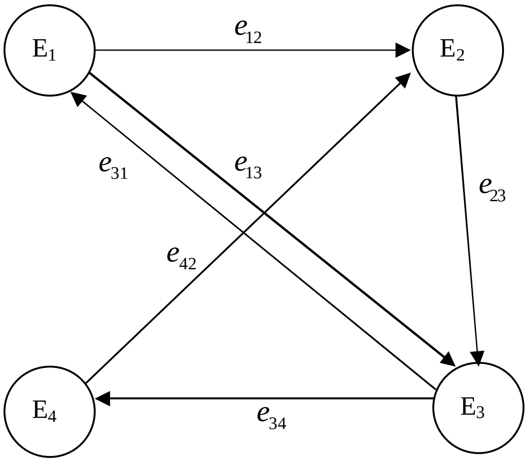


Figure 3.22 Digraph showing four attributes of Cogeneration Cycle Power Plant and their interdependencies in the system

3.1.7.2. VARIABLE PERMANENT SYSTEM EFFICIENCY MATRIX (VPSEM)

For the efficiency analysis, SED is converted into matrix form which is known as VPSEM and explained in section (3.1.3.2). VPSEM corresponding to SED shown in Figure 3.22 is written as:

$$
E^* = \begin{array}{c} \\ \\ \\ \\ \end{array}
\begin{array}{cccc|c}
1 & 2 & 3 & 4 & \textit{Systems} \\
\end{array}
$$

$$
\begin{array}{cc}
 & \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \quad \textit{Systems} \\
E^* = & \begin{bmatrix} E_1 & e_{12} & e_{13} & 0 \\ 0 & E_2 & e_{23} & 0 \\ e_{31} & 0 & E_3 & e_{34} \\ 0 & e_{42} & 0 & E_4 \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}
\end{array} \tag{3.36}
$$

In matrix E*, the diagonal elements E_1, E_2, E_3, E_4 represent the impact of different categories of systems on the CGCPP efficiency on the basis of their design parameters and e_{ij} represents the interdependency of the system category *i* and *j*, represented by the edge e_{ij} from *i* to *j* in the digraph.

3.1.7.3. PERMANENT REPRESENTATION OF CGCPP SYSTEM MATRIX

Both digraph and matrix representations are not unique in nature because they are altered by changing the labels of their nodes. Hence, to develop a unique representation that is independent of labeling, a permanent function of the CGCPP system matrix is proposed here. The permanent is a standard matrix function and is used in combinatorial mathematics. The permanent function is obtained in a similar manner as the determinant but unlike in a determinant where a negative sign appears in the calculation, in a variable permanent function positive signs replace these negative signs.

The expression for permanent function corresponding to four-element digraph, as shown in Figure 3.22, is written as:

$$
\begin{aligned}
\text{Per}(E^*) = \; & E_1 E_2 E_3 E_4 \\
& + e_{12} e_{21} E_3 E_4 + e_{13} e_{31} E_2 E_4 + e_{14} e_{41} E_2 E_3 \\
& + e_{23} e_{32} E_1 E_4 + e_{24} e_{42} E_1 E_3 + e_{34} e_{43} E_1 E_2 \\
& \quad + e_{12} e_{23} e_{31} E_4 + e_{13} e_{32} e_{21} E_4 + e_{12} e_{24} e_{41} E_3
\end{aligned} \tag{3.37}
$$

$+ e_{14}\, e_{42}\, e_{21}\, E_3 + e_{13}\, e_{34}\, e_{41}\, E_2 + e_{14}\, e_{43}\, e_{31}\, E_2$

$+ e_{23}\, e_{34}\, e_{42}\, E_1 + e_{24}\, e_{43}\, e_{32}\, E_1$

$+ e_{12}\, e_{21}\, e_{34}\, e_{43} + e_{13}\, e_{31}\, e_{24}\, e_{42} + e_{14}\, e_{41}\, e_{23}\, e_{32}$

$+ e_{12}\, e_{23}\, e_{34}\, e_{41} + e_{14}\, e_{43}\, e_{32}\, e_{21} + e_{13}\, e_{34}\, e_{42}\, e_{21}$

$+ e_{12}\, e_{24}\, e_{43}\, e_{31} + e_{14}\, e_{42}\, e_{23}\, e_{31} + e_{13}\, e_{32}\, e_{24}\, e_{41}$

Equation (3.37), i.e. the permanent function of the CGCPP system matrix, is a mathematical expression in symbolic form and contains a number of terms which are structure invariants. If the values of CGCPP system matrix, i.e. equation (3.36) are substituted in equation (3.37), then, some of the terms in various groupings are nullified and resultant permanent representation is as follows:

$$Per\left[E^{*}\right] = [E_1E_2E_3E_4 + \left(e_{13}e_{31}\right)\left(E_2E_4\right) + \left(e_{31}e_{23}\right)\left(E_1E_4\right) + \ E_1\left(e_{23}e_{34}e_{42}\right)] \qquad (3.38)$$

To calculate this index, the values of E_i and e_{ij} are required. Quantification of the E_i and e_{ij} can be done on the basis of industrial data or literature survey in conjunction with Tables 3.1 and 3.2.

Efficiency of four systems is dependent on many design and operating parameters. Therefore, at the system level also digraph for efficiency is developed by taking into consideration inheritance and interdependencies of design. Procedure for calculating RTEI at system level is explained in sections: from 3.1.3.4 to 3.1.3.8. Design parameters affecting the air compressor, combustion chamber, gas turbine and process heater system efficiency in CGCPP are the same as identified for the air compressor, combustion chamber, gas turbine and HRSG system of CCPP. Calculation of RTEI for the systems of CGCPP is explained in next section.

3.1.7.4. RTEI FOR SYSTEMS

As discussed earlier if design parameters are large in number then efficiency index of

CGCPP is so high that it becomes impractical to analyse the index. Secondly, system with higher number of parameters will be dominating the CGCPP system efficiency index irrespective of its own inheritance in the system. For the simplification of methodology a relative index called as Real Time Efficiency Index (RTEI) at system level is used for each system of CGCPP. It is the ratio of efficiency in real time [$(\text{Efficiency})_{RT}$] to design efficiency [$(\text{Efficiency})_{D}$] and for four systems is given by following relations:

$$RTEI_{AirCompressor} = \frac{(Efficiency)_{\mathrm{Re}alTimeAirCompressor}}{(Efficiency)_{DesignAirCompressor}} \tag{3.39}$$

$$RTEI_{CombustionChamber} = \frac{(Efficiency)_{\mathrm{Re}alTimeCombustionChamber}}{(Efficiency)_{DesignCombustionChamber}} \tag{3.40}$$

$$RTEI_{GasTurbine} = \frac{(Efficiency)_{\mathrm{Re}alTimeGasTurbine}}{(Efficiency)_{DesignGasTurbine}} \tag{3.41}$$

$$RTEI_{\mathrm{Pr}ocessHeater} = \frac{(Efficiency)_{\mathrm{Re}alTime\,\mathrm{Pr}ocessHeater}}{(Efficiency)_{Design\,\mathrm{Pr}ocessHeater}} \tag{3.42}$$

Design parameters affecting $E_1,\ E_2,\ E_3\ and\ \ E_4$ are same as for $D_1,\ D_2,\ D_3\ and\ \ D_4$ respectively an explained in section 3.1.3.4 of this chapter. Method for the quantification and calculation is also same as explained in that section. Procedure for calculating CIER for CGCPP is also same as explained in section 3.1.4.

3.1.7.5. STEP BY STEP PROCEDURE FOR DETERMINING ($\mathbf{RTEI_{CGCPP}}$)

The main steps of the methodology developed for the evaluation of are $\text{RTEI}_{\text{CGCPP}}$ as following:

1. Identify the various systems affecting the CGCPP efficiency.
2. Develop SED for CGCPP system. This is the digraph at the system level.
3. Identify the various design parameters for each system category of CGCPP system.
4. For each system category, develop a digraph among the design parameters based on the interactions among them. This is the digraph at each system level.
5. Based on the above-mentioned digraphs amongst design parameters, develop the VPSEPM for each system category.
6. Calculate the permanent function at each system level. For avoiding the complexity, the numerical values of inheritance and interactions may be used.
7. The value of RTEI at system level may be calculated with the help of expressions (3.39) to (3.42) for all four systems.
8. Develop the CGCPP system matrix for the CGCPP system efficiency digraph. This will be M x M matrix with diagonal elements of E_i and off-diagonal elements of e_{ij}. The value of the permanent function at each system level provides guidance for inheritance (diagonal elements of E_i) for each system category. The values of interaction among these system categories (i.e. off-diagonal elements of e_{ij}) are to be decided by the experts on the basis of scale of 1-5.
9. Calculate the permanent function of CGCPP system matrix. This is the value of CGCPP efficiency index which is based on the different design parameters and their interdependence.

3.1.8. COMPOSITE INDEX FOR EFFICIENCY AND RELIABILITY (CIER)

Complete analysis of a CGCPP needs to study the interdependency of operating parameters e.g. efficiency, reliability, pollution emission etc. In the present work analysis is carried out on efficiency and reliability basis by considering inheritance and interdependency of efficiency and reliability. For this purpose a composite index for efficiency and reliability can be calculated on the basis of proposed methodology in the section 3.1.4. This index may be used for the performance evaluation of CGCPP on efficiency and reliability basis.

3.2. EXERGETIC ANALYSIS

In this section, thermodynamics of a 30 MW cogeneration cycle (Figure 3.23) is studied. Ambient air enters the compressor (point 1) and after compression its temperature and pressure is increased. Compressed air (point 2) is passed through a regenerator where high temperature combustion gases coming out of gas turbine transfer their heat to the compressed air. After gaining heat in regenerator (point 3), compressed air comes to combustion chamber and fuel is added. After burning with air, chemical energy of fuel is converted into thermal energy. Combustion products temperature depends upon Turbine Inlet Temperature (TIT) (point 4) which is fixed by thermal stress limit of gas turbine blade material. Combustion product temperature is controlled by making A/F mixture a lean mixture. Gas coming out from gas turbine (point 5) have large amount of thermal energy. Major part of this thermal energy is transferred to compressed air in regenerator (point 5 to 6) and high pressure water in process heater (point 8 to 9). Flue gas temperature at process heater outlet (point 7) depends upon the dew point temperature of flue gas. Temperature below dew point causes the corrosion of stack by flue gas.

The performance of the cogeneration cycle is investigated at ISO day condition (15°C, 101.325 kPa, 60% relative humidity). For the present analysis, air is considered to be a combination of N_2 (77.48%), O_2 (20.59%), CO_2 (0.03%) and H_2O (1.9%) and their properties are inbuilt function of software EES. The energy balance equations for various parts of the gas turbine plant (Figure 3.23) are as follows in next sections.

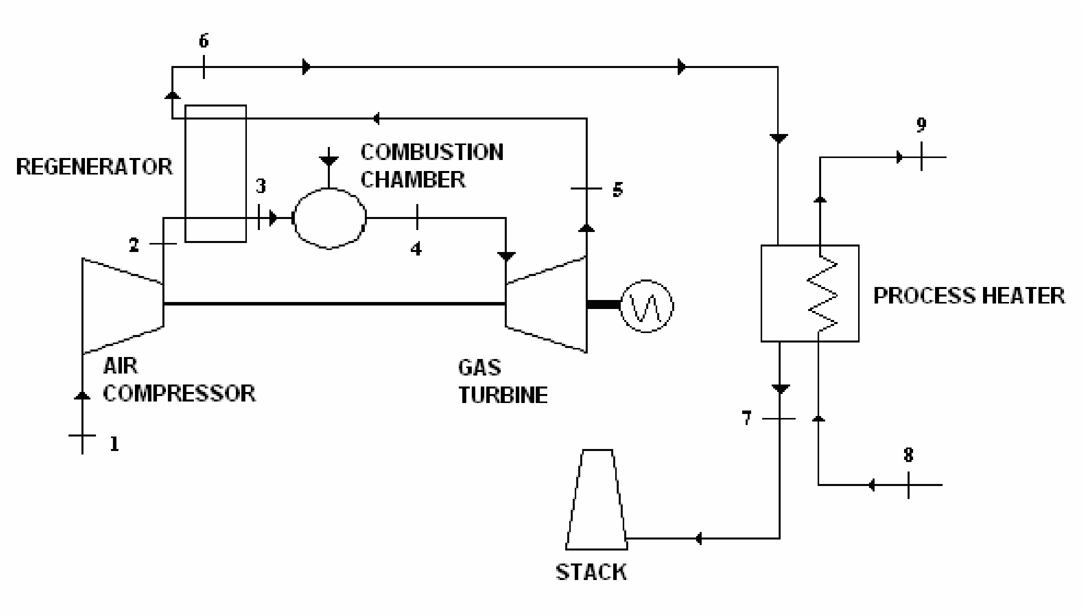


Figure 3.23 Schematic diagram of Cogeneration cycle with regenerator

3.2.1. AIR COMPRESSOR

Axial flow type compressor is used in the cycle. The thermodynamic losses in compressor are incorporated in the model by introducing the concept of efficiency. For isentropic compressor efficiency, we have

$$\eta_{sAC} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{3.43}$$

For h_{2s} to calculate, isentropic temperature at compressor outlet is required. As the air composition is fixed, ideal-gas mixture principles allow the isentropic compression to be described as

$$s(T_{2s}, p_2) - s(T_1, p_1) = s^0(T_{2s}) - s^0(T_1) - R\ln\frac{p_2}{p_1} = 0 \tag{3.44}$$

Above equation is used to find temperature at compressor outlet. Work required for the compressor is

$$W_{AC} = \dot{m}_a (h_2 - h_1) \tag{3.45}$$

3.2.2. COMBUSTION CHAMBER

Combustor model includes the consideration of losses in combustor and estimation of fuel requirement for achieving specified temperature at its exit. The combustor losses considered are due to incomplete fuel combustion and pressure loss. Loss due to incomplete fuel combustion is taken care by the use of the concept of combustion efficiency, while pressure loss is accounted by taking percentage pressure drop of the combustor inlet pressure. Fuel requirement for attaining the desired TIT is obtained from the mass and energy balances across the combustor.

For complete combustion of methane the chemical equation takes the form

$$\begin{aligned}\lambda CH_4 + \left[0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O\right] \\ \longrightarrow \left[1+\lambda\right]\left[x_{N_2}N_2 + x_{O_2}O_2 + x_{CO_2}CO_2 + x_{H_2O}H_2O\right]\end{aligned} \tag{3.46}$$

Where λ is the fuel-air ratio on the molar basis and the molar flow rates of the fuel, air, and combustion products are related by

$$\lambda = \frac{n_f}{n_a} \quad \text{and} \quad 1+\lambda = \frac{n_g}{n_a} \tag{3.47}$$

Balancing carbon, hydrogen, oxygen and nitrogen, the mole fractions of the components of the combustion products are

$$x_{N_2} = \frac{0.7748}{1+\lambda} \tag{3.48}$$

$$x_{O_2} = \frac{0.2059 - 2\lambda}{1+\lambda}$$

(3.49)

$$x_{CO_2} = \frac{0.0003 + \lambda}{1+\lambda}$$

(3.50)

and $$x_{H_2O} = \frac{0.019 + 2\lambda}{1+\lambda}$$

(3.51)

Mass of fuel supplied can be calculated by energy balance between the energy supplied by the fuel and change in enthalpy of combustion products due to this heat addition. Change in enthalpy of air after adding fuel in combustion chamber is given by following relationship:

$$\dot{m}_a h_3 + \dot{m}_f LHV = \dot{m}_g h_4 + (1-\eta_{cc})\dot{m}_f LHV$$

(3.52)

Some of the pressure of compressed air and flue gases is lost in combustion chamber and it is calculated as:

$$\frac{p_4}{p_3} = (1 - \Delta p_{cc}) \tag{3.53}$$

3.2.3. GAS TURBINE

The turbine is treated as an expander whose walls continuously extract work. The objective for the development of a gas turbine model in the present work is to study cogeneration cycle performance. If we represent gas turbine efficiency by η_{GT} then actual temperature T_5 at the exit of the turbine can be calculated by

$$\eta_{GT} = \frac{T_4 - T_5}{T_4 - T_{5s}}$$

(3.54)

and $s(T_{5s}, p_5) - s(T_4, p_4) = s^0(T_{5s}) - s^0(T_4) - R\ln\frac{p_5}{p_4} = 0$ (3.55)

And the inlet and outlet humidity ratios will be the same. Work produced by gas turbine is used for driving air compressor and Turbo-Generator (TG).

$$W_{GT} = \dot{m}_g (h_5 - h_6) \tag{3.56}$$

$$\dot{W}_{NetGT} = \dot{W}_{GT} - \dot{W}_{AC} \tag{3.57}$$

Mass of flue gas is dependent on the mass of air and fuel, but volume is dependent on the number of moles of molecules present in flue gas.

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \tag{3.58}$$

3.2.4. PROCESS HEATER (PH)

For regenerator and process heater simple mass and enthalpy balance equations are used. The amount of heat transferred to water may be calculated as

$$Q_p = h_6 - h_7 = h_9 - h_8 \tag{3.59}$$

3.2.5. REGENERATOR

Temperature of gas at regenerator outlet may be given as

$$\varepsilon_r = \frac{T_3 - T_2}{T_5 - T_2} \tag{3.60}$$

Applying the energy balance equation across regenerator yields

$$m_a\left(h_2 - h_3\right) = m_g\left(h_6 - h_5\right) \tag{3.61}$$

Pressure loss in regenerator is calculated by the following relationship:

$$\frac{p_3}{p_2} = (1 - \Delta p_r) \tag{3.62}$$

3.2.6. EXERGY ANALYSIS

The first law efficiency is a measure of the amount of energy transferred while second law efficiency represents how effectively the energy is transferred. Second law analysis makes it possible to compare many different interactions in a system, and to identify the major sources of exergy destructions/losses (Dunbar and Lior, 1994). In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy destruction of a system can be divided into four distinct components (Bejan et al., 1996). The two important ones are the physical exergy (E^{PH}) and chemical exergy (E^{CH}). In this study, the two other components which are kinetic exergy (E^{KN}) and potential exergy (E^{PT}) are assumed to be negligible, as the changes in them are negligible (Dincer, 2002). The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy is an important part of exergy in combustion processes. The physical exergy of a closed system at a specified state is given by the expression (3.63).

$$E^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{3.63}$$

Where U, V, and S denote, respectively, the internal energy, volume, and entropy of the system at the specified state, and U_0, V_0, and S_0 are the values of the same properties when the system is in equilibrium with surrounding.

The physical exergy on a unit-of-mass basis can be expressed as

$$e^{PH} = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) \tag{3.64}$$

The chemical exergy on a unit-of-mass basis of mixture is given by

$$e^{CH} = \sum x_k e_k^{CH} + RT_0 \sum x_k \ln x_k \tag{3.65}$$

For evaluation of the fuel exergy, the following relation is used

$$e_f = \xi \times LHV \tag{3.66}$$

where $\xi = 1.033 + 0.0169 \dfrac{y}{x} - \dfrac{0.0698}{x}$ for the fuel $C_x H_y$. (3.67)

The exergy factor of process heat is the ratio of exergy of process heat to the amount of process heat production. The exergy factor of process heat depends on steam conditions and is given by the following relation:

$$\varepsilon_p = 1 - \left[\frac{T_0(s_g - s_c)}{(h_g - h_c)} \right] \tag{3.68}$$

Where s_g (kJ/kg°C), h_g (kJ/kg) are entropy and enthalpy of saturated vapour at process steam pressure respectively. s_c (kJ/kg°C), h_c (kJ/kg) are entropy and enthalpy of condensate return. The exergetic efficiency of cogeneration cycle is as expressed by the expression (3.69).

$$\eta_{Exergy} = \frac{\left(\dot{W}_{Net} + \dot{Q}_P \right)}{\dot{m}_f \times e_f} \tag{3.69}$$

In this work for the exergy analysis of the plant, the exergy of each line is calculated at all states and the changes in the exergy are determined for each major component. The exergy destruction rate and the exergy efficiency for each component in the cycle (Figure 3.23) are shown in Table 3.5. The exergetic efficiency of a process or system is given as the ratio of useful exergy outputs to exergy inputs.

Table 3.5 Exergy destruction rate and exergetic efficiency equations for CGCPP

components

Components	**Exergy Destruction Rate**	**Exergy Efficiency**
Air Compressor	$e_{D,AC} = e_1 - e_2 + \dot{W}_{AC}$	$\eta_{ex,AC} = \frac{e_2 - e_1}{\dot{W}_{AC}}$
Combustion Chamber	$e_{D,CC} = e_3 + e_f - e_4$	$\eta_{ex,CC} = \frac{e_4}{e_3 + e_f}$
Gas Turbine	$e_{D,GT} = (e_4 - e_5) - \dot{W}_{GT}$	$\eta_{ex,GT} = \frac{\dot{W}_{GT}}{e_4 - e_5}$
Regenerator	$e_{D,R} = (e_2 - e_3) + (e_5 - e_6)$	$\eta_{ex,AP} = 1 - \frac{e_{D,AP}}{\sum_{i,AP} e}$
Process Heater	$e_{D,PH} = (e_6 - e_7) - \mathrm{m}_w(e_9 - e_8)$	$\eta_{ex,PH} = 1 - \frac{e_{D,PH}}{\sum_{i,PH} e}$

The operating conditions for base case of the gas turbine power plant such as fuel mass flow rate and calorific value, output electrical power and efficiencies of compressor and GT are listed in Table 3.6.

Table 3.6 Operating conditions of cogeneration cycle power plant

Name	**Unit**	**Value**
Output Power	MW	30
Process Heat	kJ	37722
Lower Heating Value of fuel	kJ/kg	50196.96
Pressure loss in regenerator air side	%	5
Pressure loss in regenerator flue gas side	%	3
Pressure loss in combustion chamber	%	5
Pressure loss in HRSG	%	5
Heat loss in combustion chamber	%	2

3.2.7. COMPUTER SIMULATION

Mathematical modeling is done on the basis of exergy, energy and mass balance across the components and a computer program is executed in the software Engineering Equation Solver (EES) for a 30 MW co-generation plant. The carefully designed program does not restrict further developments or modifications with respect to the system. In Figure 3.24 a generalized design philosophy of a simple CGCPP is shown in the form of a flow chart. Information flow diagram for the simulation of cogeneration cycle is shown in Figure 3.25. Results obtained from the code developed in this section are compared with the results available in literature and are found in good agreement with them.

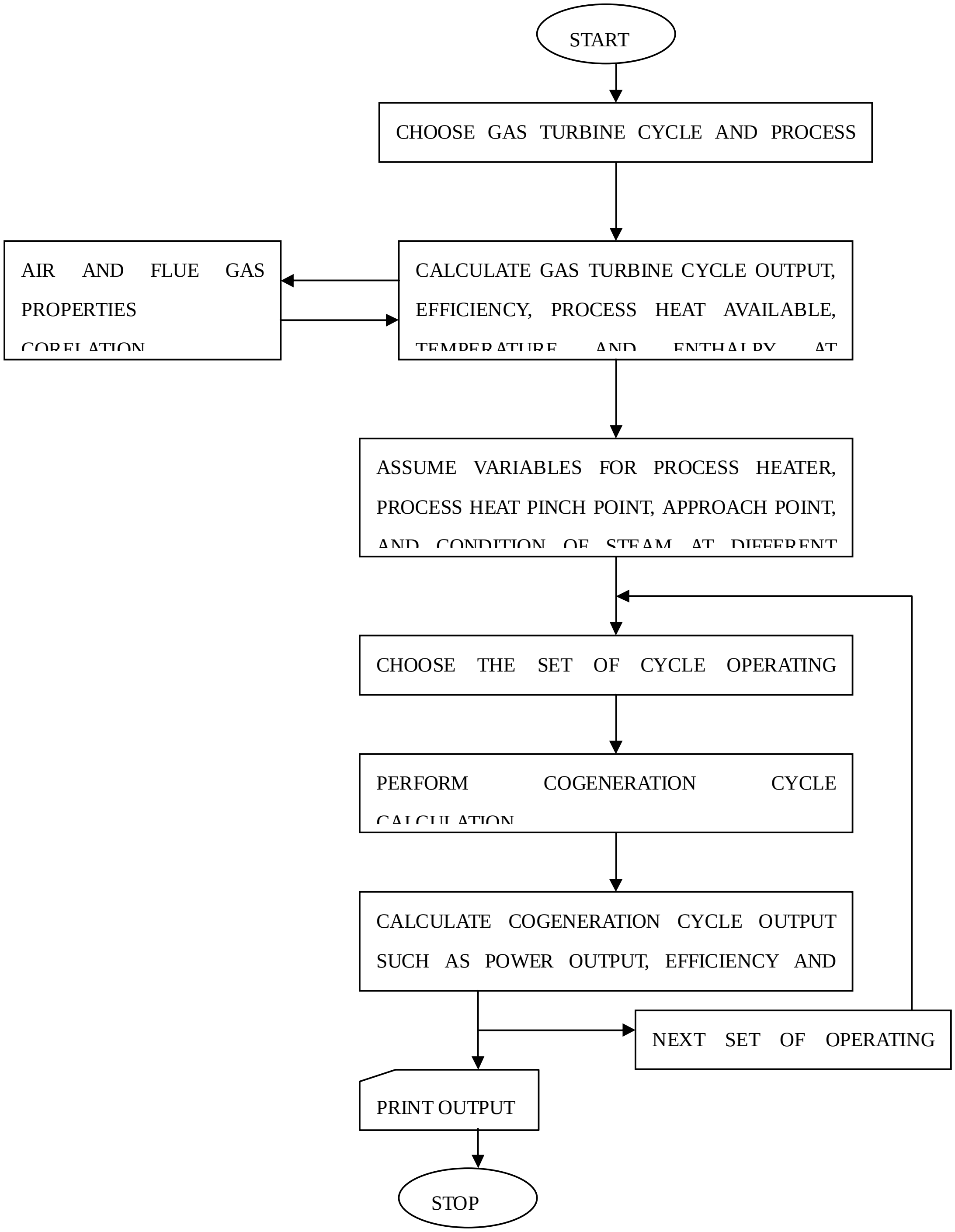


Figure 3.24 Flow chart for design philosophy of a simple CGCPP

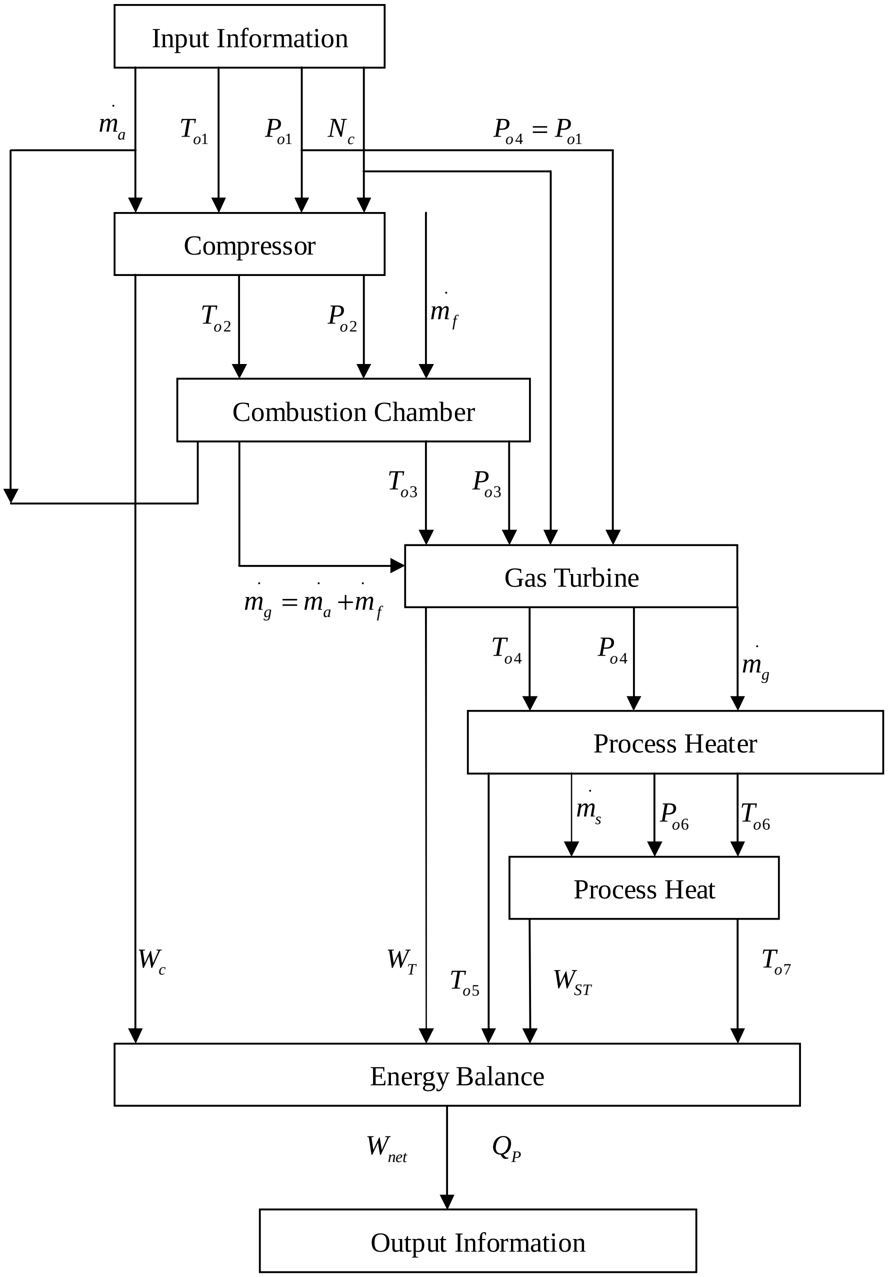


Figure 3.25 Information flow diagram of a simple cogeneration cycle

CHAPTER-IV

RESULTS AND DISCUSSIONS

In this chapter results of the GTA for the CCPP and CGCPP and thermodynamic analysis of CGCPP are discussed. Results obtained with thermodynamic modelling are found to be helpful in the identification and quantification of design parameters. In the next section results of the GTA are discussed.

4.1. CCPP ANALYSIS USING GTA

Methodology developed in the last chapter for the evaluation of CCPP performance, RTRI and RTEI is used in this chapter to calculate the index and importance of these indexes is discussed afterwards. The methodology developed is demonstrated with the help of examples.

4.1.1. PERFORMANCE ANALYSIS

For the performance analysis using GTA, it is desired to develop SSG and VPSSM for the CCPP system. In sections 3.1.1.1 and 3.1.1.2 SSG and VPSSM for CCPP are developed. Corresponding to VPSSM, a VPSSF is developed in section 3.1.1.3. For the performance assessment values of different elements are assigned in the matrix (3.7). Diagonal elements in expression (3.7) are the inheritance of systems and signify the importance of system in power plant performance. If a system is having higher inheritance and interdependencies then any change in the performance of this system will affect the power plant more than other systems. Values for the off-diagonal elements represent interdependencies amongst systems and explanation of quantification on the basis of Table 3.2 is as following.

In CCPP performance of combustion chamber is dependent upon the ambient conditions, combustion chamber efficiency and air compressor outlet temperature. Performance of air compressor has a direct effect on the performance of combustion chamber and that is why c_{12} is assigned a value of 5.

Compressed air from the compressor is sent to the gas turbine for the cooling of gas turbine blades. This cooling air decreases the temperature of flue gases in the gas turbine. Their effect is not much pronounced and hence c_{13} is assigned with the value of 3.

Gas turbine and air compressor are attached with each other and power to drive the compressor comes from the turbine. But there is no power transfer from combustion chamber to the air compressor. Therefore, c_{21} is assigned value 0 and c_{31} as 3.

After combustion in combustion chamber flue gas enter the gas turbine. As the performance of gas turbine is dependent upon the condition of flue gas coming out of combustion chamber and gas turbine efficiency, a value of 5 is given to c_{23}. When the Gas Turbine operates at design base loads with inlet guide vanes in open position, the Gas Turbine internal polytropic losses are at its minimum. On the other hand the Gas Turbine internal polytropic losses increase when the Gas Turbine operates at part loads with inlet guide vanes partially open. In present example gas turbine is considered to be operating at full load.

In HRSG, waste heat of flue gases is transferred to water and pressurized water is converted in to superheated steam. As HRSG is next to gas turbine, therefore, its performance is more affected by the gas turbine than combustion chamber and c_{34} is given a value of 4. c_{42} is with 2 because combustion chamber performance has weak dependence on HRSG.

Steam generated in HRSG is at high temperature and pressure. Its thermal energy is converted in to mechanical energy by steam turbine and further to electric energy by turbo-generator. Performance of steam turbine depends upon the condition of steam, steam turbine efficiency and generator losses. The generator losses and efficiency depend mainly on the generator cooling. Hydrogen’s low density, high specific heat and thermal conductivity make it a superior coolant for rotating electrical machines and it lends itself to a compact, highly efficient, reliable design. For the present analysis generator losses are considered under the steam turbine losses. Due to very high effect of steam condition on steam turbine performance, c_{45} is assigned a value of 5.

There are water losses in the steam cycle. The extra amount of water comes from the water system. Therefore, c_{64} is taken as 3. The temperature of steam entering the steam turbine is controlled by spraying extra amount of water. Steam turbine system and water system affects each other equally. Therefore c_{65} and c_{56} are given an equal value of 3. Some amount of steam is taken from the HRSG which goes to water system and helps in water purification. As this amount of steam is not very high, c_{46} is assigned value of 2. All other non-diagonal elements are assigned a value of zero because it is supposed that they are not affecting the plant performance at present.

All these values are assigned in the expression (3.7) and inheritance of all the elements is taken to be nine because it is supposed that they will be performing to their best. Resultant expression is as shown below.

$$P_c = \begin{bmatrix} 9 & 5 & 3 & 0 & 0 & 0 \\ 0 & 9 & 5 & 0 & 0 & 0 \\ 3 & 0 & 9 & 4 & 0 & 0 \\ 0 & 2 & 0 & 9 & 5 & 2 \\ 0 & 0 & 0 & 0 & 9 & 3 \\ 0 & 0 & 0 & 3 & 3 & 9 \end{bmatrix} \tag{4.1}$$

For the assessment of relative importance of six systems it is desired to know the performance index values (Per P_c) when it is performing its best and poorest. Therefore, inheritance of each system is varied from one to nine and index value is calculated using a computer program developed in language C^{++} and codes are attached as appendix-III. The system, for which the variance in performance index is highest, can be considered as the most important system of CCPP. Results obtained for the performance index are tabulated in Table 4.1.

Table.4.1 Change in CCPP index with change in the assigned values of factors

System	Assigned value of factors	Index Value	Change in Index Value
S_1	1	219033	617832
S_1	9	836865	
S_2	1	182385	654480
S_2	9	836865	
S_3	1	187833	649032
S_3	9	836865	
S_4	1	199665	637200
S_4	9	836865	
S_5	1	194985	641880
S_5	9	836865	
S_6	1	237465	599400
S_6	9	836865	

From the results it came out that combustion chamber system is the most important system of combined cycle power plant. Steam turbine system is most important system in steam turbine cycle. Index value for the CCPP performance is changed highest for the change in assigned value to the combustion chamber. After that gas turbine system, steam turbine system, HRSG system, air compressor system and water system are important in the decreasing order. In CCPP combustion chamber is responsible for the maximum losses. In combustion chamber losses are due to heat transfer and exergy destruction. These results are found in line with the published literature.

To face the challenges of World Trade Organization and ease the opportunities to remain competitive in global business free from trade barriers, following salient features of proposed methodology are identified:

1. It is a qualitative cum quantitative method for modeling CCPP performance.
2. It permits modeling of interactions/dependencies existing between factors/subsystems.
3. CCPP performance can be represented by graph theoretic, matrix and permanent function models.

4. Performance is quantified by a single numerical index representing its competitiveness and suitability.

5. These models can easily be modified to consider new factors/subsystems emerging with technological development.

6. Sensitivity analysis to identify the critical elements is easily carried out.

7. The method permits to generate alternative for CCPP performance improvement.

8. This is an effective tool for evaluation, comparison, ranking and selection of an optimum CCPP system.

Practical implementation of the proposed methodology in a systematic manner will help industry to identify, analyse and evaluate factors responsible for CCPP performance. Evaluation and comparison will also lead to identify critical areas that are roadblocks to CCPP performance. The CCPP performance index not only help an organization to achieve intangible objectives- better efficiency, reliability through continuous improvement but also have long lasting effects on tangible objective – profitability through productivity.

4.1.2. RELIABILITY ANALYSIS

For the demonstration of proposed methodology, failure of bearing lubricating oil cooler in a combined cycle power plant is taken as an example. For smooth revolution of turbo generator (TG), the bearings are lubricated through the lube oil system. The hot oil from the bearing is cooled through water cooler before feeding back into the lube oil tank. Suppose four coolers are used in series for this purpose. In the present analysis TG is considered a part of the steam turbine system. Now if one of the cooler is not available then the value of $RTRI_{CCPP}$ for the present case will be calculated as following:

Step 1: Consider the combined cycle power plant shown in Figure 3.1.

Step 2: Block diagram of CCPP system is shown in Figure 3.2.

Step 3: System reliability digraph (SRD) corresponding to the block diagram of CCPP (Figure 3.2) is shown in Figure 3.5.

Step 4: Under design conditions, it is presumed that all the six systems and components are available at their designed reliabilities during plant operation. Let reliability of these six systems be $(R_i)_d$ (i = 1, 2, . . . , 6). Let reliability of interconnections under designed conditions is denoted by $(r_{ij})_d$ (i, j = 1, 2, . . . , 6 and $i \neq j$). It is also assumed that all these interconnections are also available during operation at designed reliability. Then the variable permanent system designed reliability matrix for combined cycle power plant under consideration, i.e. $(Q_c)_d$ will be corresponding to matrix Q_c (equation 3.9).

$$(Q_c)_d = \begin{array}{cccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & Systems \\ \left[\begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array} \right. & \begin{array}{c} R_{1d} \\ 0 \\ r_{31d} \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} r_{12d} \\ R_{2d} \\ 0 \\ r_{42d} \\ 0 \\ 0 \end{array} & \begin{array}{c} r_{13d} \\ r_{23d} \\ R_{3d} \\ r_{43d} \\ 0 \\ 0 \end{array} & \begin{array}{c} 0 \\ 0 \\ r_{34d} \\ R_{4d} \\ r_{54d} \\ r_{64d} \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ r_{45d} \\ R_{5d} \\ r_{65d} \end{array} & \begin{array}{c} 0 \\ 0 \\ 0 \\ r_{46d} \\ r_{56d} \\ R_{6d} \end{array} \left. \begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array} \right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \qquad (4.2)$$

The matrices Q_c and $(Q_c)_d$ are similar and number of nodes and interconnections among the nodes are same. If $(R_i)_d = R_i$ and $(r_{ij})_d = r_{ij}$, then the values of Per (Q_c) and Per$(Q_c)_d$ will be equal. Therefore, in this case $RTRI_{CCPP}$ = 1. The Per $(Q_c)_d$ value gives the measure of designed reliability of combined cycle power plant, i.e. under the conditions when all its systems and subsystems, and the interconnection between them are available at their designed reliability. This condition exists only during the performance guarantee tests, which are conducted at the time of handing over a newly commissioned power plant (Mohan et al., 2008). Thereafter, the reliability of various systems and subsystems during operation starts falling below their designed values, and is required to be restored back by adopting proper maintenance strategies (Mohan et al., 2004). On the other hand, the Per$(Q_c)_{RT}$

represents reliability function of combined cycle power plant under normal operating conditions or real-time conditions when all the systems and subsystems are available but may not be operating at their designed reliabilities.

In real time situation, if one of the four coolers are out, real-time reliability gets reduced to three-fourth of its design value and correspondingly the value of R_{5d} will also get reduced to its three-fourth. The real-time value of $(Q_c)_{RT}$ in this case will be obtained by replacing in matrix (equation 4.2), the values of R_{5d} and r_{56d}, r_{64d} and r_{65d} by their three-fourth values: three-fourth R_{5d}, three-fourth r_{56d}, three-fourth r_{64d}, and three-fourth r_{65d}, respectively. Since the reliability, R_{5d}, of steam turbine system is getting reduced; it will correspondingly limit the reliability of the interconnections connected with this system (Figure 3.5), e.g. r_{56d}, r_{64d} and r_{65d}. Then from the matrix, equation (4.2), the value of $(Q_c)_{RT}$ is

$$\left(Q_c\right)_{RT} = \begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & Systems \\ \begin{bmatrix} R_{1d} & r_{12d} & r_{13d} & 0 & 0 & 0 \\ 0 & R_{2d} & r_{23d} & 0 & 0 & 0 \\ r_{31d} & 0 & R_{3d} & r_{34d} & 0 & 0 \\ 0 & r_{42d} & r_{43d} & R_{4d} & r_{45d} & r_{46d} \\ 0 & 0 & 0 & 0.75R_{54d} & 0.75R_{5d} & 0.75r_{56d} \\ 0 & 0 & 0 & 0.75r_{64d} & 0.75r_{65d} & R_{6d} \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \tag{4.3}$$

Step 5: Assuming that the reliability of R_{id}s and r_{ijd} is equal to unity then value for permanent function of matrix in equation (4.2), will be equal to 22 and matrix in equation (4.3) will be equal to 13.88.

Step 6: RTRI is the ratio of real time reliability, i.e. $(\text{Reliability})_{RT}$ to the designed reliability that is $(\text{Reliability})_D$ and is expressed as

$$RTRI_{CCPP} = \frac{(\text{Reliability})_{RT}}{(\text{Reliability})_{D}} = \frac{(VPF - r)_{RT}}{(VPF - r)_{D}} \tag{4.4}$$

Therefore the RTRI for this case is = 13.88/22 = 0.631 of its designed value.

Based on the value of RTRI, the operating staff can adjust the process performance, e.g. reduce the electricity generation so as to match with the real-time reliability value. In case plant is allowed to run above the reliability index, it will lead to inefficient and unsafe operations which may lead to safety hazards or complete shut down at a later stage.

A methodology based on GTA is developed for evaluating Real Time Reliability Index for combined cycle power plant. Using this procedure, an appropriate maintenance strategy for any combined cycle power plant can also be recommended. The proposed structural approach for the evaluation of real-time reliability index for a CCPP has the following features:

- Reliability assessment of power plant is more accurate with graph theory as quantitative measure of interrelations among different systems is taken care of.
- Graph theoretic model is flexible enough to add on different systems, subsystems of and interaction among them in reliability analysis of a CCPP.
- The methodology is proficient in quantifying the influence of various system, subsystems and parameters on the reliability of power plant.
- The value of real-time reliability index is useful for designers in selecting an optimum design in terms of reliability from available alternatives.
- The real-time reliability index enables the plant manager to know the reliable availability of power plant on real-time basis which will help them to take commercial decision on real-time basis.
- Sensitivity analysis may be carried out to identify the critical component or system affecting the power plant reliability.

Practical implementation of the proposed methodology in a systematic manner will help power generation industry to identify, categorize, analyse and evaluate parameters responsible for CCPP reliability. Thus, CCPP reliability index will help an organization to carry out SWOT (strength-weakness-opportunities-threats) of their system and take strategic decision to achieve profitability through productivity.

4.1.3. EFFICIENCY ANALYSIS

In this section the value of CCPP efficiency is calculated. For this purpose, some numerical values of all parameters and their interdependencies are required i.e. the value of all terms of VPM_{CCPP} (expression 3.13). The value of diagonal elements in VPM_{CCPP}, i.e., the value of all six systems D_1, D_2, D_3, $D_{4,}$ D_5 and D_6 are evaluated by applying GTA for design parameters of the respective system. The methodology explained in section 3.1.3 is used to evaluate CCPP efficiency index.

1. Various system categories affecting the CCPP efficiency are identified and presented in Figure 3.2.
2. A digraph is developed for these six systems as shown in Figure 3.7.
3. Design parameters are identified for each category of CCPP system and presented in Figure 3.9.
4. Digraphs for each system have been developed in section 3.1.3.5 and they are represented by figures from 3.10 to 3.15.
5. At system level, Tables 3.1 and 3.2 are used to determine numerical values for inheritance of parameters and their interactions. The VPSEPM for six systems are corresponding to equations from 3.16 to 3.21 and after quantification they are as written below:

$$E^1 = VPM_{AirCompressor} = \begin{array}{cc} \begin{array}{cccccc} E_1^1 & \mathrm{E}_2^1 & \mathrm{E}_3^1 & \mathrm{E}_4^1 & \mathrm{E}_5^1 & \mathrm{E}_6^1 \end{array} & \textit{Design Parameters} \\ \left[\begin{array}{cccccc} 9 & 3 & 4 & 0 & 3 & 5 \\ 0 & 1 & 0 & 0 & 0 & 2 \\ 0 & 0 & 9 & 5 & 4 & 0 \\ 0 & 0 & 3 & 5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 3 \end{array}\right] & \begin{array}{c} E_1^1 \\ E_2^1 \\ E_3^1 \\ E_4^1 \\ E_5^1 \\ E_6^1 \end{array} \end{array} \tag{4.5}$$

$$E^2 = VPM_{CombustionChamber} = \begin{array}{cc} \begin{array}{cccccccccc} E_1^2 & E_2^2 & E_3^2 & E_4^2 & E_5^2 & E_6^2 & E_7^2 & E_8^2 & E_9^2 & E_{10}^2 \end{array} & \textit{Design Parameters} \\ \left[\begin{array}{cccccccccc} 9 & 0 & 0 & 5 & 0 & 4 & 4 & 0 & 2 & 1 \\ 0 & 9 & 0 & 5 & 1 & 5 & 0 & 0 & 0 & 3 \\ 0 & 0 & 8 & 3 & 1 & 2 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5 & 0 & 0 & 4 & 4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & 3 & 1 \\ 0 & 0 & 0 & 1 & 0 & 4 & 7 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 6 \end{array}\right] & \begin{array}{c} E_1^2 \\ E_2^2 \\ E_3^2 \\ E_4^2 \\ E_5^2 \\ E_6^2 \\ E_7^2 \\ E_8^2 \\ E_9^2 \\ E_{10}^2 \end{array} \end{array} \tag{4.6}$$

$$E^3 = VPM_{GasTurbine} = \begin{array}{cc} \begin{array}{cccccccc} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 \end{array} & \textit{Design Parameters} \\ \left[\begin{array}{cccccccc} 9 & 0 & 4 & 5 & 0 & 0 & 0 & 0 \\ 0 & 8 & 1 & 0 & 4 & 5 & 0 & 3 \\ 0 & 0 & 9 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 6 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 6 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{array}\right] & \begin{array}{c} E_1^3 \\ E_2^3 \\ E_3^3 \\ E_4^3 \\ E_5^3 \\ E_6^3 \\ E_7^3 \\ E_8^3 \end{array} \end{array} \tag{4.7}$$

$$E^4 = VPM_{HRSG} = \begin{array}{cccccccccc} E_1^4 & E_2^4 & E_3^4 & E_4^4 & E_5^4 & E_6^4 & E_7^4 & E_8^4 & E_9^4 & \textit{Design Parameters} \\ 9 & 0 & 2 & 0 & 4 & 0 & 1 & 0 & 0 & E_1^4 \\ 0 & 9 & 4 & 5 & 3 & 2 & 1 & 5 & 0 & E_2^4 \\ 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & E_3^4 \\ 0 & 0 & 3 & 6 & 0 & 0 & 1 & 1 & 0 & E_4^4 \\ 0 & 0 & 4 & 0 & 8 & 2 & 5 & 1 & 0 & E_5^4 \\ 0 & 0 & 4 & 0 & 0 & 6 & 0 & 0 & 0 & E_6^4 \\ 5 & 0 & 4 & 0 & 3 & 0 & 7 & 0 & 0 & E_7^4 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 5 & 0 & E_8^4 \\ 0 & 0 & 4 & 0 & 0 & 0 & 5 & 0 & 7 & E_9^4 \end{array} \tag{4.8}$$

$$E^5 = VPM_{SteamTurbine} = \begin{array}{ccccccccccc} E_1^5 & E_2^5 & E_3^5 & E_4^5 & E_5^5 & E_6^5 & E_7^5 & E_8^5 & E_9^5 & E_{10}^5 & \textit{Design Parameters} \\ 9 & 2 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_1^5 \\ 2 & 9 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & E_2^5 \\ 0 & 0 & 9 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & E_3^5 \\ 0 & 0 & 2 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & E_4^5 \\ 0 & 0 & 4 & 4 & 8 & 0 & 0 & 0 & 0 & 0 & E_5^5 \\ 0 & 0 & 0 & 0 & 0 & 7 & 0 & 0 & 4 & 3 & E_6^5 \\ 0 & 0 & 4 & 4 & 0 & 0 & 9 & 0 & 0 & 0 & E_7^5 \\ 0 & 0 & 0 & 0 & 3 & 0 & 0 & 5 & 5 & 0 & E_8^5 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 5 & 0 & E_9^5 \\ 0 & 0 & 3 & 3 & 0 & 0 & 0 & 0 & 0 & 4 & E_{10}^5 \end{array} \tag{4.9}$$

$$E^6 = VPM_{WaterSystem} = \begin{array}{cccccc} E_1^6 & \mathrm{E}_2^6 & \mathrm{E}_3^6 & \mathrm{E}_4^6 & \mathrm{E}_5^6 & \textit{Design Parameters} \\ 9 & 5 & 0 & 0 & 0 & E_1^6 \\ 0 & 7 & 0 & 0 & 5 & E_2^6 \\ 0 & 0 & 7 & 5 & 0 & E_3^6 \\ 0 & 3 & 0 & 9 & 0 & E_4^6 \\ 0 & 0 & 0 & 0 & 7 & E_5^6 \end{array} \tag{4.10}$$

6. The value of permanent function for each category is calculated using a computer programme developed in language C^{++}. The values of permanent function of different systems are written as under:

Per [E^1] = 1620

Per [E^2] = $2.3882 \text{ X } 10^7$

Per [E^3] = 186624

Per [E^4] = $4.5730 \text{ X } 10^7$

Per [E^5] = $3.6414 \text{ X } 10^8$

Per [E^6] = 27783

7. Now for example Turbine Inlet Temperature (TIT) is decreased from 1300°C to 1100°C and inheritance of is 7 in place 8, then expression (4.7) will become

$$VPM_{GasTurbine\mathrm{Re}alTime} = \begin{array}{cc} \begin{matrix} E_1^3 & E_2^3 & E_3^3 & E_4^3 & E_5^3 & E_6^3 & E_7^3 & E_8^3 \end{matrix} & \textit{Design Parameters} \\ \begin{bmatrix} 9 & 0 & 4 & 5 & 0 & 0 & 0 & 0 \\ 0 & 7 & 1 & 0 & 4 & 5 & 0 & 3 \\ 0 & 0 & 9 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 6 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 & 6 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix} & \begin{matrix} E_1^3 \\ E_2^3 \\ E_3^3 \\ E_4^3 \\ E_5^3 \\ E_6^3 \\ E_7^3 \\ E_8^3 \end{matrix} \end{array} \tag{4.11}$$

and $VPM_{GasTurbineDesign}$ will be as expression (4.7). The value of RTEI for gas turbine is calculated as expression (3.25). It is the ratio of permanent function of matrix of expression (4.11) to (4.7). Let the permanent functions of (4.11) and (4.7) are represented by (VPF-e gas turbine)$_{\mathrm{RealTime}}$ and (VPF-e gas turbine)$_{\mathrm{Design}}$ then RTEI for gas turbine is represented by the expression as following:

$$RTEI_{GASTURBINE} = \frac{(VPF - e \text{ gas turbine})_{\mathrm{Re}alTime}}{(VPF - e \text{ gas turbine})_{Design}} = \frac{163296}{186624} = .875 \tag{4.12}$$

8. In the plant when all the systems are working at their design value then RTEI for each system will be 1. If it is not working at designed conditions then value for RTEI is between 0 and 1. If all the systems of CCPP are working at their maximum efficiency, which is the ideal case, then VPSEM for CCPP system corresponding to the expression (3.12) is:

$$VPM_{CCPPIsentropic}=\begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & Systems \\ \begin{bmatrix} 9 & 5 & 3 & 0 & 0 & 0 \\ 0 & 9 & 5 & 0 & 0 & 0 \\ 3 & 0 & 9 & 4 & 0 & 0 \\ 0 & 2 & 5 & 9 & 5 & 2 \\ 0 & 0 & 0 & 3 & 9 & 3 \\ 0 & 0 & 0 & 3 & 3 & 9 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (4.13)$$

But for a practical system, it is not possible to give 100% efficiency. In actual life power plant is performing its best when it is operating at design conditions. Design specifications for CCPP with gas turbine V94.3 are given in appendix-IV. Corresponding to these design specifications, the quantified values of inheritance for air compressor system, combustion chamber system, gas turbine system, HRSG system, steam turbine system and water system is obtained iteratively and these are 8.5, 7, 8.5, 8, 8.5 and 7 respectively. Corresponding to the design efficiency of different systems of CCPP, VPSEM is as given below:

$$VPM_{CCPPDesign}=\begin{array}{cc} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} & Systems \\ \begin{bmatrix} 8.5 & 5 & 3 & 0 & 0 & 0 \\ 0 & 7 & 5 & 0 & 0 & 0 \\ 3 & 0 & 8.5 & 4 & 0 & 0 \\ 0 & 2 & 5 & 8 & 5 & 2 \\ 0 & 0 & 0 & 3 & 8.5 & 3 \\ 0 & 0 & 0 & 3 & 3 & 7 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (4.14)$$

The quantification of diagonal and non diagonal elements in the matrices (4.13) and (4.14) are done corresponding to the data available in the literature (Bolland, 1991). For the validation of methodology, data available in literature (Bolland, 1991) for other configuration is also used. Efficiency for a CCPP is the ratio of permanent of equation (4.14) to the permanent of equation (4.13).

$$Efficiency_{CCPP} = \frac{Per(VPM_{CCPPDesign})}{Per(VPM_{CCPPIsentropic})} \times 100 = \frac{598561}{1118070} \times 100 = 53.54\% \qquad (4.15)$$

In the similar manner results obtained for the other configurations are shown in the Table 4.2 and they are found in good agreement with the results available in literature. The values of inheritance for different systems are considered on the basis of design data available in literature (Bolland, 1991) and reproduced in appendix-IV.

Table 4.2 Comparison of results for CCPP efficiency

Type of cycle	V94.3 η_{ccpp} (%) (Bolland, 1991)	V94.3 η_{ccpp} (%) (GTA)
Dual pressure	53.61	53.54
Dual pressure reheat	54.06	53.92
Dual pressure with supercritical reheat	54.60	54.72
Triple pressure	54.12	54.32
Triple pressure reheat	54.57	54.72
Triple pressure with supercritical reheat	55.03	55.12

As calculated in step 7, for the decrease in TIT from 1300°C to 1100°C RTEI for gas turbine system is 0.875 of the designed value. Therefore, $VPM_{CCPP\,\mathrm{Re}alTime}$ corresponding to expression (4.14) is written as following:

$$VPM_{CCPP\,\mathrm{Re}alTime} = \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \end{array}\begin{array}{cccccc|c} 1 & 2 & 3 & 4 & 5 & 6 & Systems \\ 8.5 & 5 & 3 & 0 & 0 & 0 & 1 \\ 0 & 7 & 5 & 0 & 0 & 0 & 2 \\ 3 & 0 & (.875\times 8.5) & 4 & 0 & 0 & 3 \\ 0 & 2 & 5 & 8 & 5 & 2 & 4 \\ 0 & 0 & 0 & 3 & 8.5 & 3 & 5 \\ 0 & 0 & 0 & 3 & 3 & 7 & 6 \end{array}$$

(4.16)

9. Value of permanent function for the design case (expression 4.14) is 1118070 and for the real time case (expression 4.16) is 548361. Value of real time efficiency for CCPP comes out to be 49.04%. From the GTA it came out that with decrease in TIT from 1300°C to 1100°C, efficiency is decreased from 53.54% to 49.04%. Results obtained from GTA are in agreement with the results available in literature.
10. CCPP efficiency calculated with the help of GTA, depends upon the inheritance and interdependencies of systems and design parameters. By carrying out similar analysis, the efficiency index for different CCPP system can be obtained.

The increasing or decreasing order of efficiency is just for ranking of power plants but managers should mainly focus on the performance parameters according to which some major decision regarding power plant performance on efficiency basis can be taken. RTEI may be used for the following analysis.

1. Index may be used to evaluate the efficiency of combined cycle power plant in real time situation and it may be used to compare with the design value of the index. From this weak parameters

may be identified and improved so that plant may achieve design value.

2. Efficiency index may be used in combination with other operating parameters such as reliability and performance of power plant may be represented by single numerical index which is easy to analyse.
3. Efficiency of two or more real life operating power plants may be compared with the help of index and they may be arranged in the descending order of their efficiency.
4. If any suggestion is given by some manufacturer for the improvement in the plant then some quantitative results may be calculated to check weather the improvement is beneficial or not.

In the era of competition, early decision with the help of some mathematical method with logical reasoning is helpful to make the presence in global market. A complex and large system such as CCPP require analysing large number of operating parameters to achieve the goal of organisation. For this purpose the methodology developed in this section may be helpful to take the organization one step forward.

The RTRI and RTEI developed in the sections 4.1.2 and 4.1.3 are used to calculate composite index for efficiency and reliability as given in the expression (3.29). For the present analysis it is supposed that reliability and efficiency are completely dependent on each other. Therefore, non diagonal elements are assigned value of one and performance parameter permanent matrix for CIER for design and real time situation are

$$J_{Design} = \begin{bmatrix} 1 & 1 \\ 1 & .5354 \end{bmatrix} \tag{4.17}$$

and

$$J_{\mathrm{Re}alTime} = \begin{bmatrix} 1 & 1 \\ 1 & .4904 \end{bmatrix} \tag{4.18}$$

The value of the permanent function for CIER, when TIT is changed from 1300°C to 1100°C, corresponding to the expression (4.17) and (4.18) are 1.5354 and 1.4904 respectively. The data in expression (4.17) and (4.18) is taken only for the demonstration of methodology. The CIER can be used to evaluate CCPP performance in association of efficiency and reliability for real life or designed condition.

4.2. CGCPP ANALYSIS USING GTA

Methodology developed in the last chapter for the evaluation of CGCPP performance, RTRI and RTEI is used in this section to calculate the index followed by discussion on importance of these indexes.

4.2.1. PERFORMANCE ANALYSIS

For demonstration of methodology developed in section 3.1.5 a CGCPP is taken as an example. It is proposed to find the value of CGCPP performance index. For determining the index, numerical values of inheritance of four systems and their interdependencies, i.e. in equation (3.31) are required. The value of VPSSF of expression (3.32) is calculated. It is suggested to find hypothetical best and hypothetical worst value of index.

Maximum value of Per [V_c] in expression (3.32) is obtained when inheritance of all systems is maximum, i.e. value taken from Table 3.1 is 9. The values of off diagonal elements are taken from Table 3.2 as explained below:

- Performance of air compressor has a direct effect on the performance of combustion chamber and that is why c_{12} is assigned a value of 5.
- Compressed air from the compressor is sent to the gas turbine for the cooling of gas turbine blades. This cooling air decreases the temperature of the combustion gases in the gas turbine. Their effect is not much pronounced and hence c_{13} is assigned with the value of 3.

- Gas turbine and air compressor is attached with each other and power to drive the compressor comes from the turbine. But there is no power transfer from combustion chamber to the air compressor. Therefore, c_{21} is assigned value 0 and c_{31} as 3. After combustion in combustion chamber flue gases enter the gas turbine. As the performance of gas turbine is dependent upon the condition of flue gases coming out of combustion chamber and gas turbine efficiency, a value of 5 is given to c_{23}.
- As process heater is at the outlet of gas turbine, therefore, its performance is more affected by the gas turbine than combustion chamber and c_{34} is given a value of 4. c_{42} is with 2 because combustion chamber performance has weak dependence on process heater.

Thus, expression (3.31) may be written for the maximum value of Per V_c as

$$P_1 = \begin{bmatrix} 9 & 5 & 3 & 0 \\ 0 & 9 & 5 & 0 \\ 3 & 0 & 9 & 4 \\ 0 & 2 & 0 & 9 \end{bmatrix} \tag{4.19}$$

The value of permanent of the above function is 8325, i.e. maximum Per $[V_c]$ = 8325.

Similarly CGCPP performance index is at its worst when the inheritance of all its systems is at its worst i.e. value taken from Table 3.1 is 1.

Thus, expression (3.31) may be rewritten for the minimum value of Per $[V_c]$ as

$$P_2 = \begin{bmatrix} 1 & 5 & 3 & 0 \\ 0 & 1 & 5 & 0 \\ 3 & 0 & 1 & 4 \\ 0 & 2 & 0 & 1 \end{bmatrix} \tag{4.20}$$

The value of permanent of the above function is 125, i.e. minimum Per [V_c] = 125.

The value of Per V_c indicates the value of CGCPP performance index. Thus, the maximum and minimum value of performance index indicates the range with in which it can vary. Experts can use this range to decide a threshold value for a given set of similar power plant.

Monitoring at regular interval may be carried out by third party to assess power plant performance. Moreover, the values may be carried out at regular interval for the assessment of power plant performance. To face the challenges of World Trade Organization and ease the opportunities to remain competitive in global business free from trade barriers, following salient features of proposed methodology are identified:

1. It is a qualitative cum quantitative method for modeling cogeneration cycle power plant performance.
2. It permits modeling of interactions/dependencies existing between systems.
3. Performance is quantified by a single numerical index representing its competitiveness and suitability.
4. These models can easily be modified to consider new factors/subsystems emerging with technological development.
5. This is a tool for evaluation, comparison, ranking and selection of an optimum cogeneration cycle power plant.

Thus, the CGCPP performance index not only help an organization to achieve intangible objectives- better efficiency, reliability through continuous improvement but also have long lasting effects on tangible objective – profitability through productivity.

4.2.2. RELIABILITY ANALYSIS

For the demonstration of the methodology developed in section (3.1.6), reliability of gas turbine is taken as an example. If the reliability of gas turbine is reduced to 90% of design value, then the value of $RTRI_{CGCPP}$ for the present case is calculated as following:

Step 1: Consider the cogeneration cycle power plant shown in Figure 3.17.

Step 2: System structure graph for the reliability of CGCPP system will be as shown in Figure 3.18.

Step 3: System reliability digraph (SRD) corresponding to the block diagram of CGCPP (Figure 3.18) is shown in Figure 3.21.

Step 4: Under design conditions, it is presumed that all the four systems and components are available at their designed reliabilities during plant operation. Let reliability of these four systems be $(A_i)_d$ (i = 1, 2, 3, 4). Let reliability of interconnections under designed conditions is denoted by $(a_{ij})_d$ (i, j = 1, 2, 3, 4 and $i \neq j$). It is also assumed that all these interconnections are also available during operation at designed reliability. Then the variable permanent system designed reliability matrix for CGCPP under consideration, i.e. $(B_c)_d$ is corresponding to matrix B_c (expression 3.33).

$$(B_c)_d = \begin{array}{cc} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} & Systems \\ \left[\begin{array}{cccc} A_{1d} & a_{12d} & a_{13d} & 0 \\ 0 & A_{2d} & a_{23d} & 0 \\ a_{31d} & 0 & A_{3d} & a_{34d} \\ 0 & a_{42d} & 0 & A_{4d} \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \end{array} \quad (4.21)$$

The matrices B_c and $(B_c)_d$ are similar and number of nodes and interconnections among the nodes are same. If $(A_i)_d = A_i$ and $(a_{ij})_d = a_{ij}$, then the values of Per (B_c) and Per$(B_c)_d$ is equal. Therefore, in this case $RTRI_{CGCPP}$ = 1. The Per $(B_c)_d$ value gives the measure of designed reliability of CGCPP, i.e. under the conditions when all its systems, and the interconnection between them are available at their designed reliability. This condition exists only during the performance guarantee tests, which are conducted at the time of handing over a newly commissioned power plant (Mohan et al., 2008). During operation the reliability of various systems starts falling below their designed values, and is required to be restored back by adopting proper maintenance strategies (Mohan et al., 2004). On the other hand, the Per$(B_c)_{RT}$ represents reliability function of CGCPP under normal operating conditions or real-time conditions when all the systems are available but may not be operating at their designed reliabilities.

In real time situation, if gas turbine reliability is reduced to 90% that of its designed value, then the value of A_{3d} will also get reduced to its 90%. The real-time value of $(B_c)_{RT}$ in this case will be obtained by replacing in matrix (expression 4.21), the values of A_{4d} and a_{31d}, a_{34d} and a_{42d} by their 90% values: $0.9A_{4d}$ and $0.9a_{31d}$, $0.9a_{34d}$ and $0.9a_{42d}$, respectively. Since the reliability, A_{3d}, of gas turbine system is getting reduced; it will correspondingly limit the reliability of the interconnections connected with this system (Figure 3.21), e.g. a_{31d}, a_{34d} and a_{42d}. Then from the matrix, equation (4.21), the value of $(B_c)_{RT}$ is

$$\begin{array}{cc} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} & \mathit{Systems} \\ (B_c)_{RT} = \begin{bmatrix} A_{1d} & a_{12d} & a_{13d} & 0 \\ 0 & A_{2d} & a_{23d} & 0 \\ 0.9a_{31d} & 0 & 0.9A_{3d} & 0.9a_{34d} \\ 0 & 0.9a_{42d} & 0 & A_{4d} \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \end{array} \qquad (4.22)$$

Step 5: Assuming that the reliability of A_{id} and a_{ijd} is equal to unity, as system is operating at designed reliability, then value for permanent function of matrix in equation (4.21), will be equal to 4 and matrix in equation (4.22) will be equal to 3.51.

Step 6: RTRI is the ratio of real time reliability, i.e. $(\text{Reliability})_{RT}$ to the designed reliability that is $(\text{Reliability})_D$ and is expressed as

$$RTRI_{CGCPP} = \frac{Reliability_{RTCGCPP}}{Reliability_{DCGCPP}} = \frac{(VPF - r)_{RTCGCPP}}{(VPF - r)_{DCGCPP}} \tag{4.23}$$

Therefore the RTRI for this case is = 3.51/4 = 0.8775 of its designed value.

Based on the value of RTRI, the operating staff can adjust the process performance, e.g. reduce the electricity generation so as to match with the real-time reliability value. In case plant is allowed to run above the design reliability index, it will lead to inefficient and unsafe operations which may lead to safety hazards or complete shut down at a later stage. After maintenance, the reliability of the plant will increase and it may be operated at full load. In this way by adjusting the load according the value of RTRI will lead to increased availability of the plant.

The value of Per $(B_c)_d$ is the maximum possible value or design value and can used for bench marking. The relative intensity of two or more fault conditions can also be evaluated by assessing the difference in the value of permanent function, under two or more different fault conditions.

The different values of permanent function for reliability at design condition for different CGCPPs are helpful in the finalization of the appropriate selection from the different available designs. CGCPP with maximum value of index will be having highest reliability.

4.2.3. EFFICIENCY ANALYSIS

The methodology explained in section 3.1.7 is explained below with the help of example.

1. Various systems affecting the CGCPP efficiency (four categories of system in the present case) are identified and presented in Figure 3.18.
2. A digraph is developed for these four system category as shown in Figure 3.22.
3. Design parameters are identified for air compressor, combustion chamber, gas turbine and

process heater system are presented in Figure 3.9. Design parameters for process heater are same as for HRSG.

4. Digraphs for four systems i.e. air compressor, combustion chamber, gas turbine and process heater are as shown in Figure 3.10, 3.11, 3.12 and 3.13 respectively.
5. Variable permanent matrix for digraphs shown in Figure 3.10, 3.11, 3.12 and 3.13 are also same as expressions (4.5), (4.6), (4.7) and (4.8) respectively.
6. The value of permanent function for each system is calculated and found to be as

Per $C_{AirCompressor} = 1620$

Per $C_{CombustionChamber} = 2.3882 \text{ X } 10^7$

Per $C_{GasTurbine} = 186624$

Per $C_{ProcessHeater} = 4.5730 \text{ X } 10^7$

7. Now for example ambient air temperature is increased from 5°C to 35°C and correspondingly inheritance of IAT is 8 in place 9 then expression (4.5) for the air compressor is as given by expression (4.24).

$$VPM_{AirCompressor\,RealTime} = \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{cccccc} C_1^1 & C_2^1 & C_3^1 & C_4^1 & C_5^1 & C_6^1 \end{array} \\ \begin{bmatrix} 8 & 3 & 4 & 0 & 3 & 5 \\ 0 & 1 & 0 & 0 & 0 & 2 \\ 0 & 0 & 9 & 5 & 4 & 0 \\ 0 & 0 & 3 & 5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 3 \end{bmatrix} \end{array} \begin{array}{c} \textit{Design Parameters} \\ C_1^1 \\ C_2^1 \\ C_3^1 \\ C_4^1 \\ C_5^1 \\ C_6^1 \end{array} \qquad (4.24)$$

The value of RTEI for air compressor is calculated with the help of expression (3.39). Let the permanent functions of (4.24) and (4.5) are represented by (VPF-e air compressor)$_{RealTime}$ and (VPF-e air compressor)$_{Design}$ then RTEI for air compressor will be represented by the expression as following:

$$RTEI_{AIRCOMPRESSOR} = \frac{(VPF - e\ air\ compressor)_{RealTime}}{(VPF - e\ air\ compressor)_{Design}} = \frac{1440}{1620} = .8889 \quad (4.25)$$

8. If all the systems of CGCPP are working at their maximum efficiency, which is the ideal case, then VPSEPM for CGCPP system, can be obtained after quantification in expression (3.36) and is as represented by expression (4.26).

$$VPM_{IsentropicCGCPP} = \begin{array}{cccccc} 1 & 2 & 3 & 4 & & Systems \\ \left[\begin{matrix} 9 \\ 0 \\ 3 \\ 0 \end{matrix}\right. & \begin{matrix} 5 \\ 9 \\ 0 \\ 2 \end{matrix} & \begin{matrix} 3 \\ 5 \\ 9 \\ 0 \end{matrix} & \left.\begin{matrix} 0 \\ 0 \\ 4 \\ 9 \end{matrix}\right] & & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \end{array} \quad (4.26)$$

In the plant when all the systems are working at their design value then VPM- Design becomes:

$$VPM_{DesignCGCPP} = \begin{array}{cccccc} 1 & 2 & 3 & 4 & & Systems \\ \left[\begin{matrix} 8 \\ 0 \\ 3 \\ 0 \end{matrix}\right. & \begin{matrix} 5 \\ 7 \\ 0 \\ 2 \end{matrix} & \begin{matrix} 3 \\ 5 \\ 8 \\ 0 \end{matrix} & \left.\begin{matrix} 0 \\ 0 \\ 4 \\ 7 \end{matrix}\right] & & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \end{array} \quad (4.27)$$

For the increase in IAT, inheritance of air compressor will also be reduced by 88.89% and VPM- Real Time for CGCPP is as written below

$$VPM_{RealTimeCGCPP} = \begin{array}{c} \\ \\ \\ \\ \\ \end{array}\begin{array}{cccc|c} 1 & 2 & 3 & 4 & Systems \\ \hline .8889\times 8 & 5 & 3 & 0 & 1 \\ 0 & 7 & 5 & 0 & 2 \\ 3 & 0 & 8 & 4 & 3 \\ 0 & 2 & 0 & 7 & 4 \end{array} \qquad (4.28)$$

9. Value of permanent function for the design case is 4422 and for the real time case is 4041.84. Design efficiency for the CGCPP is the ratio of expression (4.27) and (4.26) and in real time it is the ratio of expression (4.28) and (4.26). Then from expressions (4.25), (4.26) and (4.27), it came out that efficiency is decreased from 53.12% to 48.54% with increase in ambient air temperature from 5°C to 35°C. Results obtained by GTA are in good agreement with the obtained with mathematical modelling as explained in next section.

4.3 EXERGETIC ANALYSIS FOR QUANTIFICATION

With the help of mathematical modeling in section (3.2), effect of various design parameters on the I^{st} and II^{nd} law efficiency of CGCPP is observed. The results obtained from the computer program executed in software EES (appendix-VI) are found in line with the results available in literature (Bejan et al., 1996) and a comparison is given in appendix-VII. The results obtained can be used for identification, quantification and validation of design parameters in GTA.

4.3.1. EFFECT OF CYCLE RATIO

For the present analysis CR is varied from 5 to 26. After CR-26, regenerator is not found useful in the cycle. Exergy is consumed during real processes, and conserved during ideal processes. The exergy consumption during a process is proportional to the entropy created due to process irreversibility. Exergy destruction in the cogeneration cycle is least at CR-15. Exergy destruction in combustion chamber, process heater and regenerator is decreased by 8.13%, 16.04% and 80.87% respectively for increase in CR from 5 to 15 and in air compressor and gas turbine is increased by 15.38% and 58.50% respectively. Exergy destruction in cycle is decreased by 15.92%. Combustion chamber is the source of highest exergy destruction 66.09%. After combustion chamber; regenerator, process heater, gas turbine and air compressor are the source of exergy destruction in decreasing order respectively

In gas turbine cycle, gas turbine is directly connected to compressor. Gas turbine develop power for the generator and as well as for the compressor also. Due to which work produced by gas turbine is more than air compressor. This leads to more exergy destruction in gas turbine than air compressor. Exergy destruction in combustion chamber is related to the amount of fuel consumed in combustion chamber. Most of irreversibility within the combustor is due to internal heat transfer between the products and reactants.

Heat transfer in a heat exchanger is an irreversible process, therefore exergy losses occur. The total exergy losses comprise the losses from the irreversible heat transfer and the losses due to the friction of both fluids. In a conventional heat exchanger, entropy is created (or exergy destroyed) in four elementary processes: heat transfer from the hot fluid to the wall, heat transfer from the wall to the cold fluid, momentum transfer (loss of mechanical energy) by friction in both fluids. The exergy losses due to friction for the liquid flow (small specific volume) are relatively small (Khaliq and Kaushik, 2004).

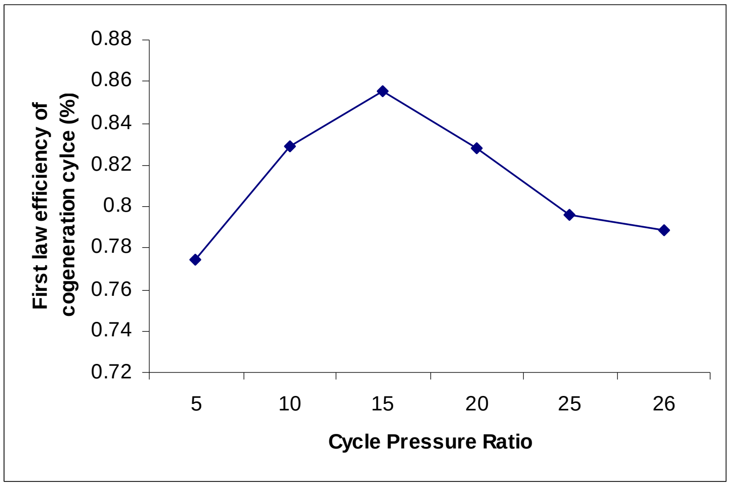


Figure 4.1 Effect of cycle pressure ratio on the efficiency of cogeneration cycle

First law efficiency of cogeneration cycle depends upon the fuel consumed in the cycle. At CR 15 fuel consumption in cycle is least, due to which maximum first law efficiency is at CR 15 that is 85.49% (Figure 4.1). With increase in CR from 5 to 15, efficiency is increased by 8.08%. Fuel consumption after CR-15 increases to maintain constant heat transfer in regenerator which is achieved by increasing air mass flow rate in the cycle.

The key performance characteristic of the gas turbine that influences cycle performance is specific power. Specific power is the power produced by the gas turbine per unit of airflow (kW output per kg/s of compressor airflow). At CR 15 maximum specific power of gas turbine is observed (Figure 4.2). With increase in CR from 5 to 15, specific power in increased by 26.22%. Cogeneration-cycle thermal efficiency increases as gas turbine specific power increases. Gas turbine firing temperature is the primary determinant of specific power. Improvements in cycle thermal efficiency have developed primarily through the increases in gas turbine firing temperature, which have resulted from the development of high-temperature / high strength materials, corrosion-resistant coatings, and improved cooling technology.

Commercial development and improvements in efficiency of cogeneration cycles have proceeded in parallel with advances in gas turbine technology. From the results it is found that Turbine Outlet Temperature (TOT) of 524°C is uniquely suited to efficient cogeneration cycle because it enables the transfer of heat from exhaust gas to the steam cycle to take place over a minimal temperature difference. This temperature range results in the maximum in thermodynamic availability while operating at highest temperature and efficiency.

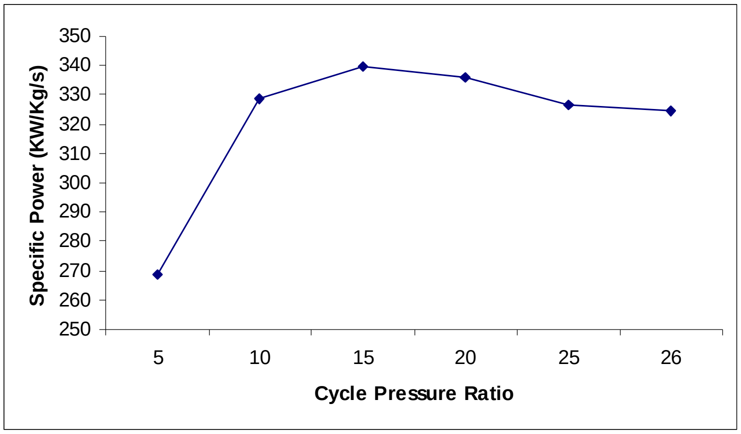
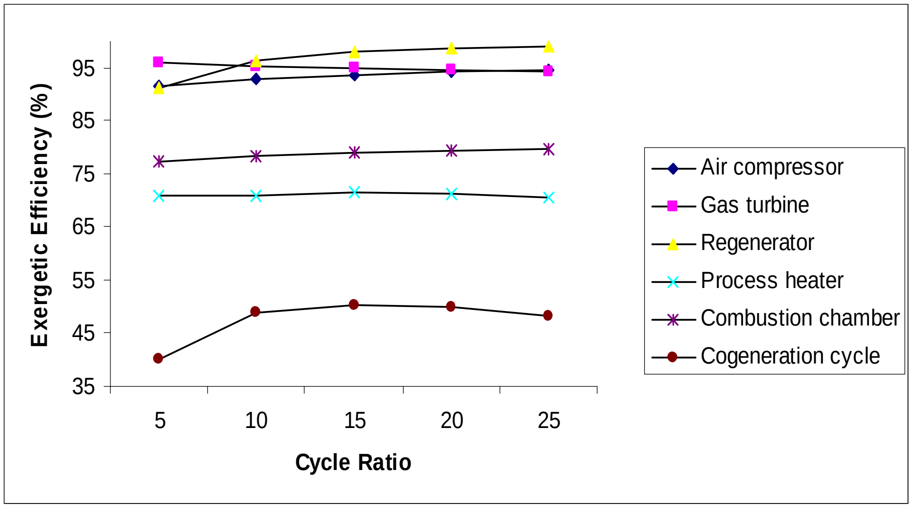


Figure 4.2 Effect of cycle pressure ratio on the specific power of gas turbine

Exergetic efficiency calculated for the different components shows that exergetic efficiency for gas turbine and process heater is decreased by 1.58% and 0.22% respectively with increase in CR from 5 to 25 and for air compressor, regenerator and combustion chamber is increased by 3%, 7.92% and 2.42% respectively (Figure 4.3). The maximum exergetic efficiency of the cycle is 50.4% at CR of 15. Therefore, the first law efficiency and second law efficiency follows the same pattern with change in CR.



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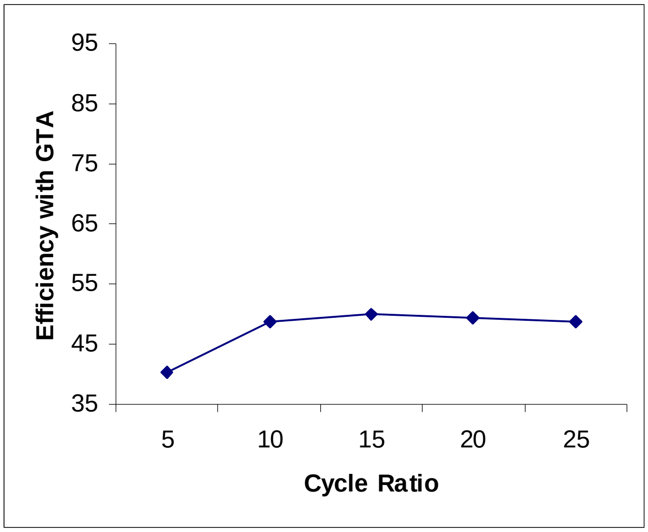


(b)

Figure 4.3 (a) Effect of cycle ratio on exergetic efficiency of different components of the cycle (b) Efficiency of the cycle calculated by GTA for different CR

Iterative values of inheritance of CR as given in Table 1 of appendix-V are found to be appropriate for quantification for calculating the efficiency of CGCPP corresponding to the methodology explained in section in 4.2.3. Results obtained are found in line with that of exergetic analysis (Figure 4.3).

The first law of thermodynamics gives partial answer for the performance of a thermodynamic cycle and it is concerned only with the conversion of energy, therefore it cannot show how or where irreversibility in a system or process occur. Thus, while producing the final design result, first law analysis has to be incorporate with second law for locating sources of thermodynamic losses. In the next section effect of inlet air temperature on the performance of cogeneration cycle is discussed.

4.3.2. EFFECT OF INLET AIR TEMPERATURE

The difference between the actual power generated and efficiency of a gas turbine and the design rated power and efficiency tagged on the gas turbine has to be observed whenever a gas turbine operates at site ambient conditions that vary from the stipulated ISO conditions. Hot air, being less dense, de-rates the gas turbine's performance. In this section effect of inlet air temperature on the cogeneration cycle is analyzed. The IAT is varied from 5 to 50°C according to the environmental conditions of Indian sub continental. With increase in ambient air temperature work consumed by the compressor to compress the same mass of air is increased due to the increase in volume of air at higher temperature. With increase in IAT from 5 to 50°C, exergy destruction in the cycle is increased by 35.94%. With increase in IAT exergy destruction of every component is increased except regenerator. Exergy destruction increase in combustion chamber, air compressor, process heater and gas turbine is 31.30%, 35.65%, 97.78% and 35% respectively. In regenerator exergy destruction is decreased by 10.11%.

First law efficiency of cogeneration cycle depends upon the fuel consumed in the cycle being other conditions same. As fuel consumption increases from 1.50 kg/s to 1.68 kg/s with increase in IAT from 5 to 50°C, first law efficiency is decreased by 12.71% (Figure 4.4). With increase in IAT from 5 to 50°C, air-fuel ratio is increased from 56.96 to 59.34 and mass of air flow is increased from 85.55 kg/s to 99.51 kg/s.

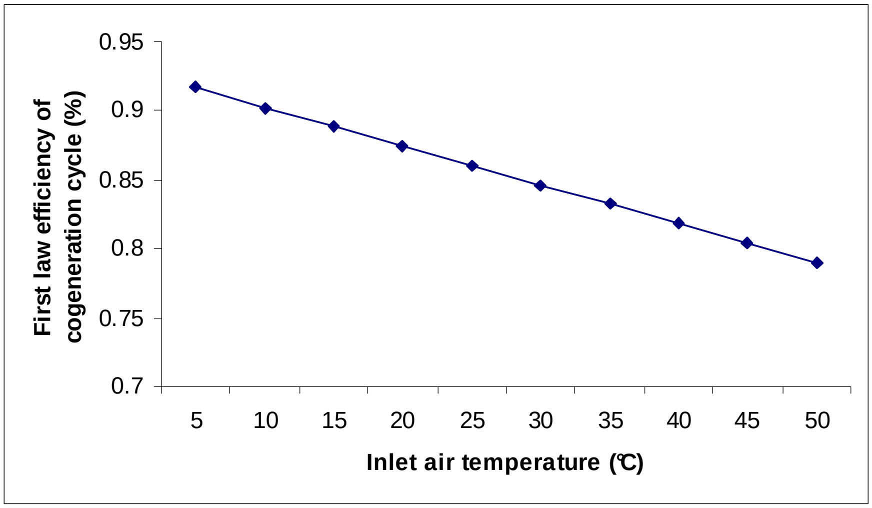


Figure 4.4 Effect of IAT on the efficiency of cogeneration cycle

Due to increase in air mass flow rate in the cycle, specific power produced by gas turbine is decreased by 14.03% with increase in IAT (Figure 4.5). A lower specific power means that size of the compressor has to be increased to maintain the flow of air so that required power output and process heat may be obtained from the cycle.

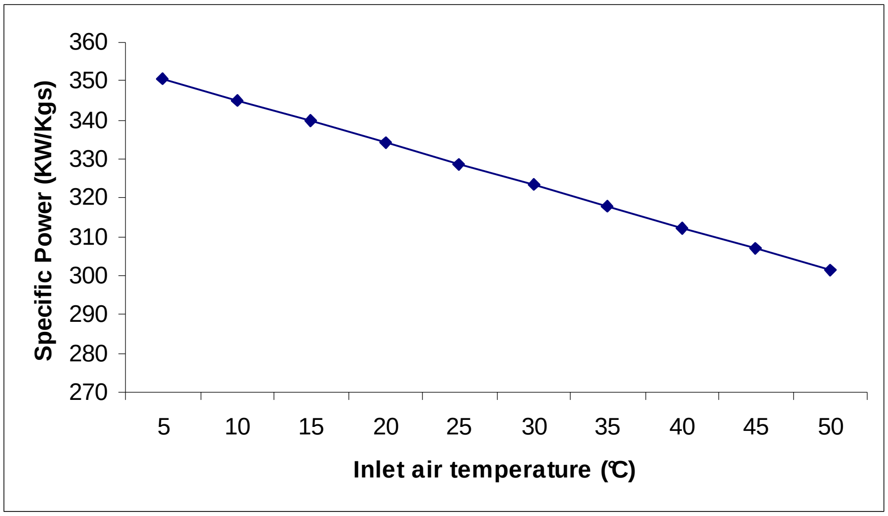
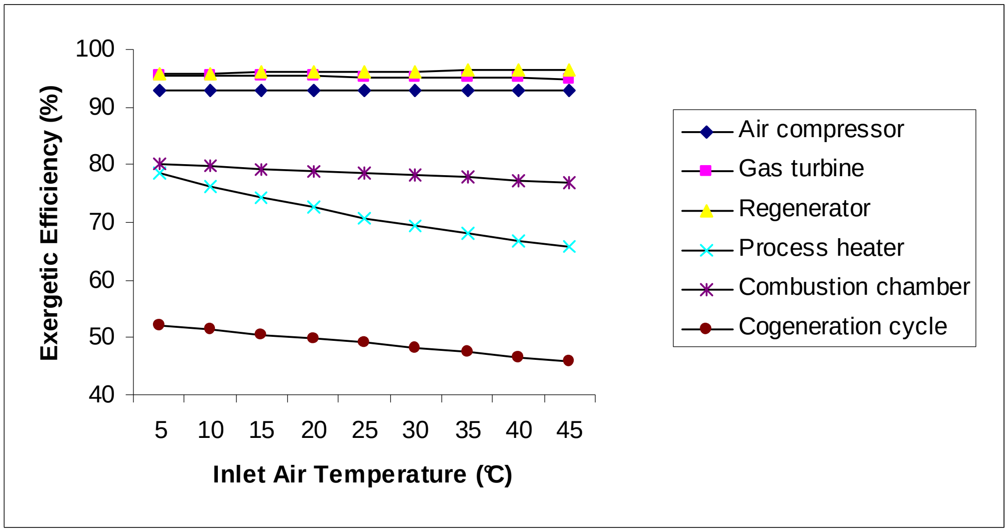


Figure 4.5 Effect of IAT on the specific power of gas turbine

With increase in IAT from 5 to 50°C second law efficiency of air compressor, combustion chamber gas turbine and process heater is decreased by 0.04%, 3.18%, 0.61% and 12.83% respectively. Second law efficiency for the regenerator is found to be increased by 0.64% (Figure 4.6). Exergetic efficiency of cycle is decreased by 10.2% with increase in IAT from 5 to 50°C. The graphical representation of data presented in this section, demonstrate that at higher ambient temperatures (than ISO conditions) the thermal efficiency and specific power output tend to be lower.

Inheritance of IAT for quantification in the GTA, methodology explained in section 4.2.3, is obtained iteratively and summarized in Table 2 of appendix-V. The results obtained with GTA are in line with the results of exergetic analysis (Figure 4.6).



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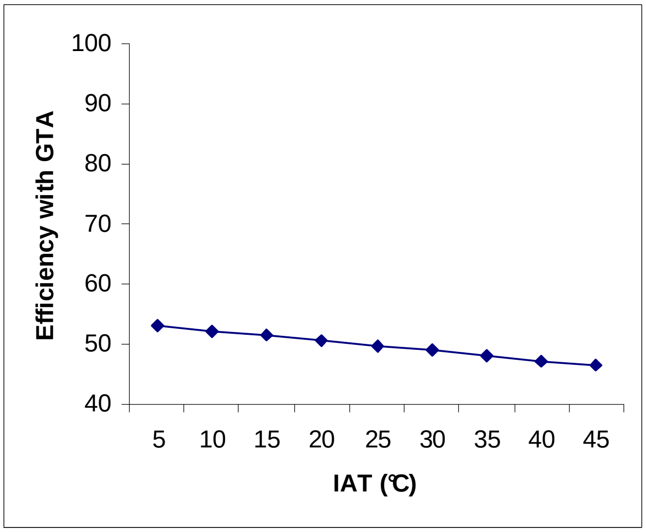


(b)

Figure 4.6 (a) Effect of IAT on exergetic efficiency of different components of CGCPP

(b) Efficiency of the cycle calculated by GTA for different IAT

4.3.3. EXERGY FACTOR OF PROCESS HEAT

Performance of process heater is evaluated on the basis of exergy factor of process heat. With increase in water pressure, exergy utilization efficiency for process heater is improved (Figure 4.7) and found to be maximum at 16 bar that is 41.28%. For the present analysis, water pressure in process heater is increased from 4 bar to 20 bar and it is found that water pressure of 18 bar is the optimum pressure. This pressure may be different for different operating conditions. For the complete analysis of cogeneration cycle, water pressure has to be simulated.

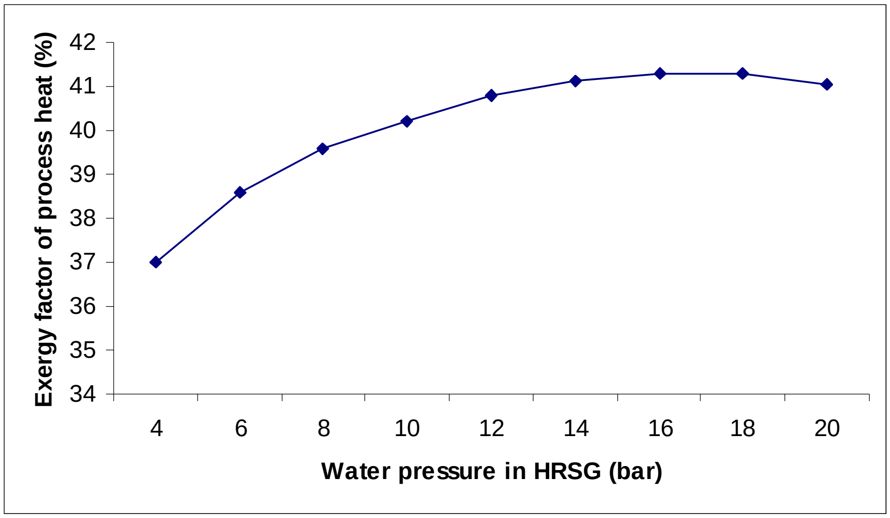


Figure 4.7 Effect of water pressure in process heater on exergy factor of process heat

4.3.4. EFFECT OF GAS TURBINE AND AIR COMPRESSOR EFFICIENCY

In the present analysis air compressor and gas turbine efficiency is varied from 70% to 95% and their effect on the cogeneration cycle is observed. With increase in gas turbine efficiency, mass flow rate of air and fuel injected in the combustion chamber is decreased from 144.3 kg/s to 75.27 kg/s and 2.61 kg/s to 1.36 kg/s. In air compressor exergy destruction is associated with work consumed, as discussed in previous section. Therefore, with decrease in air mass flow rate exergy destruction of air compressor comes down. Reduction in combustion chamber exergy destruction is also recorded due to decrease in air mass flow rate and mass of fuel injected in combustion chamber. But exergetic efficiency of air compressor and combustion chamber remains unaffected after variation in gas turbine efficiency.

With increase in gas turbine efficiency from 70% to 95%, second law efficiency of gas turbine, regenerator and process heater is found to be increased by 9.55%, 1.28% and 12.33% respectively (Figure 4.8). From the results it is also observed that 25% (70% to 95%) increase in gas turbine efficiency, increases second law efficiency of cogeneration cycle by 28.34%. This is because of the improvement in exergetic efficiency of regenerator and process heater and with reduction in fuel consumption in the cycle. For the process heater minimum exergetic efficiency is found when gas turbine efficiency is 80% and after that it starts increasing again.

With increase in gas turbine efficiency from 70% to 95%, exergy destruction in combustion chamber, compressor, heat recovery steam generator, regenerator and gas turbine is decreased by 47.84%, 47.84%, 84.06%, 68.73% and 6.12% respectively. While for air compressor with increase in efficiency from 70% to 95% exergy destruction in compressor, heat recovery steam generator and gas turbine is decreased by 29.22%, 90.60%, 51.83%, and 29.24% respectively. Irrespective of results obtained for gas turbine, exergy destruction in regenerator is increased by 9.09% due to increase in air compressor efficiency.

With increase in air compressor efficiency from 70% to 95%, second law efficiency of the cycle is improved by 15.69% (Figure 4.9) which is lesser than the efficiency improvement (28.34%) observed with same increase in GT efficiency.

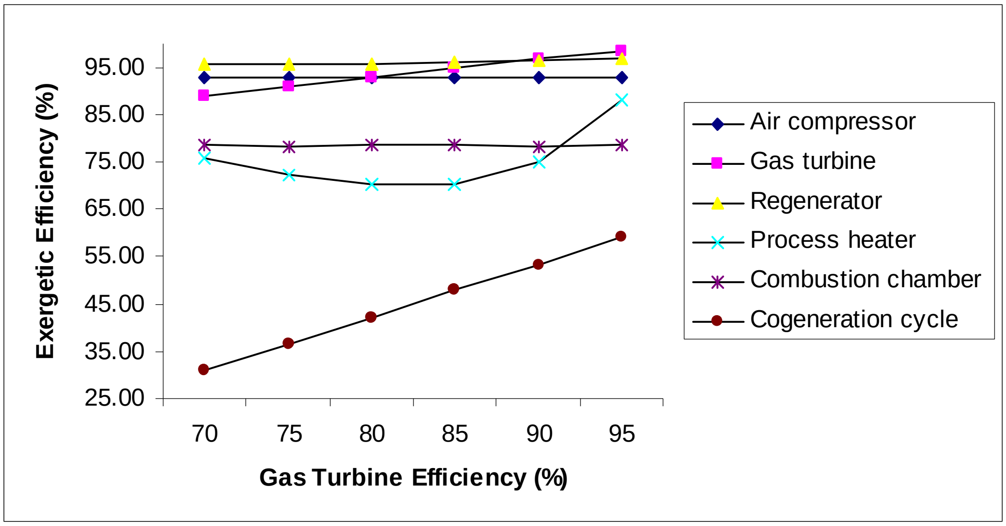
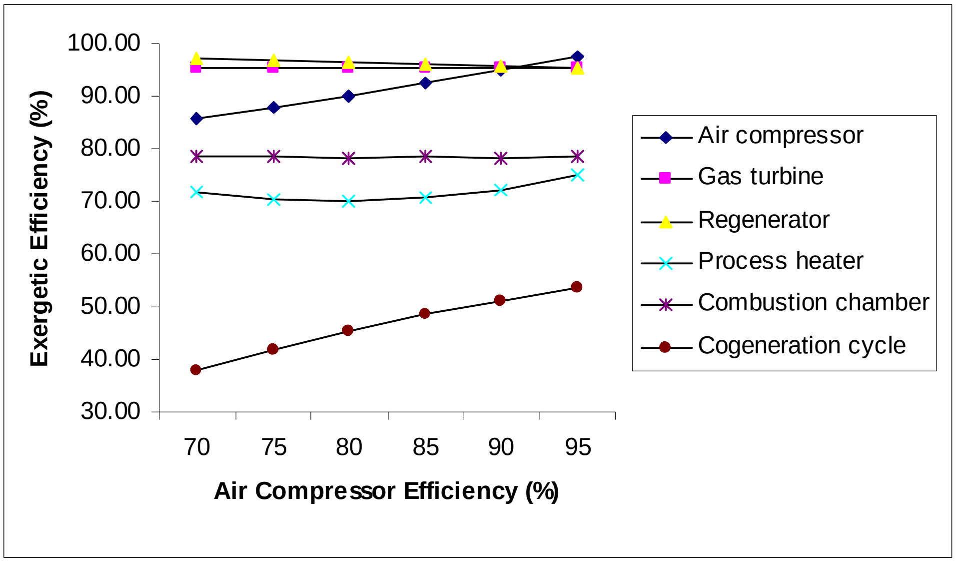


Figure 4.8 Effect of GT efficiency on exergetic efficiency of different components



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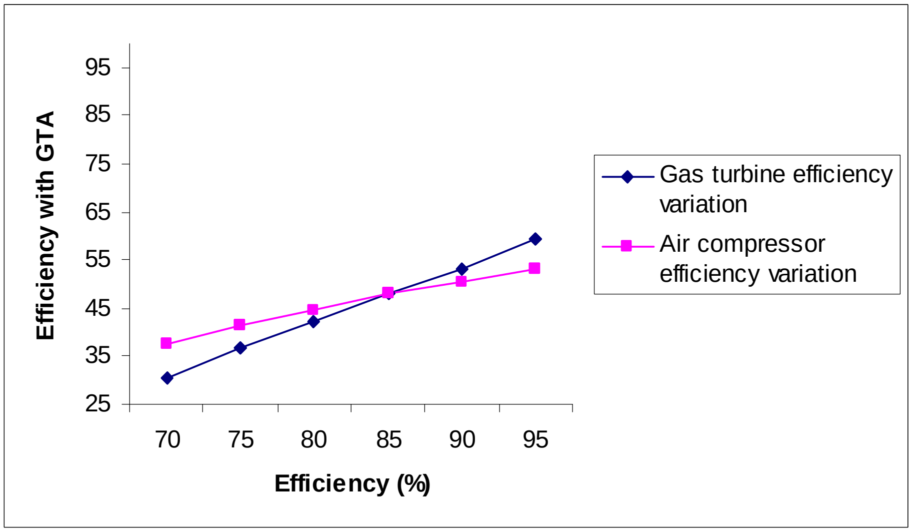


(b)

Figure 4.9 (a) Effect of air compressor efficiency on exergetic efficiency of different components of the cycle (b) Efficiency of the cycle calculated by GTA for different air compressor and gas turbine efficiency

With increase in air compressor efficiency, mass flow rate of air and fuel injected in combustion chamber is decreased from 117.5 kg/s to 83.14 kg/s and 2.12 kg/s to 1.5 kg/s respectively.

Reduction in fuel consumption and air mass flow rate is more for increase in gas turbine efficiency than air compressor efficiency because of increase in heat transfer in the regenerator. Although there is reduction in fuel consumption, even then exergetic efficiency for combustion chamber and gas turbine remain constant. But due to decreased mass flow rate of air and fuel injected in combustion chamber, exergy destruction in gas turbine and combustion chamber is reduced. Inheritance for air compressor and gas turbine efficiency obtained iteratively is given in Table 3 and 4 respectively of appendix-V. Results obtained with GTA are represented in Figure 4.9.

Specific power of air compressor and gas turbine increases with improvement in efficiency. For the air compressor and gas turbine specific power is improved from

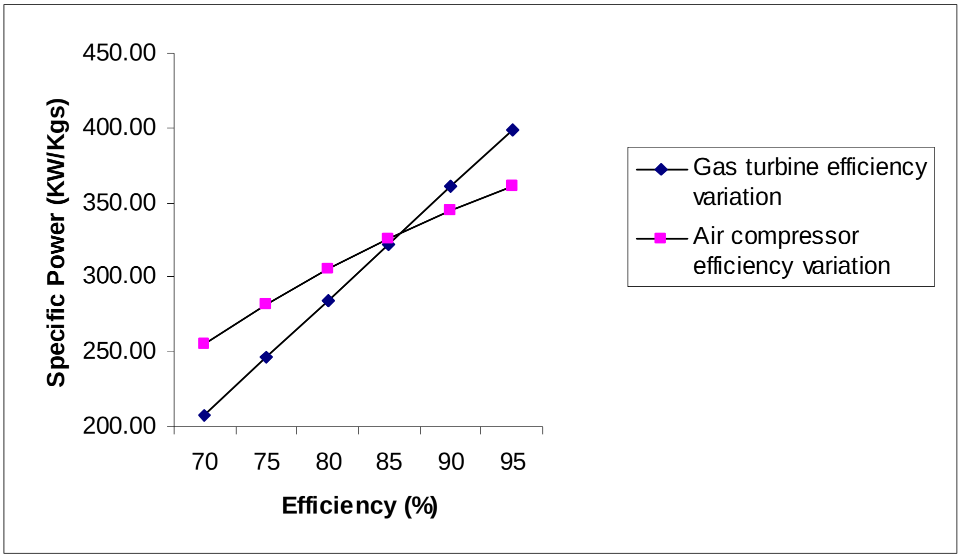


Figure 4.10 Effect of gas turbine and air compressor efficiency on specific power

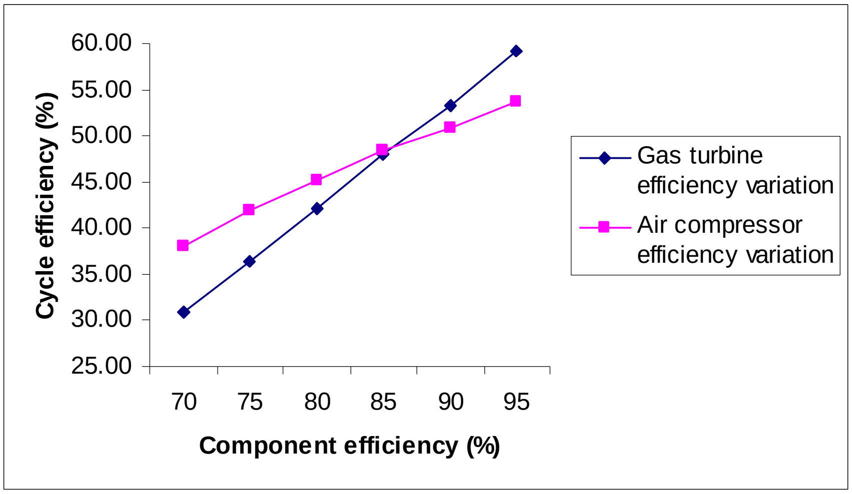


Figure 4.11 Effect of air compressor and GT efficiency on first law efficiency

255.32 kW/kgs to 344.43 kW/kgs and 207.90 kW/kgs to 398.57 kW/kgs respectively (Figure 4.10) as efficiency is changed from 70% to 95%. Therefore, with increase in efficiency of air compressor and gas turbine not only fuel consumption is reduced but also the size of plant.

Effect of increase in efficiency of gas turbine has more effect on cogeneration cycle efficiency than air compressor efficiency. Increase in gas turbine and air compressor efficiency from 70% to 95%, augment cycle first law efficiency by 28.34% and 15.69% respectively (Figure 4.11).

4.3.5. EFFECT OF TURBINE INLET TEMPERATURE (TIT)

The gas turbine history has been characterized by a continuous increase of turbine inlet temperatures about 13°C/year (Chiesa et al., 1993). It is, therefore, interesting to investigate how future TIT increases could affect performance of the considered advanced cycles.

With increase in TIT from 1000°C to 1400°C slope of variation of fuel-air ratio is upwards. As higher fuel-air ratio is required to achieve higher TIT, therefore, mass of fuel injected is increased from 1.55 kg/s to 1.69 kg/s and mass flow rate of air is decreased from 142.3 kg/s to 73.87 kg/s. First law efficiency is decreased from 86.80% to 80.12% with increase in TIT from 1000°C to 1400°C (Figure 4.12) and specific power for cogeneration cycle is increased by 92.64%.

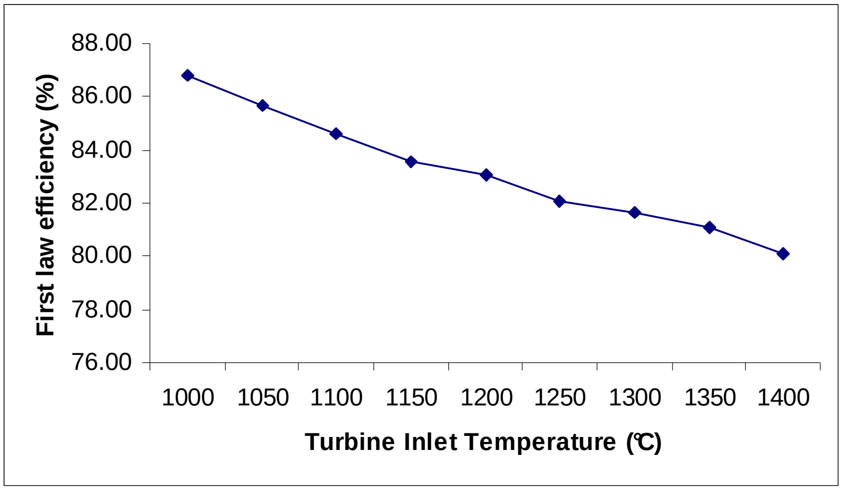
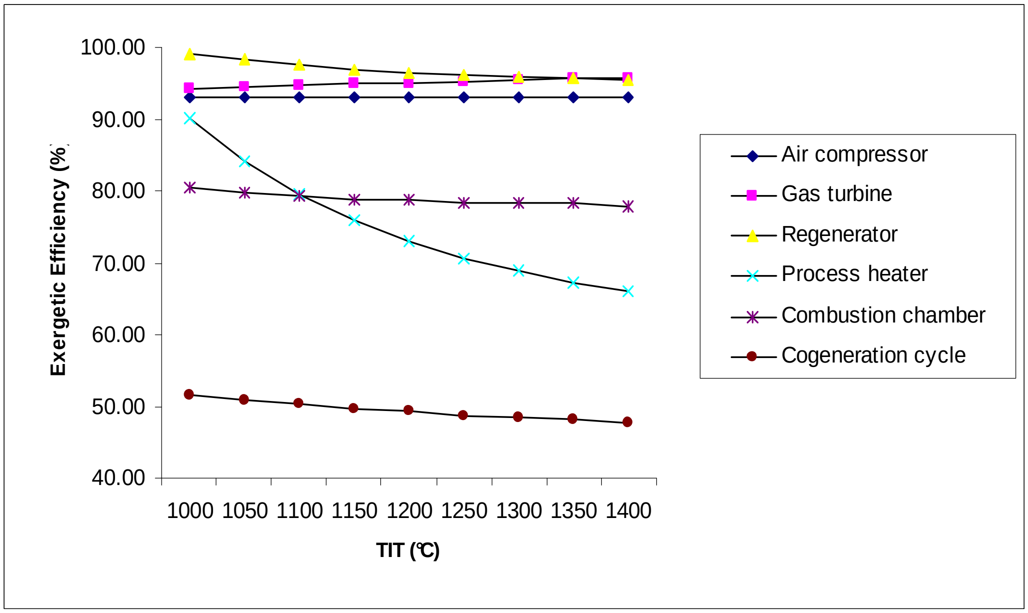


Figure 4.12 Effect of TIT on first law efficiency of cogeneration cycle



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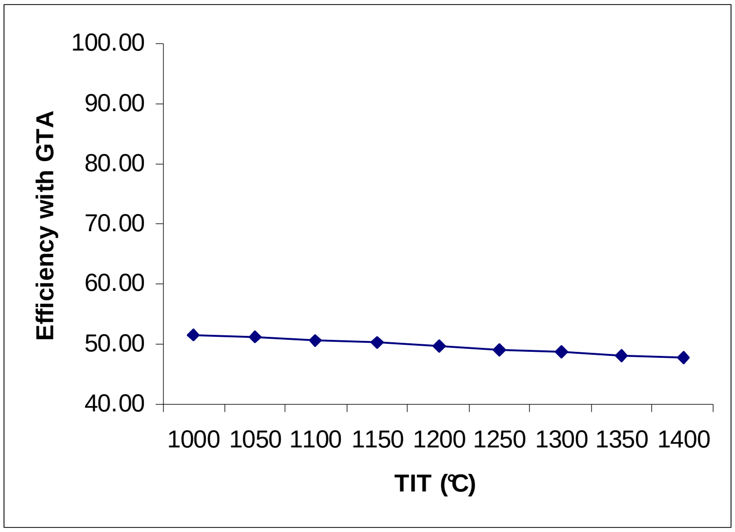

(b)

Figure 4.13 (a) Effect of TIT on exergetic efficiency of different components of the cogeneration cycle (b) Efficiency of the cycle calculated by GTA for different TIT

Exergetic efficiency of cogeneration cycle is also decreased from 51.59% to 48.19%. With increase in TIT from 1000°C to 1400°C, it is observed that air compressor efficiency remains unaffected. Exergetic efficiency of gas turbine is increased by 1.46% and that of combustion chamber, regenerator and process heater is decreased by 2.5%, 3.71% and 24.02% respectively (Figure 4.13). Increase in TIT from 1000 to 1400°C, exergy destruction is increased by 9.99%. Increased TIT decreases exergy destruction in combustion chamber, air compressor and gas turbine by 6.87 %, 48.02 % and 47.88% respectively. Increased TIT increases exergy destruction in process heater and regenerator by 469 % and 309.5 % respectively. With increase in TIT exergy destruction in cycle is increased due to increase in exergy destruction of heat transfer process of regenerator and process heater.

Iterative values of TIT inheritance are given in Table 5 of appendix-V and after quantification in the methodology developed in section 4.2.3, results obtained with GTA are found in line with that of exergetic analysis (Figure 4.13).

4.3.6. EFFECT OF REGENERATOR EFFECTIVENESS

In the present analysis regenerator effectiveness is increased from 60% to 85%. Due to which exergy destruction of air compressor and gas turbine is increased by 0.01% and 0.7% respectively. It is due to increase in air mass flow rate in the cycle due to which higher work is consumed in the compressor. With increase in regenerator effectiveness from 60% to 85% fuel mass injected in combustion chamber is decreased from 1.64 kg/s to 1.43 kg/s. Exergetic efficiency of regenerator, combustion chamber and PH is increased by 1.13%, 2.49% and 15.15% respectively. Net effect is that exergy destruction in the cycle decreased by 22.55% (Figure 4.14).

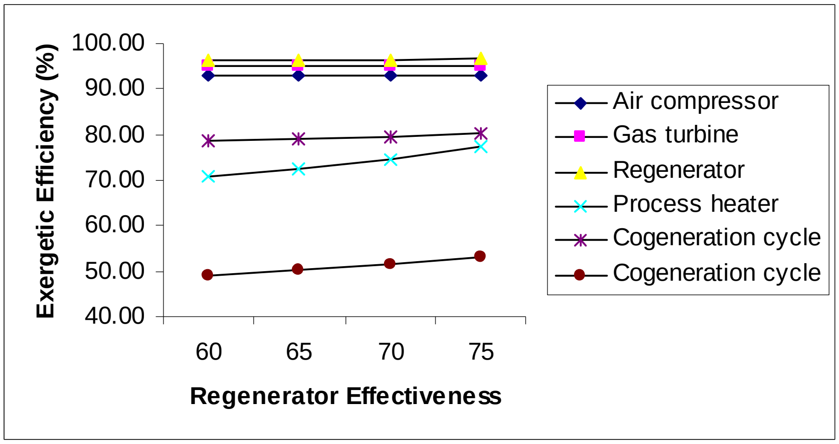

Figure 4.14 Effect of regenerator effectiveness on the second law efficiency of cogeneration cycle and its components

With increase in regenerator effectiveness from 60% to 85% first and second law efficiency is increased from 82.57% to 92.11% (Figure 4.15) and from 49.07% to 56.28% (Figure 4.16) respectively. Specific power is decreased from 329.92 kW/kgs to 326.30 kW/kgs (Figure 4.16). It is due to the increased mass flow rate of the air. Air mass flow rate is increased from 90.93 kg/s to 91.75 kg/s to maintain process heat availability in process heater so that steam may be had at design condition. Due to increased mass flow rate of air specific power is decreased and exergy destruction in air compressor and gas turbine is increased.

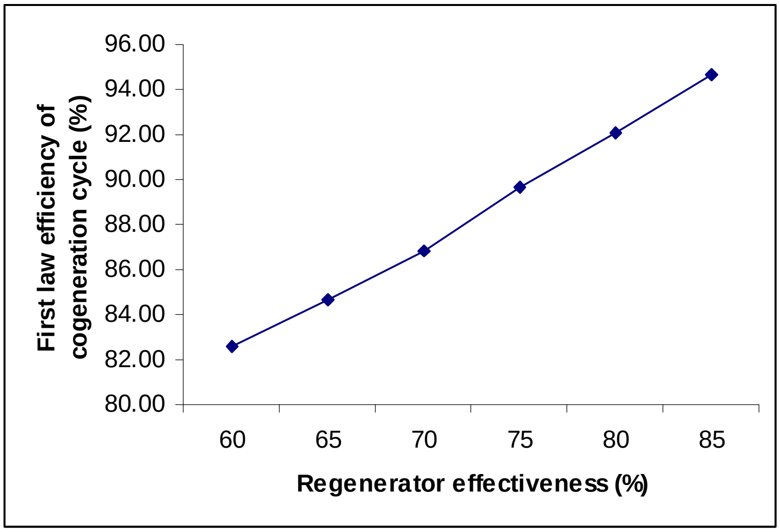

Figure 4.15 Effect of regenerator effectiveness on first law efficiency of CGCPP

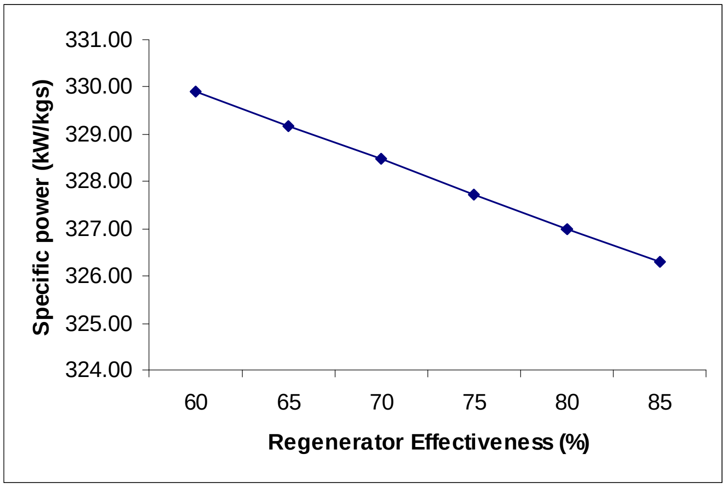

Figure 4.16 Effect of regenerator effectiveness on specific power of CGCPP

4.3.7. EFFECT OF SPECIFIC HEAT

Specific heat of air at compressor inlet is increased from 1.1 kJ/kg°C to 1.4 kJ/kg°C by increasing the concentration of CO_2 and H_2O in ambient air. For efficiency improvement of CGCPP, steam injection and exhaust gas recirculation are employed which increase concentration of CO_2 and H_2O respectively.

It is found that with increase in specific heat first law efficiency is decreased from 82.52% to 81.87% (Figure 4.17) because mass of fuel consumption is increased from 1.64 kg/s to 1.66 kg/s.

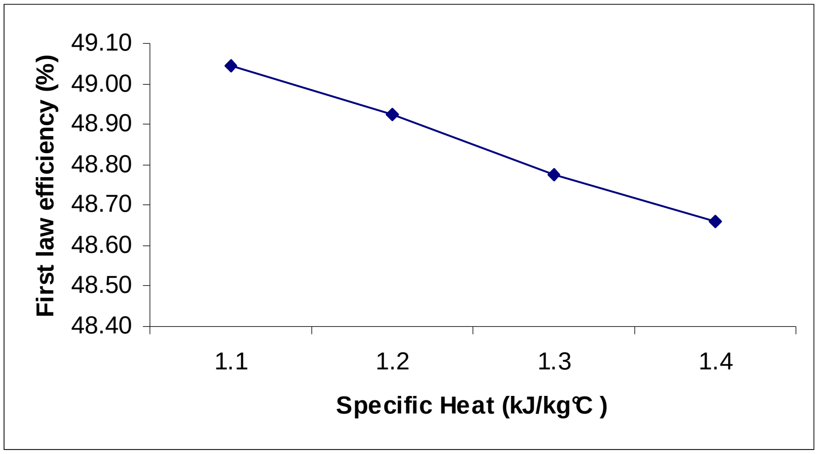

Figure 4.17 Effect of specific heat at constant pressure on first law efficiency of cogeneration cycle

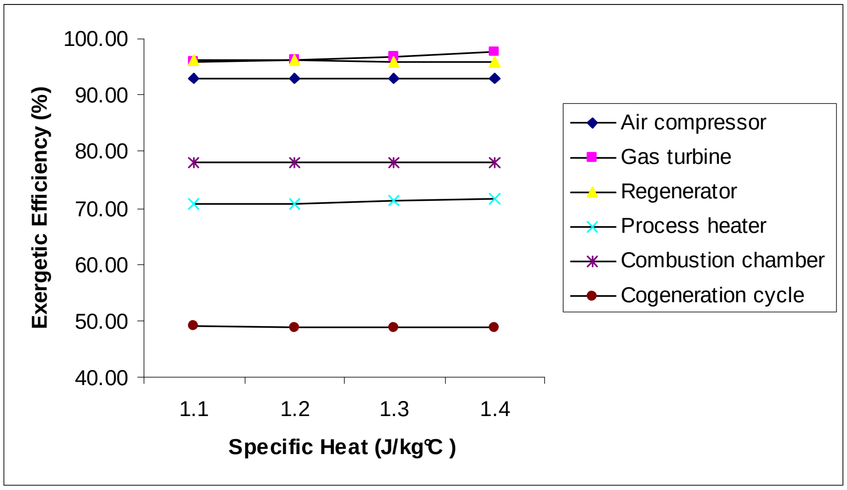

Figure 4.18 Effect of specific heat at constant pressure on the second law efficiency of cogeneration cycle and its components

With increase in specific heat from 1.1 kJ/kg°C to 1.4 kJ/kg°C exergetic efficiency of gas turbine and process heat is found to be increased by 1.64% and 0.83% respectively. Exergetic efficiency in air compressor, regenerator and combustion chamber is decreased by 0.08%, 0.18% and

0.11% respectively (Figure 4.18). Exergy destruction in the cogeneration cycle is decreased by 1.33%.

Specific power for the cycle is found to be increased from 328.55 kW/kgs to 335.27kW/kgs (Figure 4.19) due to decrease in air mass flow rate from 91.31 kg/s to 89.48 kg/s.

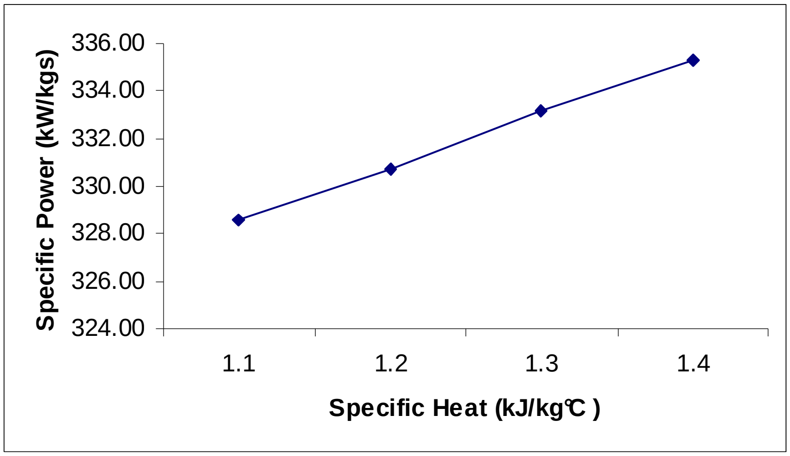

Figure 4.19 Effect of regenerator effectiveness on specific power of cogeneration cycle

Exergy, the essential concept in second law analysis, is always consumed or destroyed in any process. If less exergy is consumed, a cycle can produce more efficiently. Therefore, by using exergy to evaluate the power plant cycles, a more accurate performance of the system can be obtained.

Second law analysis gives much more meaningful evaluation by indicating the association of irreversibility or exergy destruction with combustion and heat transfer processes and allows thermodynamic evaluation of energy conservation options in cogeneration cycle, and thereby provides an indicator that points in the direction in which engineers should concentrate their efforts to improve the performance of thermal power plant.

CHAPTER-V

CONCLUSIONS AND SCOPE OF FUTURE WORK

In the present work, graph theory and matrix method is used to analyze efficiency and reliability of CCPP and CGCPP. Energy and exergy analysis of CGCPP has also been carried by varying different design parameters. For the analysis, a methodology is developed for performance, efficiency and reliability analysis and result comes out in the form of a number called as index. For the development of methodology, CCPP and CGCPP are divided into sub-systems in such a way that no sub-system is independent. Digraphs for the interdependencies of sub-systems and design parameters are organized. Effect of design parameters on sub-systems is also quantified for efficiency analysis. After quantification of inheritance and interdependencies of sub-systems and parameters, efficiency for CCPP is obtained to be 53.54% (for the conditions as given in appendix-IV) that is in close approximation to the results available in literature i.e. 53.61% with the similar parameters. Similar analysis is carried for different configurations of CCPP. Effect of design parameters on CCPP efficiency is also observed by changing the TIT and other design parameters also. Results obtained are in satisfactory proximity of the results available in literature. Therefore, it is concluded that GTA can be used for calculating the efficiency and reliability of CCPP taking into consideration interactions amongst different systems. The graph theoretic methodology developed for CCPP is used for the analysis of a CGCPP. The validated graph theory and matrix method has also been extended to find composite index for efficiency and reliability (CIER), which takes care of inheritance and interdependency of efficiency and reliability for CCPP and CGCPP.

For the validation of GTA and quantification of inheritance for different design parameter, exergetic analysis of CGCPP is carried out. From the exergetic analysis it has been found that at CR of 15, CGCPP has highest exergetic efficiency of 50.4%. The value of efficiency for different IAT, air compressor and gas turbine efficiency and TIT has also been calculated with thermodynamic modeling. The value of efficiency for exergetic and graph theoretic analysis is found to be 50.4% and 50.12% respectively. Results, thus, obtained from both the approaches i.e. graph theory and exergy analysis for these parameters are in close proximity.

In the present work graph theoretic methodology for the CCPP and CGCPP analysis is developed with a view that power plant managers can take early decision for selection, improvements and comparison, amongst the various options available, without having in-depth knowledge of thermodynamics and reliability analysis. A systematic and logical methodology is helpful in convincing the financers also, so that new power plants may be commissioned and existing may be improved.

The proposed methodology can be extended for the analysis of power plants for many other tangible and intangible performance parameters i.e. cost, human factor, pollution emission etc. Reliability analysis is base for the maintainability and availability of power plant, which may be carried out in future with the help of developed methodology in present work. In the present work, basis of quantification is on the scale of 1-9 and 1-5. In future some fuzzy score may be used for the quantification of inheritance and interdependencies in the systems.

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Appendix-I

Expansion for permanent function of 5x5 matrix

$$\begin{bmatrix} S_1 & S_{12} & S_{13} & S_{14} & S_{15} \\ S_{21} & S_2 & S_{23} & S_{24} & S_{25} \\ S_{31} & S_{32} & S_3 & S_{34} & S_{35} \\ S_{41} & S_{42} & S_{43} & S_4 & S_{45} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_5 \end{bmatrix}_{5\times 5}$$

Group I (1 Term)

$S_1\ S_2\ S_3\ S_4\ S_5$

Group II

Absent

Group III (10 Terms)

$+ S_{12}\ S_{21}\ S_3\ S_4\ S_5 + S_{13}\ S_{31}\ S_2\ S_4\ S_5 + S_{14}\ S_{41}\ S_2\ S_3\ S_5 + S_{15}\ S_{51}\ S_2\ S_3\ S_4$

$+ S_{23}\ S_{32}\ S_1\ S_4\ S_5 + S_{24}\ S_{42}\ S_1\ S_3\ S_5 + S_{25}\ S_{52}\ S_1\ S_3\ S_4 + S_{34}\ S_{43}\ S_1\ S_2\ S_5$

$+ S_{35}\ S_{53}\ S_1\ S_2\ S_4 + S_{45}\ S_{54}\ S_1\ S_2\ S_3$

Group IV (20 Terms)

$+ S_1\ S_2\ (S_{34}\ S_{45}\ S_{53} + S_{35}\ S_{54}\ S_{43}) + S_1\ S_4\ (S_{23}\ S_{35}\ S_{52} + S_{25}\ S_{53}\ S_{32})$

$+ S_1\ S_5\ (S_{23}\ S_{34}\ S_{42} + S_{24}\ S_{43}\ S_{32}) + S_1\ S_3\ (S_{25}\ S_{54}\ S_{42} + S_{24}\ S_{45}\ S_{52})$

$+ S_2\ S_3\ (S_{14}\ S_{45}\ S_{51} + S_{15}\ S_{54}\ S_{41}) + S_2\ S_4\ (S_{13}\ S_{35}\ S_{51} + S_{15}\ S_{53}\ S_{31})$

$+ S_2\ S_5\ (S_{13}\ S_{34}\ S_{41} + S_{14}\ S_{43}\ S_{31}) + S_3\ S_4\ (S_{12}\ S_{25}\ S_{51} + S_{15}\ S_{52}\ S_{21})$

$+S_3\ S_5\ (S_{12}\ S_{24}\ S_{41} + S_{14}\ S_{42}\ S_{21}) + S_4\ S_5\ (S_{12}\ S_{23}\ S_{31} + S_{13}\ S_{32}\ S_{21})$

Group V

Subgroup I (15 Terms)

$+ S_1\ [(S_{23}\ S_{32})(S_{45}\ S_{54})] + S_1\ [(S_{24}\ S_{42})(S_{35}\ S_{53})] + S_1\ [(S_{25}\ S_{52})(S_{34}\ S_{43})]$

$+ S_2\ [(S_{13}\ S_{31})(S_{45}\ S_{54})] + S_2\ [(S_{14}\ S_{41})(S_{35}\ S_{53})] + S_2\ [(S_{15}\ S_{51})(S_{34}\ S_{43})]$

$+ S_3 [(S_{12} S_{21})(S_{45} S_{54})] + S_3 [(S_{14} S_{41})(S_{25} S_{53})] + S_3 [(S_{15} S_{51})(S_{24} S_{42})]$

$+ S_4 [(S_{12} S_{21})(S_{35} S_{53})] + S_4 [(S_{13} S_{31})(S_{25} S_{52})] + S_4 [(S_{15} S_{51})(S_{23} S_{32})]$

$+ S_5 [(S_{13} S_{31})(S_{24} S_{42})] + S_5 [(S_{12} S_{21})(S_{34} S_{43})] + S_5 [(S_{23} S_{32})(S_{41} S_{14})]$

Subgroup II (30 Terms)

$+S_1 [(S_{23} S_{34} S_{45} S_{52}) + (S_{23} S_{35} S_{54} S_{42}) + (S_{24} S_{45} S_{53} S_{32}) + (S_{24} S_{43} S_{35} S_{52})$

$+ (S_{25} S_{54} S_{43} S_{32}) + (S_{25} S_{53} S_{34} S_{42})]$

$+ S_2 [(S_{13} S_{34} S_{45} S_{51}) + (S_{13} S_{35} S_{54} S_{41}) + (S_{14} S_{45} S_{53} S_{31}) + (S_{14} S_{43} S_{35} S_{51})$

$+ (S_{15} S_{54} S_{43} S_{31}) + (S_{15} S_{53} S_{34} S_{41})]$

$+ S_3 [(S_{12} S_{24} S_{45} S_{51}) + (S_{14} S_{42} S_{25} S_{51}) + (S_{15} S_{52} S_{24} S_{41}) + (S_{15} S_{54} S_{42} S_{21})$

$+ (S_{12} S_{25} S_{54} S_{41}) + (S_{14} S_{45} S_{52} S_{21})]$

$+ S_4 [(S_{12} S_{23} S_{35} S_{51}) + (S_{13} S_{35} S_{52} S_{21}) + (S_{13} S_{32} S_{25} S_{51}) + (S_{15} S_{53} S_{32} S_{21})$

$+ (S_{15} S_{52} S_{23} S_{31}) + (S_{12} S_{25} S_{53} S_{31})]$

$+ S_5 [(S_{12} S_{23} S_{34} S_{41}) + (S_{12} S_{24} S_{43} S_{31}) + (S_{13} S_{34} S_{42} S_{21}) + (S_{13} S_{32} S_{24} S_{41})$

$+ (S_{14} S_{43} S_{32} S_{21}) + (S_{14} S_{42} S_{23} S_{31})]$

Group VI

Subgroup I (20 Terms)

$+ (S_{12} S_{21}) (S_{34} S_{45} S_{53}) + (S_{12} S_{21}) (S_{35} S_{54} S_{43})$

$+ (S_{13} S_{31}) (S_{25} S_{54} S_{42}) + (S_{13} S_{31}) (S_{24} S_{45} S_{52})$

$+ (S_{14} S_{41}) (S_{25} S_{53} S_{32}) + (S_{14} S_{41}) (S_{23} S_{35} S_{52})$

$+ (S_{15} S_{51}) (S_{24} S_{43} S_{32}) + (S_{15} S_{51}) (S_{23} S_{34} S_{42})$

$+ (S_{24} S_{42}) (S_{13} S_{35} S_{51}) + (S_{24} S_{42}) (S_{15} S_{53} S_{31})$

$+ (S_{35} S_{53}) (S_{12} S_{24} S_{41}) + (S_{35} S_{53}) (S_{14} S_{42} S_{21})$

$+ (S_{45} S_{54}) (S_{12} S_{23} S_{31}) + (S_{45} S_{54}) (S_{13} S_{32} S_{21})$

$+ (S_{34} S_{43}) (S_{12} S_{25} S_{51}) + (S_{34} S_{43}) (S_{15} S_{52} S_{21})$

$+ (S_{25} S_{52}) (S_{13} S_{34} S_{41}) + (S_{25} S_{52}) (S_{14} S_{43} S_{31})$

$+ (S_{23}\ S_{32})\ (S_{14}\ S_{45}\ S_{51}) + (S_{23}\ S_{32})\ (S_{15}\ S_{54}\ S_{41})$

Subgroup II (24 Terms)

$+ S_{12}\ S_{23}\ S_{34}\ S_{45}\ S_{51} + S_{12}\ S_{23}\ S_{35}\ S_{54}\ S_{41} + S_{12}\ S_{24}\ S_{45}\ S_{53}\ S_{31}$

$+ S_{12}\ S_{24}\ S_{43}\ S_{35}\ S_{51} + S_{12}\ S_{25}\ S_{54}\ S_{43}\ S_{31} + S_{12}\ S_{25}\ S_{53}\ S_{34}\ S_{41}$

$+ S_{13}\ S_{34}\ S_{45}\ S_{52}\ S_{21} + S_{13}\ S_{35}\ S_{54}\ S_{42}\ S_{21} + S_{13}\ S_{32}\ S_{24}\ S_{45}\ S_{51}$

$+ S_{13}\ S_{35}\ S_{52}\ S_{24}\ S_{41} + S_{13}\ S_{32}\ S_{25}\ S_{54}\ S_{41} + S_{13}\ S_{34}\ S_{42}\ S_{25}\ S_{51}$

$+ S_{14}\ S_{45}\ S_{53}\ S_{32}\ S_{21} + S_{14}\ S_{43}\ S_{35}\ S_{52}\ S_{21} + S_{14}\ S_{42}\ S_{25}\ S_{53}\ S_{31}$

$+ S_{14}\ S_{42}\ S_{23}\ S_{35}\ S_{51} + S_{14}\ S_{42}\ S_{32}\ S_{25}\ S_{51} + S_{14}\ S_{45}\ S_{52}\ S_{23}\ S_{31}$

$+ S_{15}\ S_{54}\ S_{43}\ S_{32}\ S_{21} + S_{15}\ S_{53}\ S_{34}\ S_{42}\ S_{21} + S_{15}\ S_{54}\ S_{42}\ S_{23}\ S_{31}$

$+ S_{15}\ S_{52}\ S_{23}\ S_{34}\ S_{41} + S_{15}\ S_{52}\ S_{24}\ S_{43}\ S_{31} + S_{15}\ S_{53}\ S_{32}\ S_{24}\ S_{41}$

Appendix-II

Expansion for permanent function of 6 x 6 matrix

$$\begin{bmatrix} S_1 & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_2 & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_3 & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_4 & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_5 & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_6 \end{bmatrix}_{6\times 6}$$

Group1 (1Term)

$S_1S_2S_3S_4S_5S_6$

Group2

Absent

Group3 (15 Terms)

$+ (S_{12}S_{21})(S_3S_4S_5S_6) + (S_{13}S_{31})(S_2S_4S_5S_6) + (S_{14}S_{41})(S_2S_3S_5S_6)$

$+ (S_{15}S_{51})(S_2S_3S_4S_6) + (S_{16}S_{61})(S_2S_3S_4S_5) + (S_{23}S_{32})(S_1S_4S_5S_6)$

$+ (S_{24}S_{42})(S_1S_3S_5S_6) + (S_{25}S_{52})(S_1S_3S_4S_6) + (S_{26}S_{62})(S_1S_3S_4S_5)$

$+ (S_{34}S_{43})(S_1S_2S_5S_6) + (S_{35}S_{53})(S_1S_2S_4S_6) + (S_{36}S_{63})(S_1S_2S_4S_5)$

$+ (S_{45}S_{54})(S_1S_2S_3S_6) + (S_{46}S_{64})(S_1S_2S_3S_5) + (S_{56}S_{65})(S_1S_2S_3S_4)$

Group4 (40 Terms)

$+ S_1S_2S_3(S_{45}S_{56}S_{64}) + S_1S_2S_3(S_{46}S_{65}S_{54}) + S_1S_2S_4(S_{35}S_{56}S_{63})$

$+ S_1S_2S_4(S_{36}S_{65}S_{53}) + S_1S_2S_5(S_{34}S_{46}S_{63}) + S_1S_2S_5(S_{36}S_{64}S_{43})$

$+ S_1S_2S_6(S_{34}S_{45}S_{53}) + S_1S_2S_6(S_{35}S_{54}S_{43}) + S_1S_3S_4(S_{25}S_{56}S_{62})$

$+ S_1S_3S_4(S_{26}S_{65}S_{52}) + S_1S_3S_5(S_{24}S_{46}S_{62}) + S_1S_3S_5(S_{26}S_{64}S_{42})$

$+ S_1S_3S_6(S_{24}S_{45}S_{52}) + S_1S_3S_6(S_{25}S_{54}S_{42}) + S_1S_4S_5(S_{23}S_{36}S_{62})$

$+ S_1S_4S_5(S_{26}S_{63}S_{32}) + S_1S_4S_6(S_{23}S_{35}S_{52}) + S_1S_4S_6(S_{25}S_{53}S_{32})$

$+ S_1S_5S_6(S_{23}S_{34}S_{42}) + S_1S_5S_6(S_{24}S_{43}S_{32}) + S_2S_3S_4(S_{15}S_{56}S_{61})$

$+ S_2S_3S_4(S_{16}S_{65}S_{51}) + S_2S_3S_5(S_{14}S_{46}S_{61}) + S_2S_3S_5(S_{16}S_{64}S_{41})$

$+ S_2S_3S_6(S_{14}S_{45}S_{51}) + S_2S_3S_6(S_{15}S_{54}S_{41}) + S_2S_4S_5(S_{13}S_{36}S_{61})$

$+ S_2S_4S_5(S_{16}S_{63}S_{31}) + S_2S_4S_6(S_{13}S_{35}S_{51}) + S_2S_4S_6(S_{15}S_{53}S_{31})$

$+ S_2S_5S_6(S_{31}S_{14}S_{43}) + S_2S_5S_6(S_{13}S_{34}S_{41}) + S_3S_4S_5(S_{12}S_{26}S_{61})$

$+ S_3S_4S_5(S_{16}S_{62}S_{21}) + S_3S_4S_6(S_{12}S_{25}S_{51}) + S_3S_4S_6(S_{15}S_{52}S_{21})$

$+ S_3S_5S_6(S_{12}S_{24}S_{41}) + S_3S_5S_6(S_{14}S_{42}S_{21}) + S_4S_5S_6(S_{12}S_{23}S_{31})$

$+ S_4S_5S_6(S_{13}S_{32}S_{21})$

Group5

Subgroup1 (45 Terms)

$+ S_1S_2(S_{34}S_{43})(S_{56}S_{65}) + S_1S_2(S_{35}S_{53})(S_{46}S_{64}) + S_1S_2(S_{36}S_{63})(S_{45}S_{54})$

$+ S_1S_3(S_{24}S_{42})(S_{56}S_{65}) + S_1S_3(S_{25}S_{52})(S_{46}S_{64}) + S_1S_3(S_{26}S_{62})(S_{45}S_{54})$

$+ S_1S_4(S_{25}S_{52})(S_{36}S_{63}) + S_1S_4(S_{26}S_{62})(S_{35}S_{53}) + S_1S_4(S_{23}S_{32})(S_{56}S_{65})$

$+ S_1S_5(S_{24}S_{42})(S_{36}S_{63}) + S_1S_5(S_{26}S_{62})(S_{34}S_{43}) + S_1S_5(S_{23}S_{32})(S_{46}S_{64})$

$+ S_1S_6(S_{24}S_{42})(S_{35}S_{53}) + S_1S_6(S_{25}S_{52})(S_{34}S_{43}) + S_1S_6(S_{23}S_{32})(S_{45}S_{54})$

$+ S_2S_3(S_{14}S_{41})(S_{56}S_{65}) + S_2S_3(S_{15}S_{51})(S_{46}S_{64}) + S_2S_3(S_{16}S_{61})(S_{45}S_{54})$

$+ S_2S_4(S_{13}S_{31})(S_{56}S_{65}) + S_2S_4(S_{15}S_{51})(S_{36}S_{63}) + S_2S_4(S_{16}S_{61})(S_{53}S_{35})$

$+ S_2S_5(S_{13}S_{31})(S_{46}S_{64}) + S_2S_5(S_{14}S_{41})(S_{36}S_{63}) + S_2S_5(S_{16}S_{61})(S_{34}S_{43})$

$+ S_2S_6(S_{13}S_{31})(S_{45}S_{54}) + S_2S_6(S_{14}S_{41})(S_{35}S_{53}) + S_2S_6(S_{15}S_{51})(S_{34}S_{43})$

$+ S_3S_4(S_{12}S_{21})(S_{56}S_{65}) + S_3S_4(S_{15}S_{51})(S_{26}S_{62}) + S_3S_4(S_{16}S_{61})(S_{25}S_{52})$

$+ S_3S_5(S_{12}S_{21})(S_{46}S_{64}) + S_3S_5(S_{14}S_{41})(S_{26}S_{62}) + S_3S_5(S_{16}S_{61})(S_{24}S_{42})$

$+ S_3S_6(S_{12}S_{21})(S_{45}S_{54}) + S_3S_6(S_{14}S_{41})(S_{25}S_{52}) + S_3S_6(S_{15}S_{51})(S_{24}S_{42})$

$+ S_4S_5(S_{12}S_{21})(S_{36}S_{63}) + S_4S_5(S_{13}S_{31})(S_{26}S_{62}) + S_4S_5(S_{16}S_{61})(S_{23}S_{32})$

$+ S_4S_6(S_{12}S_{21})(S_{35}S_{53}) + S_4S_6(S_{13}S_{31})(S_{25}S_{52}) + S_4S_6(S_{15}S_{51})(S_{23}S_{32})$

$+ S_5S_6(S_{12}S_{21})(S_{34}S_{43}) + S_5S_6(S_{13}S_{31})(S_{24}S_{42}) + S_5S_6(S_{14}S_{41})(S_{23}S_{32})$

Group5

Subgroup2 (90 Terms)

$+ S_1S_2(S_{34}S_{45}S_{56}S_{63}) + S_1S_2(S_{34}S_{46}S_{53}S_{65}) + S_1S_2(S_{35}S_{43}S_{56}S_{64})$

$+ S_1S_2(S_{35}S_{54}S_{46}S_{63}) + S_1S_2(S_{36}S_{65}S_{54}S_{43}) + S_1S_2(S_{36}S_{64}S_{45}S_{53})$

$+ S_1S_3(S_{24}S_{45}S_{56}S_{62}) + S_1S_3(S_{24}S_{46}S_{65}S_{52}) + S_1S_3(S_{25}S_{56}S_{64}S_{42})$

$+ S_1S_3(S_{25}S_{54}S_{46}S_{62}) + S_1S_3(S_{26}S_{65}S_{54}S_{42}) + S_1S_3(S_{26}S_{64}S_{45}S_{52})$

$+ S_1S_4(S_{23}S_{36}S_{65}S_{52}) + S_1S_4(S_{23}S_{35}S_{56}S_{62}) + S_1S_4(S_{25}S_{56}S_{63}S_{32})$

$+ S_1S_4(S_{25}S_{53}S_{36}S_{62}) + S_1S_4(S_{26}S_{65}S_{53}S_{32}) + S_1S_4(S_{26}S_{63}S_{35}S_{52})$

$+ S_1S_5(S_{23}S_{34}S_{46}S_{62}) + S_1S_5(S_{23}S_{36}S_{42}S_{64}) + S_1S_5(S_{24}S_{46}S_{63}S_{32})$

$+ S_1S_5(S_{24}S_{43}S_{36}S_{62}) + S_1S_5(S_{26}S_{64}S_{43}S_{32}) + S_1S_5(S_{26}S_{63}S_{34}S_{42})$

$+ S_1S_6(S_{23}S_{34}S_{45}S_{52}) + S_1S_6(S_{23}S_{35}S_{54}S_{42}) + S_1S_6(S_{24}S_{32}S_{45}S_{53})$

$+ S_1S_6(S_{24}S_{43}S_{35}S_{52}) + S_1S_6(S_{25}S_{54}S_{43}S_{32}) + S_1S_6(S_{25}S_{34}S_{42}S_{53})$

$+ S_2S_3(S_{14}S_{45}S_{56}S_{61}) + S_2S_3(S_{14}S_{46}S_{65}S_{51}) + S_2S_3(S_{15}S_{54}S_{46}S_{61})$

$+ S_2S_3(S_{15}S_{56}S_{64}S_{41}) + S_2S_3(S_{16}S_{65}S_{54}S_{41}) + S_2S_3(S_{16}S_{64}S_{45}S_{51})$

$+ S_2S_4(S_{13}S_{35}S_{56}S_{61}) + S_2S_4(S_{13}S_{36}S_{65}S_{51}) + S_2S_4(S_{15}S_{56}S_{63}S_{31})$

$+ S_2S_4(S_{15}S_{53}S_{36}S_{61}) + S_2S_4(S_{16}S_{65}S_{53}S_{31}) + S_2S_4(S_{16}S_{63}S_{35}S_{51})$

$+ S_2S_5(S_{13}S_{34}S_{46}S_{61}) + S_2S_5(S_{13}S_{36}S_{64}S_{41}) + S_2S_5(S_{14}S_{43}S_{36}S_{61})$

$+ S_2S_5(S_{14}S_{46}S_{63}S_{31}) + S_2S_5(S_{16}S_{63}S_{34}S_{41}) + S_2S_5(S_{16}S_{64}S_{43}S_{31})$

$+ S_2S_6(S_{13}S_{34}S_{45}S_{51}) + S_2S_6(S_{13}S_{35}S_{54}S_{41}) + S_2S_6(S_{14}S_{43}S_{35}S_{51})$

$+ S_2S_6(S_{14}S_{45}S_{53}S_{31}) + S_2S_6(S_{15}S_{54}S_{43}S_{31}) + S_2S_6(S_{15}S_{53}S_{34}S_{41})$

$+ S_3S_4(S_{12}S_{25}S_{56}S_{61}) + S_3S_4(S_{12}S_{26}S_{65}S_{51}) + S_3S_4(S_{15}S_{56}S_{62}S_{21})$

$+ S_3S_4(S_{15}S_{52}S_{26}S_{61}) + S_3S_4(S_{16}S_{65}S_{52}S_{21}) + S_3S_4(S_{16}S_{62}S_{25}S_{51})$

$+ S_3S_5(S_{12}S_{24}S_{46}S_{61}) + S_3S_5(S_{12}S_{26}S_{64}S_{41}) + S_3S_5(S_{14}S_{46}S_{62}S_{21})$

$+ S_3S_5(S_{14}S_{42}S_{26}S_{61}) + S_3S_5(S_{16}S_{64}S_{42}S_{21}) + S_3S_5(S_{16}S_{62}S_{24}S_{41})$

$+ S_3S_6(S_{12}S_{24}S_{45}S_{51}) + S_3S_6(S_{12}S_{25}S_{54}S_{41}) + S_3S_6(S_{14}S_{45}S_{52}S_{21})$

$+ S_3S_6(S_{14}S_{42}S_{25}S_{51}) + S_3S_6(S_{15}S_{54}S_{42}S_{21}) + S_3S_6(S_{15}S_{52}S_{24}S_{41})$

$+ S_4S_5(S_{12}S_{23}S_{36}S_{61}) + S_4S_5(S_{12}S_{26}S_{63}S_{31}) + S_4S_5(S_{13}S_{36}S_{62}S_{21})$

$+ S_4S_5(S_{13}S_{32}S_{26}S_{61}) + S_4S_5(S_{16}S_{63}S_{32}S_{21}) + S_4S_5(S_{16}S_{62}S_{23}S_{31})$

$+ S_4S_6(S_{12}S_{23}S_{35}S_{51}) + S_4S_6(S_{12}S_{25}S_{53}S_{31}) + S_4S_6(S_{13}S_{35}S_{52}S_{21})$

$+ S_4S_6(S_{13}S_{32}S_{25}S_{51}) + S_4S_6(S_{15}S_{52}S_{23}S_{31}) + S_4S_6(S_{15}S_{53}S_{32}S_{21})$

$+ S_5S_6(S_{12}S_{23}S_{34}S_{41}) + S_5S_6(S_{12}S_{24}S_{43}S_{31}) + S_5S_6(S_{13}S_{34}S_{42}S_{21})$

$+ S_5S_6(S_{13}S_{32}S_{24}S_{41}) + S_5S_6(S_{14}S_{43}S_{32}S_{21}) + S_5S_6(S_{14}S_{42}S_{23}S_{31})$

Group6

Subgroup1 (120 Terms)

$+ S_1(S_{23}S_{32})(S_{45}S_{56}S_{64}) + S_1(S_{23}S_{32})(S_{46}S_{65}S_{54}) + S_1(S_{24}S_{42})(S_{35}S_{56}S_{63})$

$+ S_1(S_{24}S_{42})(S_{36}S_{65}S_{53}) + S_1(S_{25}S_{52})(S_{34}S_{46}S_{63}) + S_1(S_{25}S_{52})(S_{36}S_{64}S_{43})$

$+ S_1(S_{26}S_{62})(S_{34}S_{45}S_{53}) + S_1(S_{26}S_{62})(S_{35}S_{54}S_{43}) + S_1(S_{34}S_{43})(S_{25}S_{56}S_{62})$

$+ S_1(S_{34}S_{43})(S_{26}S_{65}S_{52}) + S_1(S_{35}S_{53})(S_{24}S_{46}S_{62}) + S_1(S_{35}S_{53})(S_{26}S_{64}S_{42})$

$+ S_1(S_{36}S_{63})(S_{24}S_{45}S_{52}) + S_1(S_{36}S_{63})(S_{25}S_{54}S_{42}) + S_1(S_{45}S_{54})(S_{23}S_{36}S_{62})$

$+ S_1(S_{45}S_{54})(S_{26}S_{63}S_{32}) + S_1(S_{46}S_{64})(S_{23}S_{35}S_{52}) + S_1(S_{46}S_{64})(S_{25}S_{53}S_{32})$

$+ S_1(S_{56}S_{65})(S_{23}S_{34}S_{42}) + S_1(S_{56}S_{65})(S_{24}S_{43}S_{32}) + S_2(S_{13}S_{31})(S_{45}S_{56}S_{64})$

$+ S_2(S_{31}S_{13})(S_{46}S_{65}S_{54}) + S_2(S_{14}S_{41})(S_{35}S_{56}S_{63}) + S_2(S_{14}S_{41})(S_{36}S_{65}S_{53})$

$+ S_2(S_{15}S_{51})(S_{36}S_{64}S_{43}) + S_2(S_{15}S_{51})(S_{34}S_{46}S_{63}) + S_2(S_{16}S_{61})(S_{35}S_{54}S_{43})$

$+ S_2(S_{16}S_{61})(S_{34}S_{45}S_{53}) + S_2(S_{34}S_{43})(S_{16}S_{65}S_{51}) + S_2(S_{34}S_{43})(S_{15}S_{56}S_{61})$

$+ S_2(S_{35}S_{53})(S_{16}S_{64}S_{41}) + S_2(S_{35}S_{53})(S_{14}S_{46}S_{61}) + S_2(S_{36}S_{63})(S_{15}S_{54}S_{41})$

$+ S_2(S_{36}S_{63})(S_{14}S_{45}S_{51}) + S_2(S_{45}S_{54})(S_{16}S_{63}S_{31}) + S_2(S_{45}S_{54})(S_{13}S_{36}S_{61})$

$+ S_2(S_{46}S_{64})(S_{15}S_{53}S_{31}) + S_2(S_{46}S_{64})(S_{13}S_{35}S_{51}) + S_2(S_{56}S_{65})(S_{14}S_{43}S_{31})$

$+ S_2(S_{56}S_{65})(S_{13}S_{34}S_{41}) + S_3(S_{12}S_{21})(S_{45}S_{56}S_{64}) + S_3(S_{12}S_{21})(S_{46}S_{65}S_{54})$

$+ S_3(S_{14}S_{41})(S_{25}S_{56}S_{62}) + S_3(S_{14}S_{41})(S_{26}S_{65}S_{52}) + S_3(S_{15}S_{51})(S_{24}S_{46}S_{62})$

$+ S_3(S_{15}S_{51})(S_{26}S_{64}S_{42}) + S_3(S_{16}S_{61})(S_{25}S_{54}S_{42}) + S_3(S_{16}S_{61})(S_{24}S_{45}S_{52})$

$+ S_3(S_{24}S_{42})(S_{16}S_{65}S_{51}) + S_3(S_{24}S_{42})(S_{15}S_{56}S_{61}) + S_3(S_{25}S_{52})(S_{16}S_{64}S_{41})$

$+ S_3(S_{25}S_{52})(S_{14}S_{46}S_{61}) + S_3(S_{26}S_{62})(S_{15}S_{54}S_{41}) + S_3(S_{26}S_{62})(S_{14}S_{45}S_{51})$

$+ S_3(S_{45}S_{54})(S_{12}S_{26}S_{61}) + S_3(S_{45}S_{54})(S_{16}S_{62}S_{21}) + S_3(S_{46}S_{64})(S_{12}S_{25}S_{51})$

$+ S_3(S_{46}S_{64})(S_{15}S_{52}S_{21}) + S_3(S_{56}S_{65})(S_{12}S_{24}S_{41}) + S_3(S_{56}S_{65})(S_{14}S_{42}S_{21})$

$+ S_4(S_{12}S_{21})(S_{35}S_{56}S_{63}) + S_4(S_{12}S_{21})(S_{36}S_{65}S_{53}) + S_4(S_{13}S_{31})(S_{25}S_{56}S_{62})$

$+ S_4(S_{13}S_{31})(S_{26}S_{65}S_{52}) + S_4(S_{15}S_{51})(S_{26}S_{63}S_{32}) + S_4(S_{15}S_{51})(S_{23}S_{36}S_{62})$

$+ S_4(S_{16}S_{61})(S_{23}S_{35}S_{52}) + S_4(S_{16}S_{61})(S_{25}S_{53}S_{32}) + S_4(S_{23}S_{32})(S_{16}S_{65}S_{51})$

$+ S_4(S_{23}S_{32})(S_{15}S_{56}S_{61}) + S_4(S_{25}S_{52})(S_{16}S_{63}S_{31}) + S_4(S_{25}S_{52})(S_{13}S_{36}S_{61})$

$+ S_4(S_{26}S_{62})(S_{13}S_{35}S_{51}) + S_4(S_{26}S_{62})(S_{15}S_{53}S_{31}) + S_4(S_{35}S_{53})(S_{12}S_{26}S_{61})$

$+ S_4(S_{35}S_{53})(S_{16}S_{62}S_{21}) + S_4(S_{36}S_{63})(S_{12}S_{25}S_{51}) + S_4(S_{36}S_{63})(S_{15}S_{52}S_{21})$

$+ S_4(S_{56}S_{65})(S_{12}S_{23}S_{31}) + S_4(S_{56}S_{65})(S_{13}S_{32}S_{21}) + S_5(S_{12}S_{21})(S_{34}S_{46}S_{63})$

$+ S_5(S_{12}S_{21})(S_{36}S_{64}S_{43}) + S_5(S_{13}S_{31})(S_{24}S_{46}S_{62}) + S_5(S_{13}S_{31})(S_{26}S_{64}S_{42})$

$+ S_5(S_{14}S_{41})(S_{26}S_{63}S_{32}) + S_5(S_{14}S_{41})(S_{23}S_{36}S_{62}) + S_5(S_{16}S_{61})(S_{24}S_{43}S_{32})$

$+ S_5(S_{16}S_{61})(S_{23}S_{34}S_{42}) + S_5(S_{23}S_{32})(S_{16}S_{64}S_{41}) + S_5(S_{23}S_{32})(S_{14}S_{46}S_{61})$

$+ S_5(S_{24}S_{42})(S_{16}S_{63}S_{31}) + S_5(S_{24}S_{42})(S_{13}S_{36}S_{61}) + S_5(S_{26}S_{62})(S_{13}S_{34}S_{41})$

$+ S_5(S_{26}S_{62})(S_{14}S_{43}S_{31}) + S_5(S_{34}S_{43})(S_{12}S_{26}S_{61}) + S_5(S_{34}S_{43})(S_{16}S_{62}S_{21})$

$+ S_5(S_{36}S_{63})(S_{12}S_{24}S_{41}) + S_5(S_{36}S_{63})(S_{14}S_{42}S_{21}) + S_5(S_{46}S_{64})(S_{12}S_{23}S_{31})$

$+ S_5(S_{46}S_{64})(S_{13}S_{32}S_{21}) + S_6(S_{12}S_{21})(S_{34}S_{45}S_{53}) + S_6(S_{12}S_{21})(S_{35}S_{54}S_{43})$

$+ S_6(S_{13}S_{31})(S_{25}S_{54}S_{42}) + S_6(S_{13}S_{31})(S_{24}S_{45}S_{52}) + S_6(S_{14}S_{41})(S_{23}S_{35}S_{52})$

$+ S_6(S_{14}S_{41})(S_{25}S_{53}S_{32}) + S_6(S_{15}S_{51})(S_{24}S_{43}S_{32}) + S_6(S_{15}S_{51})(S_{23}S_{34}S_{42})$

$+ S_6(S_{23}S_{32})(S_{15}S_{54}S_{41}) + S_6(S_{23}S_{32})(S_{14}S_{45}S_{51}) + S_6(S_{24}S_{42})(S_{15}S_{53}S_{31})$

$+ S_6(S_{24}S_{42})(S_{13}S_{35}S_{51}) + S_6(S_{25}S_{52})(S_{14}S_{43}S_{31}) + S_6(S_{25}S_{52})(S_{13}S_{34}S_{41})$

$+ S_6(S_{34}S_{43})(S_{12}S_{25}S_{51}) + S_6(S_{34}S_{43})(S_{15}S_{52}S_{21}) + S_6(S_{35}S_{53})(S_{12}S_{24}S_{41})$

$+ S_6(S_{35}S_{53})(S_{14}S_{42}S_{21}) + S_6(S_{45}S_{54})(S_{12}S_{23}S_{31}) + S_6(S_{45}S_{54})(S_{13}S_{32}S_{21})$

Group6

Subgroup2 (144 Terms)

$+ S_1(S_{23}S_{34}S_{45}S_{56}S_{62}) + S_1(S_{23}S_{34}S_{46}S_{65}S_{52}) + S_1(S_{23}S_{35}S_{56}S_{64}S_{42})$

$+ S_1(S_{23}S_{35}S_{54}S_{46}S_{62}) + S_1(S_{23}S_{36}S_{65}S_{54}S_{42}) + S_1(S_{23}S_{36}S_{64}S_{45}S_{52})$

$+ S_1(S_{24}S_{45}S_{56}S_{63}S_{32}) + S_1(S_{24}S_{45}S_{53}S_{36}S_{62}) + S_1(S_{24}S_{46}S_{65}S_{53}S_{32})$

$+ S_1(S_{24}S_{46}S_{63}S_{35}S_{52}) + S_1(S_{24}S_{43}S_{35}S_{56}S_{62}) + S_1(S_{24}S_{43}S_{36}S_{65}S_{52})$

$+ S_1(S_{25}S_{56}S_{64}S_{43}S_{32}) + S_1(S_{25}S_{56}S_{63}S_{34}S_{42}) + S_1(S_{25}S_{54}S_{46}S_{63}S_{32})$

$+ S_1(S_{25}S_{54}S_{43}S_{36}S_{62}) + S_1(S_{25}S_{53}S_{34}S_{46}S_{62}) + S_1(S_{25}S_{53}S_{36}S_{64}S_{42})$

$+ S_1(S_{26}S_{63}S_{34}S_{45}S_{52}) + S_1(S_{26}S_{63}S_{35}S_{54}S_{42}) + S_1(S_{26}S_{64}S_{45}S_{53}S_{32})$

$+ S_1(S_{26}S_{64}S_{43}S_{35}S_{52}) + S_1(S_{26}S_{65}S_{53}S_{34}S_{42}) + S_1(S_{26}S_{65}S_{54}S_{43}S_{32})$

$+ S_2(S_{13}S_{34}S_{45}S_{56}S_{61}) + S_2(S_{13}S_{34}S_{46}S_{65}S_{51}) + S_2(S_{13}S_{35}S_{56}S_{64}S_{41})$

$+ S_2(S_{13}S_{35}S_{54}S_{46}S_{61}) + S_2(S_{13}S_{36}S_{65}S_{54}S_{41}) + S_2(S_{13}S_{36}S_{64}S_{45}S_{51})$

$+ S_2(S_{14}S_{43}S_{35}S_{56}S_{61}) + S_2(S_{14}S_{43}S_{36}S_{65}S_{51}) + S_2(S_{14}S_{45}S_{56}S_{63}S_{31})$

$+ S_2(S_{14}S_{45}S_{53}S_{36}S_{61}) + S_2(S_{14}S_{46}S_{65}S_{53}S_{31}) + S_2(S_{14}S_{46}S_{63}S_{35}S_{51})$

$+ S_2(S_{15}S_{53}S_{34}S_{46}S_{61}) + S_2(S_{15}S_{53}S_{36}S_{64}S_{41}) + S_2(S_{15}S_{54}S_{43}S_{36}S_{61})$

$+ S_2(S_{15}S_{54}S_{46}S_{63}S_{31}) + S_2(S_{15}S_{56}S_{64}S_{43}S_{31}) + S_2(S_{15}S_{56}S_{63}S_{34}S_{41})$

$+ S_2(S_{16}S_{63}S_{34}S_{45}S_{51}) + S_2(S_{16}S_{63}S_{35}S_{54}S_{41}) + S_2(S_{16}S_{64}S_{45}S_{53}S_{31})$

$+ S_2(S_{16}S_{64}S_{43}S_{35}S_{51}) + S_2(S_{16}S_{65}S_{54}S_{43}S_{31}) + S_2(S_{16}S_{65}S_{53}S_{34}S_{41})$

$+ S_3(S_{12}S_{24}S_{45}S_{56}S_{61}) + S_3(S_{12}S_{24}S_{46}S_{65}S_{51}) + S_3(S_{12}S_{25}S_{56}S_{64}S_{41})$

$+ S_3(S_{12}S_{25}S_{54}S_{46}S_{61}) + S_3(S_{12}S_{26}S_{65}S_{54}S_{41}) + S_3(S_{12}S_{26}S_{64}S_{45}S_{51})$

$+ S_3(S_{14}S_{42}S_{25}S_{56}S_{61}) + S_3(S_{14}S_{42}S_{26}S_{65}S_{51}) + S_3(S_{14}S_{45}S_{56}S_{62}S_{21})$

$+ S_3(S_{14}S_{45}S_{52}S_{26}S_{61}) + S_3(S_{14}S_{46}S_{65}S_{52}S_{21}) + S_3(S_{14}S_{46}S_{62}S_{25}S_{51})$

$+ S_3(S_{15}S_{52}S_{24}S_{46}S_{61}) + S_3(S_{15}S_{52}S_{26}S_{64}S_{41}) + S_3(S_{15}S_{54}S_{46}S_{62}S_{21})$

$+ S_3(S_{15}S_{54}S_{42}S_{26}S_{61}) + S_3(S_{15}S_{56}S_{64}S_{42}S_{21}) + S_3(S_{15}S_{56}S_{62}S_{24}S_{41})$

$+ S_3(S_{16}S_{62}S_{25}S_{54}S_{41}) + S_3(S_{16}S_{62}S_{24}S_{45}S_{51}) + S_3(S_{16}S_{64}S_{45}S_{52}S_{21})$

$+ S_3(S_{16}S_{64}S_{42}S_{25}S_{51}) + S_3(S_{16}S_{65}S_{52}S_{24}S_{41}) + S_3(S_{16}S_{65}S_{54}S_{42}S_{21})$

$+ S_4(S_{12}S_{23}S_{35}S_{56}S_{61}) + S_4(S_{12}S_{23}S_{36}S_{65}S_{51}) + S_4(S_{12}S_{25}S_{56}S_{63}S_{31})$

$+ S_4(S_{12}S_{25}S_{53}S_{36}S_{61}) + S_4(S_{12}S_{26}S_{65}S_{53}S_{31}) + S_4(S_{12}S_{26}S_{63}S_{35}S_{51})$

$+ S_4(S_{13}S_{35}S_{56}S_{62}S_{21}) + S_4(S_{13}S_{36}S_{65}S_{52}S_{21}) + S_4(S_{13}S_{32}S_{25}S_{56}S_{61})$

$+ S_4(S_{13}S_{36}S_{62}S_{25}S_{51}) + S_4(S_{13}S_{32}S_{26}S_{65}S_{51}) + S_4(S_{13}S_{35}S_{52}S_{26}S_{61})$

$+ S_4(S_{15}S_{56}S_{63}S_{32}S_{21}) + S_4(S_{15}S_{53}S_{36}S_{62}S_{21}) + S_4(S_{15}S_{56}S_{62}S_{23}S_{31})$

$+ S_4(S_{15}S_{52}S_{23}S_{36}S_{61}) + S_4(S_{15}S_{52}S_{26}S_{63}S_{31}) + S_4(S_{15}S_{53}S_{32}S_{26}S_{61})$

$+ S_4(S_{16}S_{65}S_{53}S_{32}S_{21}) + S_4(S_{16}S_{63}S_{35}S_{52}S_{21}) + S_4(S_{16}S_{65}S_{52}S_{23}S_{31})$

$+ S_4(S_{16}S_{62}S_{23}S_{35}S_{51}) + S_4(S_{16}S_{62}S_{25}S_{53}S_{31}) + S_4(S_{16}S_{63}S_{32}S_{25}S_{51})$

$+ S_5(S_{12}S_{23}S_{34}S_{46}S_{61}) + S_5(S_{12}S_{23}S_{36}S_{64}S_{41}) + S_5(S_{12}S_{24}S_{46}S_{63}S_{31})$

$+ S_5(S_{12}S_{24}S_{43}S_{36}S_{61}) + S_5(S_{12}S_{26}S_{64}S_{43}S_{31}) + S_5(S_{12}S_{26}S_{63}S_{34}S_{41})$

$+ S_5(S_{13}S_{32}S_{24}S_{46}S_{61}) + S_5(S_{13}S_{32}S_{26}S_{64}S_{41}) + S_5(S_{13}S_{34}S_{46}S_{62}S_{21})$

$+ S_5(S_{13}S_{34}S_{42}S_{26}S_{61}) + S_5(S_{13}S_{36}S_{64}S_{42}S_{21}) + S_5(S_{13}S_{36}S_{62}S_{24}S_{41})$

$+ S_5(S_{14}S_{42}S_{26}S_{63}S_{31}) + S_5(S_{14}S_{42}S_{23}S_{36}S_{61}) + S_5(S_{14}S_{43}S_{32}S_{26}S_{61})$

$+ S_5(S_{14}S_{43}S_{36}S_{62}S_{21}) + S_5(S_{14}S_{46}S_{63}S_{32}S_{21}) + S_5(S_{14}S_{46}S_{62}S_{23}S_{31})$

$+ S_5(S_{16}S_{62}S_{24}S_{43}S_{31}) + S_5(S_{16}S_{62}S_{23}S_{34}S_{41}) + S_5(S_{16}S_{63}S_{32}S_{24}S_{41})$

$+ S_5(S_{16}S_{63}S_{34}S_{42}S_{21}) + S_5(S_{16}S_{64}S_{43}S_{32}S_{21}) + S_5(S_{16}S_{64}S_{42}S_{23}S_{31})$

$+ S_6(S_{12}S_{23}S_{34}S_{45}S_{51}) + S_6(S_{12}S_{23}S_{35}S_{54}S_{41}) + S_6(S_{12}S_{24}S_{45}S_{53}S_{31})$

$+ S_6(S_{12}S_{24}S_{43}S_{35}S_{51}) + S_6(S_{12}S_{25}S_{54}S_{43}S_{31}) + S_6(S_{12}S_{25}S_{53}S_{34}S_{41})$

$+ S_6(S_{13}S_{32}S_{24}S_{45}S_{51}) + S_6(S_{13}S_{32}S_{25}S_{54}S_{41}) + S_6(S_{13}S_{34}S_{45}S_{52}S_{21})$

$+ S_6(S_{13}S_{34}S_{42}S_{25}S_{51}) + S_6(S_{13}S_{35}S_{54}S_{42}S_{21}) + S_6(S_{13}S_{35}S_{52}S_{24}S_{41})$

$+ S_6(S_{14}S_{42}S_{25}S_{53}S_{31}) + S_6(S_{14}S_{42}S_{23}S_{35}S_{51}) + S_6(S_{14}S_{43}S_{35}S_{52}S_{21})$

$+ S_6(S_{14}S_{43}S_{32}S_{25}S_{51}) + S_6(S_{14}S_{45}S_{53}S_{32}S_{21}) + S_6(S_{14}S_{45}S_{52}S_{23}S_{31})$

$+ S_6(S_{15}S_{52}S_{23}S_{34}S_{41}) + S_6(S_{15}S_{52}S_{24}S_{43}S_{31}) + S_6(S_{15}S_{53}S_{32}S_{24}S_{41})$

$+ S_6(S_{15}S_{53}S_{34}S_{42}S_{21}) + S_6(S_{15}S_{54}S_{43}S_{32}S_{21}) + S_6(S_{15}S_{54}S_{42}S_{23}S_{31})$

Group7

Subgroup1 (15+90+40=145 Terms)

$+ (S_{16}S_{61})(S_{23}S_{32})(S_{45}S_{54}) + (S_{16}S_{61})(S_{25}S_{52})(S_{34}S_{43}) + (S_{16}S_{61})(S_{24}S_{42})(S_{35}S_{53})$

$+ (S_{15}S_{51})(S_{32}S_{23})(S_{46}S_{64}) + (S_{15}S_{51})(S_{26}S_{62})(S_{34}S_{43}) + (S_{15}S_{51})(S_{36}S_{63})(S_{24}S_{42})$

$+ (S_{14}S_{41})(S_{23}S_{32})(S_{56}S_{65}) + (S_{14}S_{41})(S_{25}S_{52})(S_{36}S_{63}) + (S_{14}S_{41})(S_{26}S_{62})(S_{35}S_{53})$

$+ (S_{13}S_{31})(S_{56}S_{65})(S_{24}S_{42}) + (S_{13}S_{31})(S_{46}S_{64})(S_{25}S_{52}) + (S_{13}S_{31})(S_{45}S_{54})(S_{26}S_{62})$

$+ (S_{12}S_{21})(S_{34}S_{43})(S_{56}S_{65}) + (S_{12}S_{21})(S_{35}S_{53})(S_{46}S_{64}) + (S_{12}S_{21})(S_{36}S_{63})(S_{45}S_{54})$

$+ (S_{12}S_{21})(S_{34}S_{45}S_{56}S_{63}) + (S_{12}S_{21})(S_{34}S_{46}S_{65}S_{53}) + (S_{12}S_{21})(S_{35}S_{56}S_{64}S_{43})$

$+ (S_{12}S_{21})(S_{35}S_{54}S_{46}S_{63}) + (S_{12}S_{21})(S_{36}S_{65}S_{54}S_{43}) + (S_{12}S_{21})(S_{36}S_{64}S_{45}S_{53})$

$+ (S_{13}S_{31})(S_{24}S_{45}S_{56}S_{62}) + (S_{13}S_{31})(S_{24}S_{46}S_{65}S_{52}) + (S_{13}S_{31})(S_{25}S_{56}S_{64}S_{42})$

$+ (S_{13}S_{31})(S_{25}S_{54}S_{46}S_{62}) + (S_{13}S_{31})(S_{26}S_{65}S_{54}S_{42}) + (S_{13}S_{31})(S_{26}S_{64}S_{45}S_{52})$

$+ (S_{14}S_{41})(S_{23}S_{35}S_{56}S_{62}) + (S_{14}S_{41})(S_{23}S_{36}S_{65}S_{52}) + (S_{14}S_{41})(S_{25}S_{53}S_{36}S_{62})$

$+ (S_{14}S_{41})(S_{25}S_{56}S_{63}S_{32}) + (S_{14}S_{41})(S_{26}S_{63}S_{35}S_{52}) + (S_{14}S_{41})(S_{26}S_{65}S_{53}S_{32})$

$+ (S_{15}S_{51})(S_{23}S_{34}S_{46}S_{62}) + (S_{15}S_{51})(S_{23}S_{36}S_{64}S_{42}) + (S_{15}S_{51})(S_{24}S_{46}S_{63}S_{32})$

$+ (S_{15}S_{51})(S_{24}S_{43}S_{36}S_{62}) + (S_{15}S_{51})(S_{26}S_{64}S_{43}S_{32}) + (S_{15}S_{51})(S_{26}S_{63}S_{34}S_{42})$

$+ (S_{16}S_{61})(S_{23}S_{35}S_{54}S_{42}) + (S_{16}S_{61})(S_{23}S_{34}S_{45}S_{52}) + (S_{16}S_{61})(S_{24}S_{45}S_{53}S_{32})$

$+ (S_{16}S_{61})(S_{24}S_{43}S_{35}S_{52}) + (S_{16}S_{61})(S_{25}S_{54}S_{43}S_{32}) + (S_{16}S_{61})(S_{25}S_{53}S_{34}S_{42})$

$+ (S_{23}S_{32})(S_{14}S_{46}S_{65}S_{51}) + (S_{23}S_{32})(S_{14}S_{45}S_{56}S_{61}) + (S_{23}S_{32})(S_{15}S_{54}S_{46}S_{61})$

$+ (S_{23}S_{32})(S_{15}S_{56}S_{64}S_{41}) + (S_{23}S_{32})(S_{16}S_{65}S_{54}S_{41}) + (S_{23}S_{32})(S_{16}S_{64}S_{45}S_{51})$

$+ (S_{24}S_{42})(S_{13}S_{35}S_{56}S_{61}) + (S_{24}S_{42})(S_{13}S_{36}S_{65}S_{51}) + (S_{24}S_{42})(S_{15}S_{56}S_{63}S_{31})$

$+ (S_{24}S_{42})(S_{15}S_{53}S_{36}S_{61}) + (S_{24}S_{42})(S_{16}S_{63}S_{35}S_{51}) + (S_{24}S_{42})(S_{16}S_{65}S_{53}S_{31})$

$+ (S_{25}S_{52})(S_{13}S_{34}S_{46}S_{61}) + (S_{25}S_{52})(S_{13}S_{36}S_{64}S_{41}) + (S_{25}S_{52})(S_{14}S_{43}S_{36}S_{61})$

$+ (S_{25}S_{52})(S_{14}S_{46}S_{63}S_{31}) + (S_{25}S_{52})(S_{16}S_{63}S_{34}S_{41}) + (S_{25}S_{52})(S_{16}S_{64}S_{43}S_{31})$

$+ (S_{26}S_{62})(S_{13}S_{34}S_{45}S_{51}) + (S_{26}S_{62})(S_{13}S_{35}S_{54}S_{41}) + (S_{26}S_{62})(S_{14}S_{45}S_{53}S_{31})$

$+ (S_{26}S_{62})(S_{14}S_{43}S_{35}S_{51}) + (S_{26}S_{62})(S_{15}S_{54}S_{43}S_{31}) + (S_{26}S_{62})(S_{15}S_{53}S_{34}S_{41})$

$+ (S_{34}S_{43})(S_{12}S_{25}S_{56}S_{61}) +(S_{34}S_{43})(S_{12}S_{26}S_{65}S_{51}) + (S_{34}S_{43})(S_{15}S_{56}S_{62}S_{21})$

$+ (S_{34}S_{43})(S_{15}S_{52}S_{26}S_{61}) + (S_{34}S_{43})(S_{16}S_{62}S_{25}S_{51}) + (S_{34}S_{43})(S_{16}S_{65}S_{52}S_{21})$

$+ (S_{35}S_{53})(S_{12}S_{26}S_{64}S_{41}) + (S_{35}S_{53})(S_{12}S_{24}S_{46}S_{61}) + (S_{35}S_{53})(S_{14}S_{42}S_{26}S_{61})$

$+ (S_{35}S_{53})(S_{14}S_{46}S_{62}S_{21}) + (S_{35}S_{53})(S_{16}S_{62}S_{24}S_{41}) + (S_{35}S_{53})(S_{16}S_{64}S_{42}S_{21})$

$+ (S_{36}S_{63})(S_{12}S_{25}S_{54}S_{41}) + (S_{36}S_{63})(S_{12}S_{24}S_{45}S_{51}) + (S_{36}S_{63})(S_{14}S_{42}S_{25}S_{51})$

$+ (S_{36}S_{63})(S_{14}S_{45}S_{52}S_{21}) + (S_{36}S_{63})(S_{15}S_{52}S_{24}S_{41}) + (S_{36}S_{63})(S_{15}S_{54}S_{42}S_{21})$

$+ (S_{45}S_{54})(S_{12}S_{23}S_{36}S_{61}) + (S_{45}S_{54})(S_{12}S_{26}S_{63}S_{31}) + (S_{45}S_{54})(S_{13}S_{36}S_{62}S_{21})$

$+ (S_{45}S_{54})(S_{13}S_{32}S_{26}S_{61}) + (S_{45}S_{54})(S_{16}S_{63}S_{32}S_{21}) + (S_{45}S_{54})(S_{16}S_{62}S_{23}S_{31})$

$+ (S_{46}S_{64})(S_{12}S_{23}S_{35}S_{51}) + (S_{46}S_{64})(S_{12}S_{25}S_{53}S_{31}) + (S_{46}S_{64})(S_{13}S_{32}S_{25}S_{51})$

$+ (S_{46}S_{64})(S_{13}S_{35}S_{52}S_{21}) + (S_{46}S_{64})(S_{15}S_{53}S_{32}S_{21}) + (S_{46}S_{64})(S_{15}S_{52}S_{23}S_{31})$

$+ (S_{56}S_{65})(S_{12}S_{23}S_{34}S_{41}) + (S_{56}S_{65})(S_{12}S_{24}S_{43}S_{31}) + (S_{56}S_{65})(S_{13}S_{34}S_{42}S_{21})$

$+ (S_{56}S_{65})(S_{13}S_{32}S_{24}S_{41}) + (S_{56}S_{65})(S_{14}S_{43}S_{32}S_{21}) + (S_{56}S_{65})(S_{14}S_{42}S_{23}S_{31})$

$+ (S_{12}S_{23}S_{31})(S_{45}S_{56}S_{64}) + (S_{12}S_{23}S_{31})(S_{46}S_{65}S_{54}) + (S_{12}S_{24}S_{41})(S_{35}S_{56}S_{63})$

$+ (S_{12}S_{24}S_{41})(S_{36}S_{65}S_{53}) + (S_{12}S_{25}S_{51})(S_{34}S_{46}S_{63}) + (S_{12}S_{25}S_{51})(S_{36}S_{64}S_{43})$

$+ (S_{12}S_{26}S_{61})(S_{34}S_{45}S_{53}) + (S_{12}S_{26}S_{61})(S_{35}S_{54}S_{43}) + (S_{13}S_{32}S_{21})(S_{45}S_{56}S_{64})$

$+ (S_{13}S_{32}S_{21})(S_{46}S_{65}S_{54}) + (S_{13}S_{35}S_{51})(S_{24}S_{46}S_{62}) + (S_{13}S_{35}S_{51})(S_{26}S_{64}S_{42})$

$+ (S_{13}S_{36}S_{61})(S_{24}S_{45}S_{52}) + (S_{13}S_{36}S_{61})(S_{25}S_{54}S_{42}) + (S_{13}S_{34}S_{41})(S_{26}S_{65}S_{52})$

$+ (S_{13}S_{34}S_{41})(S_{25}S_{56}S_{62}) + (S_{14}S_{42}S_{21})(S_{35}S_{56}S_{63}) + (S_{14}S_{42}S_{21})(S_{36}S_{65}S_{53})$

$+ (S_{14}S_{43}S_{31})(S_{25}S_{56}S_{62}) + (S_{14}S_{43}S_{31})(S_{26}S_{65}S_{52}) + (S_{14}S_{45}S_{51})(S_{23}S_{36}S_{62})$

$+ (S_{14}S_{45}S_{51})(S_{26}S_{63}S_{32}) + (S_{14}S_{46}S_{61})(S_{23}S_{35}S_{52}) + (S_{14}S_{46}S_{61})(S_{25}S_{53}S_{32})$

$+ (S_{15}S_{52}S_{21})(S_{36}S_{64}S_{43}) + (S_{15}S_{52}S_{21})(S_{34}S_{46}S_{63}) + (S_{15}S_{54}S_{41})(S_{26}S_{63}S_{32})$

$+ (S_{15}S_{54}S_{41})(S_{23}S_{36}S_{62}) + (S_{15}S_{56}S_{61})(S_{24}S_{43}S_{32}) + (S_{15}S_{56}S_{61})(S_{23}S_{34}S_{42})$

$+ (S_{15}S_{53}S_{31})(S_{24}S_{46}S_{62}) + (S_{15}S_{53}S_{31})(S_{26}S_{64}S_{42}) + (S_{16}S_{62}S_{21})(S_{34}S_{45}S_{53})$

$+ (S_{16}S_{62}S_{21})(S_{35}S_{54}S_{43}) + (S_{16}S_{63}S_{31})(S_{25}S_{54}S_{42}) + (S_{16}S_{63}S_{31})(S_{24}S_{45}S_{52})$

$+ (S_{16}S_{64}S_{41})(S_{25}S_{53}S_{32}) + (S_{16}S_{64}S_{41})(S_{23}S_{35}S_{52}) + (S_{16}S_{65}S_{51})(S_{24}S_{43}S_{32})$

$+ (S_{16}S_{65}S_{51})(S_{23}S_{34}S_{42})$

Group7

Subgroup2 (120 Terms)

$+ S_{12}S_{23}S_{34}S_{45}S_{56}S_{61} + S_{12}S_{23}S_{34}S_{46}S_{65}S_{51} + S_{12}S_{23}S_{35}S_{56}S_{64}S_{41}$

$+ S_{12}S_{23}S_{35}S_{54}S_{46}S_{61} + S_{12}S_{23}S_{36}S_{65}S_{54}S_{41} + S_{12}S_{23}S_{36}S_{64}S_{45}S_{51}$

$+ S_{12}S_{24}S_{45}S_{56}S_{63}S_{31} + S_{12}S_{24}S_{46}S_{65}S_{53}S_{31} + S_{12}S_{24}S_{43}S_{35}S_{56}S_{61}$

$+ S_{12}S_{24}S_{46}S_{63}S_{35}S_{51} + S_{12}S_{24}S_{43}S_{36}S_{65}S_{51} + S_{12}S_{24}S_{45}S_{53}S_{36}S_{61}$

$+ S_{12}S_{25}S_{56}S_{64}S_{43}S_{31} + S_{12}S_{25}S_{54}S_{46}S_{63}S_{31} + S_{12}S_{25}S_{56}S_{63}S_{34}S_{41}$

$+ S_{12}S_{25}S_{53}S_{34}S_{46}S_{61} + S_{12}S_{25}S_{53}S_{36}S_{64}S_{41} + S_{12}S_{25}S_{54}S_{43}S_{36}S_{61}$

$+ S_{12}S_{26}S_{65}S_{54}S_{43}S_{31} + S_{12}S_{26}S_{64}S_{45}S_{53}S_{31} + S_{12}S_{26}S_{65}S_{53}S_{34}S_{41}$

$+ S_{12}S_{26}S_{63}S_{34}S_{45}S_{51} + S_{12}S_{26}S_{63}S_{35}S_{54}S_{41} + S_{12}S_{26}S_{64}S_{43}S_{35}S_{51}$

$+ S_{13}S_{34}S_{45}S_{56}S_{62}S_{21} + S_{13}S_{34}S_{46}S_{65}S_{52}S_{21} + S_{13}S_{34}S_{42}S_{25}S_{56}S_{61}$

$+ S_{13}S_{34}S_{46}S_{62}S_{25}S_{51} + S_{13}S_{34}S_{42}S_{26}S_{65}S_{51} + S_{13}S_{34}S_{45}S_{52}S_{26}S_{61}$

$+ S_{13}S_{35}S_{56}S_{64}S_{42}S_{21} + S_{13}S_{35}S_{54}S_{46}S_{62}S_{21} + S_{13}S_{35}S_{56}S_{62}S_{24}S_{41}$

$+ S_{13}S_{35}S_{52}S_{24}S_{46}S_{61} + S_{13}S_{35}S_{52}S_{26}S_{64}S_{41} + S_{13}S_{35}S_{54}S_{42}S_{26}S_{61}$

$+ S_{13}S_{36}S_{65}S_{54}S_{42}S_{21} + S_{13}S_{36}S_{64}S_{45}S_{52}S_{21} + S_{13}S_{36}S_{65}S_{52}S_{24}S_{41}$

$+ S_{13}S_{36}S_{62}S_{24}S_{45}S_{51} + S_{13}S_{36}S_{62}S_{25}S_{54}S_{41} + S_{13}S_{36}S_{64}S_{42}S_{25}S_{51}$

$+ S_{13}S_{32}S_{24}S_{45}S_{56}S_{61} + S_{13}S_{32}S_{24}S_{46}S_{65}S_{51} + S_{13}S_{32}S_{25}S_{56}S_{64}S_{41}$

$+ S_{13}S_{32}S_{25}S_{54}S_{46}S_{61} + S_{13}S_{32}S_{26}S_{65}S_{54}S_{41} + S_{13}S_{32}S_{26}S_{64}S_{45}S_{51}$

$$+ S_{14}S_{45}S_{56}S_{63}S_{32}S_{21} + S_{14}S_{45}S_{53}S_{36}S_{62}S_{21} + S_{14}S_{45}S_{53}S_{32}S_{26}S_{61}$$

$$+ S_{14}S_{45}S_{56}S_{62}S_{23}S_{31} + S_{14}S_{45}S_{52}S_{23}S_{36}S_{61} + S_{14}S_{45}S_{52}S_{26}S_{63}S_{31}$$

$$+ S_{14}S_{46}S_{65}S_{53}S_{32}S_{21} + S_{14}S_{46}S_{63}S_{35}S_{52}S_{21} + S_{14}S_{46}S_{63}S_{32}S_{25}S_{51}$$

$$+ S_{14}S_{46}S_{65}S_{52}S_{23}S_{31} + S_{14}S_{46}S_{62}S_{23}S_{35}S_{51} + S_{14}S_{46}S_{62}S_{25}S_{53}S_{31}$$

$$+ S_{14}S_{43}S_{35}S_{56}S_{62}S_{21} + S_{14}S_{43}S_{36}S_{65}S_{52}S_{21} + S_{14}S_{43}S_{32}S_{25}S_{56}S_{61}$$

$$+ S_{14}S_{43}S_{32}S_{26}S_{65}S_{51} + S_{14}S_{43}S_{36}S_{62}S_{25}S_{51} + S_{14}S_{43}S_{35}S_{52}S_{26}S_{61}$$

$$+ S_{14}S_{42}S_{23}S_{35}S_{56}S_{61} + S_{14}S_{42}S_{23}S_{36}S_{65}S_{51} + S_{14}S_{42}S_{25}S_{56}S_{63}S_{31}$$

$$+ S_{14}S_{42}S_{25}S_{53}S_{36}S_{61} + S_{14}S_{42}S_{26}S_{65}S_{53}S_{31} + S_{14}S_{42}S_{26}S_{63}S_{35}S_{51}$$

$$+ S_{15}S_{56}S_{64}S_{43}S_{32}S_{21} + S_{15}S_{56}S_{63}S_{34}S_{42}S_{21} + S_{15}S_{56}S_{62}S_{24}S_{43}S_{31}$$

$$+ S_{15}S_{56}S_{63}S_{32}S_{24}S_{41} + S_{15}S_{56}S_{64}S_{42}S_{23}S_{31} + S_{15}S_{56}S_{62}S_{23}S_{34}S_{41}$$

$$+ S_{15}S_{54}S_{46}S_{63}S_{32}S_{21} + S_{15}S_{54}S_{46}S_{62}S_{23}S_{31} + S_{15}S_{54}S_{43}S_{36}S_{62}S_{21}$$

$$+ S_{15}S_{54}S_{43}S_{32}S_{26}S_{61} + S_{15}S_{54}S_{42}S_{23}S_{36}S_{61} + S_{15}S_{54}S_{42}S_{26}S_{63}S_{31}$$

$$+ S_{15}S_{53}S_{34}S_{46}S_{62}S_{21} + S_{15}S_{53}S_{36}S_{64}S_{42}S_{21} + S_{15}S_{53}S_{32}S_{24}S_{46}S_{61}$$

$$+ S_{15}S_{53}S_{32}S_{26}S_{64}S_{41} + S_{15}S_{53}S_{36}S_{62}S_{24}S_{41} + S_{15}S_{53}S_{34}S_{42}S_{26}S_{61}$$

$$+ S_{15}S_{52}S_{24}S_{43}S_{36}S_{61} + S_{15}S_{52}S_{26}S_{64}S_{43}S_{31} + S_{15}S_{52}S_{23}S_{34}S_{46}S_{61}$$

$$+ S_{15}S_{52}S_{23}S_{36}S_{64}S_{41} + S_{15}S_{52}S_{24}S_{46}S_{63}S_{31} + S_{15}S_{52}S_{26}S_{63}S_{34}S_{41}$$

$$+ S_{16}S_{65}S_{54}S_{43}S_{32}S_{21} + S_{16}S_{65}S_{53}S_{34}S_{42}S_{21} + S_{16}S_{65}S_{54}S_{42}S_{23}S_{31}$$

$$+ S_{16}S_{65}S_{52}S_{24}S_{43}S_{31} + S_{16}S_{65}S_{53}S_{32}S_{24}S_{41} + S_{16}S_{65}S_{52}S_{23}S_{34}S_{41}$$

$$+ S_{16}S_{64}S_{45}S_{53}S_{32}S_{21} + S_{16}S_{64}S_{43}S_{35}S_{52}S_{21} + S_{16}S_{64}S_{43}S_{32}S_{25}S_{51}$$

$$+ S_{16}S_{64}S_{45}S_{52}S_{23}S_{31} + S_{16}S_{64}S_{42}S_{23}S_{35}S_{51} + S_{16}S_{64}S_{42}S_{25}S_{53}S_{31}$$

$$+ S_{16}S_{63}S_{35}S_{54}S_{42}S_{21} + S_{16}S_{63}S_{32}S_{25}S_{54}S_{41} + S_{16}S_{63}S_{34}S_{45}S_{52}S_{21}$$

$$+ S_{16}S_{63}S_{32}S_{24}S_{45}S_{51} + S_{16}S_{63}S_{35}S_{52}S_{24}S_{41} + S_{16}S_{63}S_{34}S_{42}S_{25}S_{51}$$

$$+ S_{16}S_{62}S_{25}S_{54}S_{43}S_{31} + S_{16}S_{62}S_{23}S_{35}S_{54}S_{41} + S_{16}S_{62}S_{24}S_{43}S_{35}S_{51}$$

$$+ S_{16}S_{62}S_{23}S_{34}S_{45}S_{51} + S_{16}S_{62}S_{24}S_{45}S_{53}S_{31} + S_{16}S_{62}S_{25}S_{53}S_{34}S_{41}$$

Appendix-III

Code of Computer Program for Solving NXN Matrix

For the calculation of permanent function of NXN matrix is given in this appendix and value of N can be upto 50. The program is based upon Laplace expansion. Suppose B=(b_{ij}) is an NXN matrix then its determinant is given by:

$$\left|B\right| = \sum_{j=1}^{N} b_{ij} C_{ij}$$

$$and \;\; C_{ij} = (-1)^{i+j} M_{ij}$$

Where M_{ij} is the i, j minor matrix of B, that is, the determinant of the (n–1) × (n–1) matrix that results from deleting the i-th row and the j-th column of B. For the calculation of permanent function, the cofactor C_{ij} is defined as:

$$C_{ij} = M_{ij}$$

Due to this all negative signs in matrix expansion are converted in to positive signs

```
Variables Used int total Column Number of columns and rows in the matrix double matrix[50][50]
The matrix input by User int z[50]
Variable Array used for calculation of perof2
Functions Used
double per(int) Recursive function that calculates the value of permanent
double perof2(); Calculates the permanent of last 2 elements
**********************************************************************/
int totalColumn;
double matrix[50][50];
int z[50];
double per(int);
double perof2();
/**********************************************************************
Local Variables for main function
int i Temporary integer variable
int j Temporary integer variable
double k Double variable that stores the value returned by per()
```

```
**********************************************************************/
void main()
{
int i,j;
double k;
clrscr();
printf("Enter the size of the matrix:");
scanf("%d",&totalColumn);
/*Input from user the elements of Matrix that is n*n, i.e., totalColumn*totalColumn*/
printf("\n Enter the elements of matrix:\n");
for (i = 0;i<=totalColumn-1;i++)
{
for(j = 0;j<=totalColumn-1;j++)
{
printf(" Element [%d][%d]: ",i+1,j+1);
scanf("%lf",&matrix[i][j]);
}
}
printf("\n\n\n\n\nPress any key to continue….");
getch();
clrscr();
/*Show to user the matrix formed or inputted*/
printf("The matrix is: \n\n");
printf("\n\t");
for(i=0;i<=totalColumn-1;i++)
{
for(j=0;j<=totalColumn-1;j++)
{
printf("%1f ",matrix[i][j]);
}
printf("\n\t");
}
k=per(totalColumn);
printf("\n\nThe final Value is %lf",k);
getch();
}
/***********************************************************************
```

This algorithm works as follows... It calculates the values in a row number, i.e., firstly it will call the value of the permanent for first element in the first row, then adds the permanent of second element of the first row and the process continues...

z keeps the check for per2, what is to be calculated for per2. per will make the values for all z elements '1' except those 2 elements whose per2 has to be calculated.

Variables used in per
int i Temporary integer variable
double res Double variable for storing the value returned from per()
double res2 Double variable for storing the value returned from perof2()
double sum Variable for calculating the sum

```
********************************************************************/
double per(int n)
{
int i;
double res, res2, sum=0;
if((n-2)!=0)
{
int c=0;
for(i=1;i<=totalColumn;i++)
{
if(z[i]==0)
{
z[i]=1;
z[c]=0;
c=i;
res=per(n-1);
res=(double)(res*matrix[totalColumn-n][i-1]);
sum=sum+res;
}
}
z[c]=0;
}
else
{
res2=perof2();
return(res2);
}
return(sum);
}
/********************************************************************
```

This function calculates the value of the matrix 2*2. The 2*2 matrix is defined by the array z[].

```
Variables used in perof2
int i,j Temporary integer variable
int n,m Temporary integer variable
int flag Contains value 0 or 1, acts as Boolean
double res Double variable for storing the value calculated by multiplication
*********************************************************************/
double perof2()
{
int i,j,flag=0,n,m;
double res;
for(i=1;i<=totalColumn;i++)
{
if(z[i]==0)
{
if(flag==0)
{
n=i;
flag=1;
}
else
m=i;
}
}
res=(double)((matrix[totalColumn-2][n-1]*matrix[totalColumn-1][m-1])+(matrix[totalColumn-2][m-1]*matrix[totalColumn-1][n-1]));
return res;
}
```

APPENDIX-IV

Data Used for CCPP Calculations

Gas Turbine

Net power output = 189.5 MW

Net efficiency > 35%

Exhaust gas mass flow rate = 565.2 kg/s

Exhaust gas temperature = 563.4°C

Pressure ratio = 16.0

Ambient temperature = 15°C

Ambient pressure = 1.013 bar

Relative humidity = 60 %

Inlet pressure drop = 10 mbar

Outlet (HRSG) pressure drop = 40 mbar

Auxiliary power for each gas turbine = 400 kW

HRSG

Pinch-point = 10°C

Minimum steam/exhaust approach temperature = 30°C

Economizer approach temperature = 2°C

Pressure drop live-steam pipes

Sub-critical cycles HP=5 %, RH=7 %, IP=7 %, LP=10 %

Super-critical cycles HP=4 %, RH=7 %, IP=7 %, LP=l0 %

Heat loss live-steam pipes = 1°C

Pressure drop super-heaters = 5 %

Pressure drop evaporators = 5 %

Pressure drop economizers = 5 %

Pressure drop feedwater pre-heater = 4 bar

Deaerator pressure = 1.2 bar

Exhaust gas due to heat loss = 2°C

Maximum steam temperature: HP=540°C, RH=560°C

Steam Turbine

Pressure drop throttle valves = 2%

Pressure drop reheat return pipe = 3 %

Isentropic efficiencies: HP=92 %, RH=92 %, IP=92 %, LP=89 % (subcritical)

Isentropic efficiencies: HP=91 %, RH=92 %, IP=92 %, LP=89 % (supercritical)

Steam leakages through seals: HP=0.2 %, RH=0.2 %, IP=0.2 %, LP=0.2 %

LP section leaving loss = 30 kJ/kg

"Wiison line" quality = 0.975

Auxiliary power fraction = 0.25 % (pump work not included)

Mechanical/generator-efficiency = 98.2 %

Condenser

Condenser pressure = 0.04 bar

Cooling water temperature = 15°C

Allowed cooling water temperature increase = 9°C

Cooling water pressure drop = 1 bar

Pumps

Mechanical efficiency = 92 %

Isentropic efficiency = 80 %

Appendix-V

Quantification of Design Parameters

Table 1 Quantification of CR for GTA

Value of CR	5	10	15	20	25
Assigned Value of Inheritance for GTA	2.5	3.8	4	3.9	3.8

Table 2 Quantification of inlet air temperature for GTA

Value of IAT (°C)	5	10	15	20	25	30	35	40	45
Assigned Value of Inheritance for GTA	8	7.84	7.68	7.52	7.36	7.12	6.96	6.8	6.64

Table 3 Quantification of air compressor efficiency for GTA

Value of Air Compressor Efficiency (%)	70	75	80	85	90	95
Assigned Value of Inheritance for GTA	5.17	5.73	6.30	6.87	7.44	8

Table 4 Quantification of gas turbine efficiency for GTA

Value of Gas Turbine Efficiency (%)	70	75	80	85	90	95

Assigned Value of Inheritance for GTA	3.5	5	6.5	8	9	9.8

Table 5 Quantification of TIT for GTA

Value of TIT (°C)	1000	1050	1100	1150	1200	1250	1300	1350	1400
Assigned Value of Inheritance for GTA	7.7	7.6	7.5	7.4	7.3	7.2	7.1	7	6.9

Appendix-VI

Code of Computer Program for Exergetic Analysis

```
{Inlet conditions for the compressor}

T1=25
P1=101.3
Prc=10
R=8.314
Prc=P2/P1
T3=577
T4=1247
LHV=802361
Wnet=30000
```

```
{HRSG Flue Gas and Steam Parameters}

P7=101.3
Phps=2000
msat=14

{Pressure losses in different components}

Plossregeneratorairside=5
Plossregeneratorgasside=3
Plosscombustionchamber=5
PlossHRSG=5

{efficiency and effectiveness parameter}

Eregenerator=0.68
effcombustion=1
effcompressor=0.86
effturbine=0.86
effelectrical=0.85

{Intial composition of air}
x1N2=0.7748
x1O2=0.2059
x1CO2=.0003
x1H2O=0.0190


{State 1- Compressor Inlet}

h1N2=Enthalpy(N2, T=T1)
h1O2=Enthalpy(O2, T=T1)
h1CO2=Enthalpy(CO2, T=T1)
h1H2O=Enthalpy(H2O, T=T1)

h1totalair=x1N2*h1N2+x1O2*h1O2+x1CO2*h1CO2+x1H2O*h1H2O

s1refN2=Entropy(N2, T=T1,P=P1)
```

```
s1refO2=Entropy(O2, T=T1,P=P1)
s1refCO2=Entropy(CO2, T=T1,P=P1)
s1refH2O=Entropy(H2O, T=T1,P=P1)

{Compressor Outlet}

s2srefN2=Entropy(N2, T=T2s,P=P1)
s2srefO2=Entropy(O2, T=T2s,P=P1)
s2srefCO2=Entropy(CO2, T=T2s,P=P1)
s2srefH2O=Entropy(H2O, T=T2s,P=P1)

0=x1N2*(s2srefN2-s1refN2-R*ln(Prc))+x1O2*(s2srefO2-s1refO2-R*ln(Prc))+x1CO2*
(s2srefCO2-s1refCO2-R*ln(Prc))+x1H2O*(s2srefH2O-s1refH2O-R*ln(Prc))

h2sN2=Enthalpy(N2, T=T2s)
h2sO2=Enthalpy(O2, T=T2s)

h2sCO2=Enthalpy(CO2, T=T2s)
h2sH2O=Enthalpy(H2O, T=T2s)

h2stotalair=x1N2*h2sN2+x1O2*h2sO2+x1CO2*h2sCO2+x1H2O*h2sH2O

h2totalair=h1totalair+((h2stotalair-h1totalair)/effcompressor)
h2N2=Enthalpy(N2, T=T2)
h2O2=Enthalpy(O2, T=T2)
h2CO2=Enthalpy(CO2, T=T2)
h2H2O=Enthalpy(H2O, T=T2)
h2totalair=x1N2*h2N2+x1O2*h2O2+x1CO2*h2CO2+x1H2O*h2H2O

{Combustion Chamber }

h3N2=Enthalpy(N2, T=T3)
h3O2=Enthalpy(O2, T=T3)
h3CO2=Enthalpy(CO2, T=T3)
h3H2O=Enthalpy(H2O, T=T3)
h3totalair=x1N2*h3N2+x1O2*h3O2+x1CO2*h3CO2+x1H2O*h3H2O

{Turbine Inlet}
```

```
h4N2=Enthalpy(N2, T=T4)
h4O2=Enthalpy(O2, T=T4)
h4CO2=Enthalpy(CO2, T=T4)
h4H2O=Enthalpy(H2O, T=T4)

dhN2=h4N2-h3N2
dhO2=h4O2-h3O2
dhCO2=h4CO2-h3CO2
dhH2O=h4H2O-h3H2O

hCH4=-74872

CombustionEfficiency=1
a=(x1N2*dhN2+x1O2*dhO2+x1CO2*dhCO2+x1H2O*dhH2O)/(hCH4-.02*effcombustion*LHV-(-2*h4O2+h4CO2+2*h4H2O))

x2N2=x1N2/(1+a)
x2O2=(x1O2-2*a)/(1+a)
x2CO2=(x1CO2+a)/(1+a)
x2H2O=(x1H2O+2*a)/(1+a)

s4refN2=Entropy(N2, T=T4,P=P1)
s4refO2=Entropy(O2, T=T4,P=P1)
s4refCO2=Entropy(CO2, T=T4,P=P1)
s4refH2O=Entropy(H2O, T=T4,P=P1)

{Turbine Outlet}

s5srefN2=Entropy(N2, T=T5s,P=P1)
s5srefO2=Entropy(O2, T=T5s,P=P1)
s5srefCO2=Entropy(CO2, T=T5s,P=P1)
s5srefH2O=Entropy(H2O, T=T5s,P=P1)

P3=(1-(Plossregeneratorairside)/100)*P2
P4=(1- (Plosscombustionchamber)/100)*P3
P7=(1-(PlossHRSG)/100)*P6
P6=(1-(Plossregeneratorgasside)/100)*P5

0=x2N2*(s5srefN2-s4refN2-R*ln(P5/P4))+x2O2*(s5srefO2-s4refO2-R*ln(P5/P4))+x2
```

```
CO2*(s5srefCO2-s4refCO2-R*ln(P5/P4))+x2H2O*(s5srefH2O-s4refH2O-R*ln(P5/P4)
)

h5sN2=Enthalpy(N2, T=T5s)
h5sO2=Enthalpy(O2, T=T5s)
h5sCO2=Enthalpy(CO2, T=T5s)
h5sH2O=Enthalpy(H2O, T=T5s)

h4totalair=x2N2*h4N2+x2O2*h4O2+x2CO2*h4CO2+x2H2O*h4H2O

h5stotalair=x2N2*h5sN2+x2O2*h5sO2+x2CO2*h5sCO2+x2H2O*h5sH2O



h5totalair=h4totalair-((h4totalair-h5stotalair)*effturbine)

h5N2=Enthalpy(N2, T=T5)
h5O2=Enthalpy(O2, T=T5)
h5CO2=Enthalpy(CO2, T=T5)
h5H2O=Enthalpy(H2O, T=T5)
h5totalair=x2N2*h5N2+x2O2*h5O2+x2CO2*h5CO2+x2H2O*h5H2O

{Net work output from the cycle}

MWair=28.649
MWfuel=16.043
ma=(MWair*Wnet )/((1+a)*(h4totalair-h5totalair)-(h2totalair-h1totalair))
mf=a*(MWfuel/MWair)*ma
mp=ma+mf
na=ma/MWair
nf=(na)*a
np=(na)*(1+a)
Wcomp=na*(h2totalair-h1totalair)
Wturb=np*(h4totalair-h5totalair)
Wel=effelectrical*Wnet

{Regenerator outlet}
na*(h3totalair-h2totalair)=np*(h5totalair-h6totalair)
h6N2=Enthalpy(N2, T=T6)
h6O2=Enthalpy(O2, T=T6)
```

```
h6CO2=Enthalpy(CO2, T=T6)
h6H2O=Enthalpy(H2O, T=T6)
h6totalair=x2N2*h6N2+x2O2*h6O2+x2CO2*h6CO2+x2H2O*h6H2O
Eregenerator*(T5-T2)+T2=T3actual

{HRSG Outlet}
Tsat9=T_sat(Water,P=Phps)
hg1=Enthalpy(Steam,P=Phps,x=1)
hfwhp=Enthalpy(Steam,T=T1,P=Phps)
MWwater=18
nsat=msat/18
np*(h6totalair-h7totalair)=nsat*(hg1-hfwhp)

h7N2=Enthalpy(N2, T=T7)
h7O2=Enthalpy(O2, T=T7)
h7CO2=Enthalpy(CO2, T=T7)
h7H2O=Enthalpy(H2O, T=T7)
h7totalair=x2N2*h7N2+x2O2*h7O2+x2CO2*h7CO2+x2H2O*h7H2O
Qp=np*(h6totalair-h7totalair)

{physical exergy analysis at different state points}

To=T1
Po=P1
ho=h1totalair
so=s1totalair
s1N2=Entropy(N2, T=T1,P=x1N2*P1)
s1O2=Entropy(O2, T=T1,P=x1O2*P1)
s1CO2=Entropy(CO2, T=T1,P=x1CO2*P1)
s1H2O=Entropy(H2O, T=T1,P=x1H2O*P1)

s1totalair=x1N2*s1N2+x1O2*s1O2+x1CO2*s1CO2+x1H2O*s1H2O

E1PH=na*((h1totalair-ho)-(To+273)*(s1totalair-so))


{compressor outlet}

s2N2=Entropy(N2, T=T2,P=x1N2*P2)
```

```
s2O2=Entropy(O2, T=T2,P=x1O2*P2)
s2CO2=Entropy(CO2, T=T2,P=x1CO2*P2)
s2H2O=Entropy(H2O, T=T2,P=x1H2O*P2)

s2totalair=x1N2*s2N2+x1O2*s2O2+x1CO2*s2CO2+x1H2O*s2H2O

E2PH=na*((h2totalair-ho)-(To+273)*(s2totalair-so))

{Combustion chamber inlet}

s3N2=Entropy(N2, T=T3,P=x1N2*P3)
s3O2=Entropy(O2, T=T3,P=x1O2*P3)
s3CO2=Entropy(CO2, T=T3,P=x1CO2*P3)
s3H2O=Entropy(H2O, T=T3,P=x1H2O*P3)

s3totalair=x1N2*s3N2+x1O2*s3O2+x1CO2*s3CO2+x1H2O*s3H2O

E3PH=na*((h3totalair-ho)-(To+273)*(s3totalair-so))


{Turbine Inlet}

s4N2=Entropy(N2, T=T4,P=x2N2*P4)
s4O2=Entropy(O2, T=T4,P=x2O2*P4)
s4CO2=Entropy(CO2, T=T4,P=x2CO2*P4)
s4H2O=Entropy(H2O, T=T4,P=x2H2O*P4)

s4totalair=x2N2*s4N2+x2O2*s4O2+x2CO2*s4CO2+x2H2O*s4H2O

hodesh=h1deshtotalair
sodesh=s1deshtotalair

x2water=1-(x2N2+x2O2+x2CO2+x2H2O)
h1water=Enthalpy(Water,T=T1,P=P1)
h1deshtotalair=x2N2*h1N2+x2O2*h1O2+x2CO2*h1CO2+x2H2O*h1H2O+x2water*
h1water

x2deshN2=(x2N2)/(x2N2+x2O2+x2CO2+x2H2O)
x2deshO2=(x2O2)/(x2N2+x2O2+x2CO2+x2H2O)
```

```
x2deshCO2=(x2CO2)/(x2N2+x2O2+x2CO2+x2H2O)
x2deshH2O=(x2H2O)/(x2N2+x2O2+x2CO2+x2H2O)

s1deshN2=Entropy(N2, T=T1,P=x2deshN2*P1)
s1deshO2=Entropy(O2, T=T1,P=x2deshO2*P1)
s1deshCO2=Entropy(CO2, T=T1,P=x2deshCO2*P1)
s1deshH2O=Entropy(H2O, T=T1,P=x2deshH2O*P1)
s1deshwater=Entropy(Water,T=T1,P=P1)
s1deshtotalair=x2N2*s1deshN2+x2O2*s1deshO2+x2CO2*s1deshCO2+x2H2O*s1deshH2O+x2water*s1deshwater
E4PH=np*((h4totalair-hodesh)-(To+273)*(s4totalair-sodesh))

{Turbine Outlet}

s5N2=Entropy(N2, T=T5,P=x2N2*P5)
s5O2=Entropy(O2, T=T5,P=x2O2*P5)
s5CO2=Entropy(CO2, T=T5,P=x2CO2*P5)
s5H2O=Entropy(H2O, T=T5,P=x2H2O*P5)

s5totalair=x2N2*s5N2+x2O2*s5O2+x2CO2*s5CO2+x2H2O*s5H2O

E5PH=np*((h5totalair-hodesh)-(To+273)*(s5totalair-sodesh))

{Regenerator outlet}

s6N2=Entropy(N2, T=T6,P=x2N2*P6)
s6O2=Entropy(O2, T=T6,P=x2O2*P6)
s6CO2=Entropy(CO2, T=T6,P=x2CO2*P6)
s6H2O=Entropy(H2O, T=T6,P=x2H2O*P6)

s6totalair=x2N2*s6N2+x2O2*s6O2+x2CO2*s6CO2+x2H2O*s6H2O

E6PH=np*((h6totalair-hodesh)-(To+273)*(s6totalair-sodesh))

{HRSG outlet}

s7N2=Entropy(N2, T=T7,P=x2N2*P7)
s7O2=Entropy(O2, T=T7,P=x2O2*P7)
s7CO2=Entropy(CO2, T=T7,P=x2CO2*P7)
```

```
s7H2O=Entropy(H2O, T=T7,P=x2H2O*P7)

s7totalair=x2N2*s7N2+x2O2*s7O2+x2CO2*s7CO2+x2H2O*s7H2O

E7PH=np*((h7totalair-hodesh)-(To+273)*(s7totalair-sodesh))

{condensate inlet to HRSG}

hof=Enthalpy(Water,T=To,P=Po)
sof=Entropy(Water,T=To,P=Po)
sconhp=Entropy(Water,T=T1,P=Phps)
E8PH=nsat*((hfwhp-hof)-(To+273)*(sconhp-sof))

{steam outlet to HRSG}

sg1=Entropy(Steam, x=1,P=Phps)
E9PH=nsat*((hg1-hof)-(To+273)*(sg1-sof))

{Fuel inlet to combustion chamber}

Pf=1200
x=ln(Pf/Po)
Rf=R/MWfuel
EfPH=mf*Rf*(To+273)*x

{CHEMICAL EXERGY ANALYSIS AT DIFFERENT STATE POINTS}

eowater=45
eoCH4=824348
eoN2=639
eoO2=3951
eoH2O=8636
eoCO2=14176
E1CH=0
E2CH=0
E3CH=0
{TURBINE INLET}
```

```
B=x2deshN2*eoN2+x2deshO2*eoO2+x2deshCO2*eoCO2+x2deshH2O*eoH2O

p=ln(x2deshN2)
q=ln(x2deshO2)
t=ln(x2deshCO2)
s=ln(x2deshH2O)

C=R*(To+273)*(x2deshN2*p+x2deshO2*q+x2deshCO2*t+x2deshH2O*s)

D=B+C

E=(x2N2+x2O2+x2CO2+x2H2O)*D+x2water*eowater
E4CH=np*E

E5CH=E4CH

E6CH=E4CH

E7CH=E4CH

E8CH=nsat*eowater

E9CH=E8CH

EfCH=nf*eoCH4

{Total Exergy}

E1=E1PH

E2=E2PH
E3=E3PH
E4=E4PH+E4CH
E5=E5PH+E5CH

E6=E6PH+E6CH

E7=E7PH+E7CH
```

E8=E8PH+E8CH

E9=E9PH+E9CH

Ef=EfPH+EfCH

Edcompressor=Wcomp+E1-E2

Edregenerator=E2+E5-E3-E6

Edcombustionchamber=E3+Ef-E4

Edturbine= -Wturb+E4-E5

EdHRSG=E6-E7+E8-E9

Appendix-VII

Validation of Exergy Analysis Results for CGCPP

State	Substance	Mass flow rate	Temperature	Pressure	Enthalpy	Exergy

1	Air	91.01 (91.27)	298.15 (298.15)	101.1 (101.3)	-4713 (-4713.3)	0
2	Air	91.01 (91.27)	611.35 (603.14)	101.1 (101.3)	4632(4596)	27586 (27538)
3	Air	91.01 (91.27)	850 (850)	962.4 (962.3)	12190 (12524)	41328 (41938)
4	Combustion Products	92.66 (92.92)	1520 (1520)	914.2 (914.2)	8963 (9304.41)	10111.3 (10168.9)
5	Combustion Products	92.66 (92.92)	1010 (1006)	109 (109)	-9237 (-8839)	38433 (38789)
6	Combustion Products	92.66 (92.92)	794 (780)	106 (106)	-16558 (-16522)	22134 (21992)
7	Combustion Products	92.66 (92.92)	430 (426)	101.1 (101.3)	-28061 (-27974)	2847 (3713)
8	Water	14.00 (14.00)	298.15 (298.15)	2000 (2000)	1920 (1884.6)	61.67 (61.6)
9	Steam	14.00 (14.00)	485 (485)	2000 (2000)	50420 (50347.8)	12842 (12810.2)
10	Methane	1.647 (1.641)	298.15 (298.15)	1200 (1200)	-74872 (-74872)	85234.6 (84993.9)

Appendix-VIII

Publications Out of Research work

A) Paper Accepted and Published in International Journal:

1. "System Modeling and Analysis of a Combined Cycle Power Plant" International journal of system assurance and management (Springer), DOI 10.1007/s13198-012-0112-y.

2. "Computational Analysis of Dual Pressure Non-reheat Combined-Cycle Power Plant with Change in Drum Pressures" International Journal of Applied Engineering Research, vol 5, No.8 (2010), p. 1307-1313.

3. "Graph Theoretic Assessment of Critical Component in Combined-Cycle Power Plant" International Journal of Engineering Studies, vol 4, No.1 (2012), p. 1-13.

4. "Exergy analysis and simulation of a 30MW cogeneration cycle" Frontiers of Mechanical Engineering (Springer) (Accepted for publication).

5. "GTA-based framework for evaluating the role of design parameters in cogeneration cycle power plant efficiency" Ain Shams Engineering Journal (Elsevier) (Accepted for publication).

B) Paper Presented in Conferences:

6. "Modeling and Analysis of Dual Pressure Non-reheat Combined-Cycle with Change in Drum Pressures" Proceeding of international conference on advances in mechanical engineering held at SVNIT Surat, 04-06 January, 2010, p-114-118.

7. "Energy and Exergy Analysis of Cogeneration Cycle With Change in Gas Turbine Operating Parameters" Proceeding of international conference on emerging technologies for sustainable environment held at AMU Aligarh, 29-30 October, 2010, p- 412-414.

8. "A Comparison of Single and Dual Pressure Steam Extraction from Steam Turbine of Combined Cycle Power Plant" Proceeding of international conference on emerging trends in Mechanical Engineering held at Thapar University Patiala, 24-26 February, 2011, p-88.

9. "Mathematical modeling and exergetic analysis of cogeneration cycle with change in gas turbine parameters" Proceeding of international conference on emerging trends in Mechanical Engineering held at Thapar University Patiala, 24-26 February, 2011, p-81.

10. "A Study of Combustion Product Concentration on Gas Turbine Performance" Proceeding of international conference CONIAPS-2011, held at UPES, Dehradun from 14-16 June, 2011, P084, pp-172.

11. "Simulation of gas turbine combustion chamber for CO_2 emission minimization" SOCPROS-2011, Advances in Intelligent and Soft Computing (AISC, Springer), 2011, Vol 131, p 235-246.

12. "Mathematical Modelling and Computer Simulation of a Combined Cycle Power Plant" SOCPROS-2011, Advances in Intelligent and Soft Computing (AISC, Springer), 2011, Vol 131, p 341-350.

13. "A review of combined cycle power plant thermodynamic cycles" Proceedings of national conference TAME-2012, from 19-20 October, 2012, p. 78-89.

C) Papers Communicated

14. "Digraph and matrix method for assessing the role of design parameters in Gas Turbine Power Plant efficiency" Alexandria Engineering Journal (Elsevier).

15. “Development of reliability index for combined cycle power plant using Graph Theoretic Approach” Ain Shams Engineering Journal (Elsevier).

16. “System modeling and analysis of a cogeneration cycle power plant using Graph Theoretic Approach” Sadhana (Springer).