Coding, Evaluation and Selection of Gas Turbine Systems

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Abstract: *This paper proposes coding, evaluation and selection methodologies for gas turbine systems. The various attributes which characterize the gas turbine systems are identified under different subsystems and different operating characteristics of the gas turbine systems. The attributes include the best load as well as off-base load application and contribute to a generalized gas turbine system rather a typical power generation application or the aircraft applications. A structured approach for coding of the attributes has been proposed in this paper which not only helps in qualitative evaluation of the attributes but also in the feature based selection of the gas turbine system for a set of constraints pertaining to a specific application using TOPSIS. For better qualitative evaluation of the attributes, Graph theoretical methodology has also been adopted for the selection of the gas turbine systems. A comparative evaluation of the techniques adopted in proposed gas turbine systems have also been carried out.*

Keywords: *Gas turbine system evaluation, graph theoretic approach, TOPSIS approach, gas turbine system selection.*

1. INTRODUCTION

Due to rapidly growing power generation global market and the developments in the gas turbine systems through usage of latest technologies, a number of features have been incorporated in the gas turbine systems by the its manufacturers with an objective to have huge share of their product in the power consumption market. Since the gas turbine systems are used for wide range of applications like marine applications, aircraft applications, industrial application, petrochemicals etc, it is not feasible for the manufacturer to design and supply a gas turbine system to meet out the specific tasks at the application domain level unless it is of most requisite concern. Thus, the gas turbine systems are manufactured to meet almost all the power generation system demands in general and to meet the standards of the specific objectives. For example, specific thrust may be area of concern in aircraft application while combined cycle efficiency of the gas turbine system in case of industrial base load applications.

The optimum selection of the gas turbine system for a particular application can be done by considering the effect of several factors or the attributes on the performance of a typical gas turbine system available for selection. Since, these attributes are quite different and conflicting in nature, it becomes very difficult to select an application specific gas turbine system from the available alternative solutions. This complexity of the solution increases further when the number of decision making attributes increases to more than 100 for a particular application.

There is no work available in the literature concerning such evaluations and selection process applied to the gas turbine systems. It is found that such search selection techniques have been successfully implemented by several researchers in other system like robot selection[1], analysis of steam power plants[2,6], TQM evaluation of an industry[4] and the thermal power plants[13]. The importance of multi-attribute decision making methods has also been explained in detail in literature[3]. Since, a number of attributes are qualitative in nature in such complex problems, the estimation of weights using intuitionistic preference relations have been suggested in the literature[7] which is widely being used now a days. In the area of gas turbines, the impact of business partnerships[5] on the gas turbine power plant operation optimization and the changing system design requirements[8] has also been critically examined by the authors in the literature. Being a premier manufacturer and service provider of the gas turbine systems, several reports have been published by general Electric[10] and Bharat heavy electrical limited[15] in India. The various performance parameters of a typical gas turbine system have been identified and compiled by Walsh[11] and Boyce[12]. The role of gas turbines in the present power generation market, its flexibility of operation and the factors[9] responsible for its success with respect to other power generation mechanism alternatives including gas turbine performance monitoring[14] have been studied in the literature. It is worthwhile to mention here that a large number of research papers have been published for the performance improvements of gas turbine systems to be used for specific applications. A few of them which are found to be quite useful in analyzing the gas turbine systems have been referred for logical representation of the data related to interdependencies of the attributes. However, efforts have been done in this paper to adopt different techniques which can help in efficient decision making for the selection of gas turbine systems.

Since the selection process is cardinal in nature, the selection procedure is carried out employing a cardinal preference MADM method called TOPSIS. Then the graph theoretical methodology is used in decision making of the selection of gas turbine system with respect to the benchmark standards of gas turbine systems through the logical interpretation of interdependencies of the preferred attributes contributing to overall system performance index.

2. IDENTIFICATION OF GAS TURBINE ATTRIBUTES

For the identification of attributes for the gas turbine systems, such systems are critically analyzed on the basis of their constructional details, typical functional contribution of its constituent parts or mechanisms for specific applications, performance analysis of the entire functional gas turbine system. These constituent parts or mechanisms are also terms as subsystems of the gas turbine systems. Various factors or attributes affecting the system performance as well as subsystem performances contributing to the achievement of objectives for the application are identified which directly or indirectly affect the selection and evaluation of gas turbines. More number of attributes may also be considered for the gas turbine systems and specific applications.

A proper identification of the attributes helps in precise evaluation of selection of gas turbine systems. As the number of attributes increases, the performance characteristics of such systems are represented precisely and the selection of gas turbine system becomes more reliable. However, with increase in number of attributes, usage of dedicated computer programs becomes more indispensable for efficient evaluation and selection of gas turbine systems. Generally, the attributes of the gas turbine systems can be classified either by different subsystems of the gas turbine system or by the different performance characteristics of the gas turbine systems as well as matching of its subsystems.

2.1 Classification on the basis of different subsystems of the gas turbine systems

Since the gas turbine systems consist of several Turbomachinery as per specific configuration or layout, various attributes have been identified at the turbine system level as well as at the subsystem level which have been mentioned:-

2.1.1 Gas turbine system physical attributes

The gas turbine system physical attributes are the attributes which define the overall configuration of the gas turbine systems. These are:

1. Gross weight of gas turbine system
2. Size or floor space
3. Power to weight ratio
4. Type of drive
5. Type of application
6. Gas turbine engine category
7. Type of turbomachinery
8. Turbomachinery layout
9. Type of fuel to be used
10. Type of power cycle
11. Air handing capacity
12. Installation (Indoor or outdoor)

2.1.2 Gas turbine engine performance attributes

The aim of gas turbine systems is to perform with desired performance level by producing power in particular power generation application. The gas turbine system performance parameters decide or affect all the other subsystem parameters directly or indirectly. The parameters which decide the performance or power of the gas turbine systems are :

13. Output power or net thrust
14. Overall pressure ratio
15. Maximum firing temperature
16. Exhaust gas power
17. Specific power or thrust
18. Specific fuel consumption
19. Thermal efficiency
20. Combined cycle efficiency
21. Heat rate
22. Exhaust temperature
23. Exhaust mass flow
24. Overall plant efficiency
25. Propulsive efficiency

2.1.3 Compressor attributes

In a gas turbine system, the intake air is initially compressed in the compressor to increase its pressure and temperature i.e. the heat energy content which is to be further utilized in other subsystems of the system in order to produce net power or thrust. The performance of the compressor significantly affects the overall performance of the gas turbine system. Since, the energy transfer during the flow of air in the compressor takes place, the thermodynamic as well as the aerodynamic and mechanical design dimensions and factors affecting these parameters play a significant role in the performance of the compressor. The various attributes affecting the compressor design and performance are:

26. Type of compressor (centrifugal or axial flow)
27. Design of inlet guide vanes
28. Compressor pressure ratio
29. Stage temperature rise
30. Stage loading
31. Number of stages
32. Number of spools in compressor
33. Rotational speed
34. Mass flow of air
35. Ambient operating conditions
36. Power input factor
37. Slip factor
38. Type of gas seals
39. Type of oil seals
40. Type of radial bearings
41. Type of thrust bearings
42. Type of impeller
43. Type of impeller attachment to shaft
44. Type and number of blades
45. Location of balance planes
46. Weight of the rotors
47. Type of coupling between tandems
48. Inlet Mach number to compressor
49. Surge margin
50. Rotating stall
51. Flexural rigidity of blades
52. Blade efficiency
53. Efficiencies of compressor
54. Hub to tip ratio
55. Blade angle
56. Air inlet velocity
57. Aspect ratio
58. Blade gapping
59. Swirl angle
60. Pitch to chord ratio
61. Foreign Object Damage (FOD) susceptibility
62. Bleed off valve performance

2.1.4 Combustion system attributes

The air with high pressure and temperature as received from the exit manifold of the compressor is fed to the combustion chamber wherein the fuel in atomized form is fed. Due to the high temperature of the air, the fuel droplets get ignited and generate thermal energy due to its burning, subsequently, increasing the temperature of the hot fluid medium in the combustor. Higher is the peak temperature achieved in the combustor, higher is the efficiency of the gas turbine. Since, the peak firing temperature is achieved within the combustor, it becomes essential to design the combustor to perform for peak temperature loadings. The various attributes affecting the design and performance of the combustion system are:

63. Type of combustors
64. Combustor loading
65. Combustor inlet temperature
66. Combustor liner material properties
67. Nature of fuel
68. Fuel properties
69. Combustion efficiency
70. Combustor pressure loss
71. Overall temperature distribution factor
72. Peak temperature in combustor
73. Combustion stability
74. ~~NOx emission level~~
75. Combustion intensity

2.1.5 Turbine attributes

The heat content of the gases obtained at the exit of the combustor is converted into work output through energy transformation in the gas turbine. The performance of gas turbine in the system is measured in terms of several attributes and is governed by the attributes of other matching turbomachinery components within the system. The designs of various subsystems of the turbine contribute in the desired gas turbine performance. The various attributes as identified which affect the design and performance of the gas turbines taking thermodynamic, aerodynamic and mechanical design constraints in to account are:

76. Blade loading coefficient
77. Degree of reaction
78. Turbine inlet temperature
79. Flow coefficients
80. Type of blade profile
81. Pitch to chord ratio
82. Aspect ratio
83. Number of blades
84. Mach number at blade inlet

85. Mach number at stage outlet
86. Blade efficiency
87. Overall turbine temperature drop
88. Number of stages
89. Turbine efficiency
90. Nozzle blades loss coefficients
91. Rotor blades loss coefficients
92. Profile loss coefficients
93. Tip clearance loss
94. Annulus losses
95. Secondary flow losses
96. Incident angle
97. Rotor blade stresses
98. Blade angles
99. Gas bending stresses
100. Matching level to compressor performance
101. Gas turbine blade material type

2.1.6 Drive system attributes

The attributes which affect the performance of drive system are:

102. Type of coupling
103. Weight of coupling
104. Overhung coupling moment level
105. Balancing potential of couplings
106. Operating speed limit
107. Misalignment capacity at varying speed
108. Axial movement capacity
109. Type of gearing
110. Type of elastomer
111. Abrupt failure resistant capacity

2.1.7 Control system (cabinet) attributes

The control system in gas turbines uses the latest microprocessor technology to manipulate, analyse and display the data to assist in troubleshooting and maintenance. The attributes which affect the performance of control system cabinet are:

112. Proximity of dedicated control cabinet to GTG
113. Housing capability of all control panels related to GTG
114. Air-conditioning quality of interior
115. Position of separate battery compartment
116. Speedtronic control panel facility
117. Position of generator relay and control panel
118. Positioning of AVR, DCDB
119. Housing capability of motor control centre
120. Positioning of battery bank
121. Positioning of battery charger
122. Auxiliary rack and fire protection panel facility

2.1.8 Inlet system attributes

The inlet system is designed to allow fresh contaminant free air, smooth and uniform flow with low aerodynamic losses, to the gas turbine. The inlet system attributes are:

123. Self cleaning pulse jet air filter efficiency
124. Air intake duct geometry with silencer
125. Inlet plenum geometry
126. Air processing unit performance for cleaning air
127. Air compressor skid performance

2.1.9 Exhaust system attributes

The exhaust gas from the gas turbine is directed to the atmosphere by the exhaust system. The exhaust system is also designed to suit the operational loads (cyclic operation associated with daily starts etc.), wind load, seismic load and the foundation load. The attributes which affect the performance of exhaust system are:

128. Internally insulated exhaust duct performance
129. Exhaust silencer part of exhaust duct performance
130. Exhaust duct geometry (to HRSG)
131. Bypass stack layout
132. Diverter damper efficiency
133. Guillotine gates layout for HRSG isolation

2.1.10 Starting system attributes

A starting system cranks the gas turbine during startup in its run-up to firing and further loadings. The attributes which affect the performance of starting system are:

134. Type of prime mover device (Diesel engine or motor)
135. Hydraulic torque converter arrangement
136. Jaw clutch arrangement between starting device and gas turbine
137. Ratcheting device performance
138. Accessory gear box transmission efficiency

2.1.11 Enclosures and ventilation system attributes

The design and layout of enclosures and ventilation system affects the performance of the gas turbine system by restricting several operational hazardous. Enclosures provide thermal isolation, acoustical attenuation, fire extinguishing media containment and enclosed space for cooling/ ventilating media for the gas turbine. The attributes which affect the performance of such a system are:

139. Type of enclosures (off-base or on-base)
140. Type of ventilation (induced draft or positive ventilation)
141. Fire protection convenience

142. Packaging convenience
143. Vent fans location for GT enclosure and load gear compartment
144. Louvered dampers position for enclosure openings
145. Number of air changes

2.1.12 Fire protection system attributes

Gas turbine operation involves high temperatures and thus the possibility of a fire hazard. A high degree of redundancy is built in fire protection system such that reliability of the system is high. The attributes which affect the performance of fire protection system are:

146. Common CO_2 based fire protection system performance (for GTG)
147. Initial and extended discharge quantity for GT compartments
148. Main and standby system discharge for generator and GAC
149. Heat rise detectors performance mounted inside enclosures
150. CO_2 cylinder bank location in an off base enclosure
151. CO_2 operated latches performance for control dampers
152. Microprocessor based addressable control panel performance

2.1.13 Liquid fuel system attributes

The liquid fuel system is generally designed to operate at high pressures on which the fuel is distributed to the combustors from the high pressure fuel pump. Due to the presence of rotating parts and the fact that the fuel needs to be metered accurately, fine adjustments and monitoring of various operating parameters of this system is desirable. The attributes which affect the performance of liquid fuel system are:

153. Shaft driven fuel pump pressure ratio
154. Linear flow divider performance
155. On base stop and bypass valve efficiency
156. Accessory gear mechanical efficiency for pump drive
157. H.P. fuel oil system pressure
158. Fuel nozzles efficiency suitable for liquid fuels
159. On base atomizing compressor and cooler efficiency

2.1.14 Atomizing air system attributes

Liquid fuel need to be atomized prior to firing in the combustion chamber. This system atomizes the liquid fuel by breaking the fuel into fine droplets of mist like mixture by using high pressure air extracted from the main compressor. The attributes which affect the performance of atomizing air system are:

160. Atomizing air pre-cooler effectiveness
161. Main atomizing air compressor efficiency
162. Atomizing fuel nozzles efficiency
163. Booster atomizing air compressor efficiency

2.1.15 Gas fuel system attributes

The gas fuel system in gas turbines is very sensitive to inlet gas pressure and temperature. Hence, a range of operating as pressures and temperatures need to be prescribed depending upon the frame size of the gas turbines. The gas fuel systems are also designed to handle hazardous gases like those containing high hydrogen content. The attributes which affect the performance of gas fuel system are:

164. Gas stop valve efficiency
165. Gas control valve performance
166. Distribution manifold efficiency
167. Gas nozzle performance
168. Wobbie Index

2.1.16 Lubricating oil system attributes

The lubricating oil system supplies the cooled and filtered lubricant to bearings, gears and couplings of the gas turbines and its associated load equipment. The system is designed to provide continuous, reliable and adequate flow of lubricating oil to the above components during start ups, operation and cool-down at proper pressure and temperature. The attributes which affect the performance of lubricating oil system are :

169. Self contained lubricating oil system performance for GTG
170. Common system performance for GT, generator and load gear box
171. Shaft driven main oil pump performance
172. AC motor driven auxiliary oil pump performance
173. DC motor driven emergency oil pump performance
174. Duplex off base Shell and Tube type lubricating oil cooler effectiveness
175. Duplex on- base lubricating oil filter performance
176. Portable lubricating oil centrifuge efficiency
177. Mist eliminator efficiency for oil recovery

2.1.17 Cooling water system attributes

Since, most of the other subsystems require that the temperatures be maintained within a reasonable design limit, for which external cooling becomes essential. Further, this system controls the flow of external cooling medium like water to the coolers to ensure that working fluid (medium being cooled) is maintained at the designed temperature irrespective of ambient. conditions and machine operating conditions. The attributes which affect the performance of cooling water system are:

178. Lube oil cooler performance
179. Atomizing air cooler performance
180. Type of cooling arrangement (open system cooling tower or industrial type water to air heat exchanger)
181. Type of antifreeze additives
182. Type of anti-corrosive additives

2.1.18 Water wash system attributes

Often a loss of performance of the gas turbine, as indicated by a reduction in the output and increase in the heat rate, is a direct result of fouling of axial flow compressor. The water washing system is primarily involved in rinsing the compressor with hot water, mixing the detergent with water in proper ratio and injecting it to the compressor after initial rinsing, soaking and subsequent rinsing of the compressor. During water wash, the gas turbine is kept under crank mode. The attributes which affect the performance of water wash system are:

183. Offline water wash system performance
184. Water wash performance on a off-base skid
185. Water storage and heating performance
186. Water pumping system performance
187. Detergent storage and pumping system performance
188. Common skid performance for each site

2.1.19 NOx abatement system attributes

Due to stringent restrictions imposed by statutory regulations, the presence and performance of NOx abatement system has been vital in a gas turbine system. Various measures have been incorporated in this subsystem to reduce the pollutants especially Nitrogen oxides etc. The attributes which affect the performance of NOx abatement system are:

189. Fuel air ratios
190. Flame temperature
191. Firing temperature
192. Residence time
193. Specific humidity
194. Off-base water injection skid performance
195. Single multistage water pump (motor driven) performance
196. Motorized control valve for flow control performance
197. Flow meter performance for flow control
198. DM water requirements level
199. Steam injection system performance
200. Water injection system performance

2.1.20 General attributes

201. Life cycle cost
202. Ease of operation
203. Availability of replaced parts
204. Maintainability
205. Efficient use
206. Cost of spare parts
207. Safety
208. Reliability
209. Security
210. Noise control
211. Aesthetic design
212. Operational flexibility

2.2 Classification on the basis of differe[nt] characteristics of the Gas turbine syste[m]

The gas turbine system performance is als[o] evaluated on different operation conditions. F[or] example, in case of power generation applicatio[n] desired outcomes are primarily combined cyc[le] efficiency and the specific fuel consumption. Sim[ilarly] in case of aircraft applications, operational performan[ce] is measured for specific thrust and the performance [of] the gas turbines at varying ambient conditions includin[g] altitude. Summarily, the various performanc[e] characteristics can also be used for the selection [of gas] turbine systems for typical applications which are:

2.2.1 Design point performance characterist[ics] attributes

For initial stage of the operating conditions, whe[re] the gas turbine engine will spend most time, is primari[ly] termed as engine design point. For an industrial [ga]s the gas turbine system would normally work on bas[e] load and for aircraft applications it will cruise a[t] altitude on ISO day. In design point performanc[e] calculations of the gas turbine systems, the input de[sign] parameters are changed in cyclic manner for a resultin[g] change in optimized geometry of the as turbine system for fixed operating conditions. The various attribute[s] which affect the design point performanc[e] characteristics of the gas turbine systems are:

1. Turbomachinery geometry parameters
2. Simple cycle gas turbine efficiency
3. Combined cycle gas turbine efficiency
4. Aerodynamic lift and drag coefficients
5. Incorporation of latest cooling technology
6. Peak firing temperature
7. Higher pressure ratios

8. Inlet system performance
9. Liquid fuel system performance
10. Atomizing air system performance
11. Gas fuel system performance
12. Cooling water system performance
13. NOx emission system performance

2.2.2 Off-design performance attributes

With the engine geometry fixed by design point studies, the performance at other key operating conditions is to be evaluated i.e. the geometric dimensions remain unchanged and the operating conditions are varying. For example, take off in aero engines etc. The various factor which affect the off- design performance of the gas turbine systems are:

1. Thermodynamic matching model attributes
2. Intake recovery factor
3. Variable stator vanes scheduling
4. Bleed off valve performance
5. Part power or thrust attributes
6. Turbine and nozzle capacities
7. Component efficiencies
8. Core flow changes impact
9. Control system design attributes

2.2.3 Transient performance characteristic attributes

Transient performance deals with the operating regimes where engine performance parameters are changing with time. The engine performance during transient maneuvers and the control system design are in-separable as the engine responds to the schedules of fuel flow, variable geometry etc. implemented via the control system. The various attributes which affect the transient performance of the gas turbine systems are:

1. Power lever angle movement
2. Control system performance
3. Exhaust system performance
4. Engine design philosophy
5. Engine aero-thermal model attributes
6. Component response attributes

2.2.4 Operational performance characteristic attributes

The design of the gas turbine system may be ideal enough that may perform to meet the desired threshold limits of the attributes. However, its performance is evaluated by taking several other factors like reliability measures, skill level required for its operation, maintainability of the system, complexity in the gas turbine system framework and the perceived quality of the system as desired by the customer. The various factors affecting the operational performance of the entire gas turbine system are:

1. Engine component performance
2. Personal or human performance
3. Reliability of turbomachinery cascade system
4. Logistic support capability
5. Exhaust system performance
6. Starting system performance
7. Fire protection system performance
8. Enclosures and ventilation system performance
9. Liquid fuel system performance
10. Lubricating oil system performance
11. Cooling water system performance
12. Water wash system performance

2.2.5 Business and economic characteristic attributes

The power generation systems are always evaluated on the basis of their life cycle cost and the net profit values per unit time of operation. As the customer demands regular uprates in its existing gas turbine system for better performance with minimum cost, a strategic evaluation is done for the gas turbine systems keeping these objectives into account. The various factors or the attributes which affect the business and economic characteristics of the gas turbine systems are:

1. Product development costs
2. New unit sales forecast and price
3. Operation and maintenance costs
4. Aftermarket sales forecast and price
5. Life cycle cost
6. Marketing strategy
7. Low cost alternative fuel flexibility

From the above attributes under different characteristics, it is found that the gas turbine system characteristics are interdependent of each other. Varying one attribute to improve one characteristic of the gas turbine system affects some other characteristics of the gas turbine systems.

3. GAS TURBINE ATTRIBUTES CLASSIFICATION AND CODING STRUCTURE

For clear identification of the attributes, the attributes can be classified and coded. Either the qualitative approach or the quantitative approach may be used for the classification of the gas turbine system attributes. A 10- Point scale may be used for the assignment of coded attribute's value for which the crisp ranges are available. The coded attribute's value may be assigned in ascending order on the scale according to their contribution in evaluation and selection of the gas turbine systems for benefit type attributes and vice versa for cost type attributes. There may be some attributes which may be represented in linguistic form or qualitatively. The presence of such attributes directly affects the evaluation and selection of the gas turbine systems. Such attributes are coded in the form of alphabets according to their nature of affect and presence in the system. On the basis of different characteristics of the attributes, the gas turbine system coding structure is developed. The number or alphabet placed in each box of the coded structure represents the corresponding attribute of the gas turbine system mentioned in the classification. The gas turbine system has been classified and coded in the form of 212 attributes which give complete information about the gas turbine systems. A typical example of a simple gas turbine system used in power generation unit has been represented in Table 1.

Table 1: Gas turbine system identification scheme

	Attribute(s)												
Physical attributes	1	2	3	4	5	6	7	8	9	10	11	12	
Engine performance attributes	13	14	15	16	17	18	19	20	21	22	23	24	25
Compressor attributes	26 39 52	27 40 53	28 41 54	29 42 55	30 43 56	31 44 57	32 45 58	33 46 59	34 47 60	35 48 61	36 49 62	37 50	38 51
Combustion system attributes	63	64	65	66	67	68	69	70	71	72	73	74	75
Turbine attributes	76 89	77 90	78 91	79 92	80 93	81 94	82 95	83 96	84 97	85 98	86 99	87 100	88 101
Drive system attributes	102	103	104	105	106	107	108	109	110	111			
Control system (Cabinet) attributes	112	113	114	115	116	117	118	119	120	121	122		
Inlet system attributes	123	124	125	126	127								
Exhaust system attributes	128	129	130	131	132	133							
Staring system attributes	134	135	136	137	138								
Enclosure and ventilation system attributes	139	140	141	142	143	144	145						
Fire protection system attributes	146	147	148	149	150	151	152						
Liquid fuel system attributes	153	154	155	156	157	158	159						
Atomizing air system attributes	160	161	162	163									
Gas fuel system attributes	164	165	166	167	168								
Lubricating oil system attributes	169	170	171	172	173	174	175	176	177				
Cooling water system attributes	178	179	180	181	182								
Water wash system attributes	183	184	185	186	187	188							
NOx abatement system attributes	189	190	191	192	193	194	195	196	197	198	199	200	
General attributes	201	202	203	204	205	206	207	208	209	210	211	212	

This coding structure is easy to understand and represents the detailed specifications of the gas turbine systems as compared to other tabular representations available in literature for the same purpose.

3.1 Illustration of coding

The proposed coding scheme explained above is illustrated here by taking examples from the attributes pertaining to a typical gas turbine system. Suppose power generation capacity of the gas turbine system and the type of application for the gas turbine system is to be coded, it can be done as follows:-

3.1 Power generation capacity of gas turbine system (Acceptable range up to 55MW) The power generation capacity of the gas turbine system can be coded as follows:

Power generation capacity of the gas turbine system	Code
Unspecified	0
Less than 15 MW	1
15 MW ≥ P ≥ 20 MW	2
20 MW ≥ P ≥ 25 MW	3
25 MW ≥ P ≥ 30 MW	4
30 MW ≥ P ≥ 35 MW	5
35 MW ≥ P ≥ 40 MW	6
40 MW ≥ P ≥ 45 MW	7
45 MW ≥ P ≥ 50 MW	8
50 MW ≥ P ≥ 55MW	9

Similarly, the type of application can be coded as below:

Table 3. Coding scheme for the type of application of gas turbine system

Type of application	Code
Unspecified	0
Aircraft	A (1)
Marine	M (1)
Petrochemicals	P (1)
Industrial	I (1)
Any other	T (1)

This coding procedure is to be used to specify the other attributes and the same has been mentioned in Table 4.

The table clearly indicates that the information supplied by the manufacturer to the user is the meager and needs to be more elaborated. Since, a number of cells have coded value as 0 which means the information about that attribute is not known to the customer. However, the user may seek information about more attributes to make database exhaustive so that evaluation and the selection procedure of the gas turbine systems can be more precise and accurate.

4. THE 3-STAGE SELECTION PROCEDURE

4.1 Elimination search

Though number of attributes has been identified for the gas turbine system, but all of them would not be equally important while evaluating and selecting the gas turbine system for a particular application. A sorting procedure is adopted for the scrutiny of the attributes which affect the gas turbine system significantly. These attributes are termed as "preferred attributes" and kept aside while as other attributes are discarded for macroscopic examination point of view for the system. The complete information about these preferred attributes must be known to the user for the alternative gas turbine systems considered for evaluation and preferred selection. On the basis of the threshold values of the preferred attributes, a shortlist of gas turbine systems is obtained. This is achieved by scanning the database for the preferred attributes, one at a time, to eliminate the gas turbine system alternative, which have one or more preferred attribute values that fall short of the threshold values.

4.2 Elimination procedure

A mini database is created for the gas turbine system alternatives which have all the preferred attributes satisfying the acceptable limits of the aspiration. Now the statement of the objective is to find the optimum or the best solution alternative and to rank all the available alternatives as per their merit.

Since most of the computational work is carried out using concise representation i.e. the matrix form, the first step is to represent the available information in the matrix form. Such a matrix is called the decision matrix **D**. Each row of this matrix corresponds to candidate gas turbine system and the elements in the columns for each row represent the preferred attributes ranges or measured levels. Thus the element, d_{ij}, gives the value of *j*th preferred attribute for *i*th candidate gas turbine system. Thus, if we have '*m*' number of alternative gas turbine systems and '*n*' number of preferred attributes, then the size of matrix, D, will be $m \times n$.

4.2.1 Normalized decision matrix

Since most of the preferred attributes have different threshold values varying in large magnitudes, the

Table 4. Coded attributes for the gas turbine system

	Attribute(s)												
Physical attributes	1	1	1	1	1	1	1	1	1	1	1	1	
Engine performance attributes	0	1	1	1	0	1	1	1	1	1	1	1	1
Compressor attributes	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	0	0	1	0	1	0	0	0	1	1	1	0
Combustion system attributes	1	0	1	0	1	1	1	0	0	1	0	1	0
Turbine attributes	0	1	1	0	1	1	1	1	0	0	0	1	1
Drive system attributes	1	0	0	0	1	0	0	1	1	0			
Control system (Cabinet) attributes	0	0	0	0	0	0	0	0	0	0	0		
Inlet system attributes	1	0	1	0	0								
Exhaust system attributes	1	0	0	0	1	0							
Staring system attributes	1	1	0	0	0								
Enclosure and ventilation system attributes	0	0	1	1	0	1	0						
Fire protection system attributes	1	0	0	0	0	1	1						
Liquid fuel system attributes	1	0	1	0	0	1	1						
Atomizing air system attributes	0	1	1	0									
Gas fuel system attributes	1	0	1	0	1								
Lubricating oil system attributes	0	0	1	1	0	1	0	0	1				
Cooling water system attributes	0	0	0	1	0								
Water wash system attributes	1	1	0	0	0	1							
NOx abatement system attributes	0	0	1	0	0	0	1	1	0	1	0	0	
General attributes	1	0	0	1	0	0	1	1	1	0	1	1	

decision matrix, D, is not a concise representation of non-dimensional nature of the attributes. In order to convert this decision matrix, D, into a concise representation of non- dimensional magnitudes of the attributes, the normalization of the attributes over a preferred common scale is carried out ranging from 0 to 1. It is a sort of value, which indicates the standing of that particular attribute magnitude when compared to whole range of the magnitudes for all candidate gas turbine systems.

An element, n_{ij}, of the normalized matrix, N can be calculated as:

$$n_{ij} \quad \frac{d_{ij}}{\left(\sum_{i=1}^{m} {}^{2}_{ij}\right)^{1/2}} \qquad \text{.... (1)}$$

where d_{ij} is an element of the decision matrix, D.

The next step is to obtain information from the user or the experts on the relative importance of one attribute over the other. This information is sought in terms of ratios. The information pertaining to such pair-wise comparison and their relative importance is stored in the relative importance matrix, A. This matrix is of order $n \times n$. this matrix has all diagonal elements as unity while as symmetric positions of elements, a_{ij} are inverse scale values (l-a_{ij}), where a_{ij} is the relative importance of attributes i over j.

This matrix contains information about the attributes on pair-wise basis and does not contain any information about the relative weights of the attributes. Thus, this matrix is further modified by incorporating the relative weights of the attributes such that the cumulative weight of all the preferred attributes is unity. The eigen vector method is adopted for this purpose as this method allows some inconsistencies due to human error in the judgment of relative importance of the attributes. According to this method, the eigen vector representation of the normalized matrix is given as:

$$A.x = \lambda.x \qquad \ldots (2)$$

Where λ is the eigen value of matrix A and x is the corresponding eigen vector. Now, the weight vector w is calculated as below:

(a) Take eigen vector, x_{max} corresponding to the largest eigen value λ_{max}, as all the elements of λ_{max}, are either positive or negative.

(b) Find the sum of elements of x_{max} as

$$a = \sum_{i=j}^{n} (x_i)_{max} \qquad \ldots (3)$$

(c) Find weight vector as

$$w = (x_{max})/\alpha$$

such that $\sum_{i=j}^{n} w_i = 1.0$ .... (3)

4.2.2 Weighted normalized representation

The weights as obtained above are to be incorporated in the relative importance matrix as all the attributes affect the gas turbine system with different measures while evaluating and selecting the gas turbine system on merit. The matrices which combine the effect of the weight of the attributes and the normalized matrix, N are called as weighted normalized matrix, V. This matrix, V is capable of true representation of the relative values of the attributes and its calculations are made as explained below:

$$\begin{bmatrix} w_1.n_{1,1} & w_2.n_{1,2} & \cdots & w_n.n_{1,n} \\ w_1.n_{2,1} & w_2.n_{2,2} & \cdots & w_n.n_{2,n} \\ \vdots & \vdots & \cdots & \vdots \\ w_m.n_{m,1} & . & \cdots & w_n.n_{m,n} \end{bmatrix} = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,n} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,n} \\ \vdots & \vdots & \cdots & \vdots \\ v_{m,1} & . & \cdots & v_{m,n} \end{bmatrix}$$

4.3 Ranking and selection procedure

The ranking of the gas turbine systems can be carried out mathematically or qualitatively. In the present paper, two approaches have been adopted for ranking the gas turbine systems on the basis of preferred attributes influence. The mathematical technique (TOPSIS method) has been adopted for calculating the preferred ranking of gas turbine systems. Similarly, qualitative ranking of gas turbine systems have also been carried out by using Graph theoretical methodology. The sequential procedure for the implementation of these techniques is explained below:

4.3.1 TOPSIS method

The weighted normalized matrix, V is used to obtain the +ve and -ve benchmark gas turbine systems, where the both benchmark gas turbine systems are hypothetical. These hypothetical benchmark gas turbine systems are supposed to be the best and worse possible combination of the attributes. The TOPSIS method works on the principle that the best possible gas turbine system should have acceptable ranking or performance in close proximity to the +ve benchmark hypothetical gas turbine system and should exhibit performance far away from the -ve hypothetical benchmark gas turbine system and vice-versa for the worse possible gas turbine system with lower ranking in the order of merit.

The separation measures from +ve benchmark and -ve benchmark gas turbine systems are calculated as S^*_i and S'_i respectively.

The separation measure from +ve benchmark gas turbine system is given by

$$S^*_i = \left[\sum_{j=1}^{n} (v_{ij} - v^*_{ij})^2\right]^{1/2} \text{ for } (i = 1,2,3 .....m) \quad ....(6)$$

and the separation measure for the -ve benchmark gas turbine system is given by

$$S'_i = \left[\sum_{j=1}^{n} (v_{ij} - v^*_{ij})^2\right]^{1/2} \text{ for } (i = 1,2,3 .....m) \quad ....(7)$$

Then the relative closeness to the +ve benchmark gas turbine system, C*, which is a measure of suitability of the gas turbine system for the given application on the basis of preferred attributes considered. Any gas turbine system with highest value of C* is preferable.

$$C^* = \frac{S'i}{(S^*_i + S'_i)} \quad ..... (8)$$

On the basis of relative closeness measure, C*, the preferred ranking of the gas turbine systems can be made and selection can be done accordingly.

4.3.2 Graph theoretical methodology

The graph theoretic approach evaluates the permanent qualitative index of a gas turbine system in terms of single numerical index, which takes into account the all qualitative measures and their interdependencies while analyzing and evaluating the system. The various steps of the proposed approach, which would be helpful in evaluation of the permanent qualitative index of the gas turbine systems with respect to the benchmark gas turbine system, are:

1. Identify the various characteristics or the broad attributes of the gas turbine system which are responsible for defining the system quality as a whole.

2. Logically develop a diagraph between the attributes or the characteristics depending upon their interdependencies. Since, the ranking is to be suggested for the best gas turbine system with reference to benchmark gas turbine system, all the attributes are to be normalized over a scale 0-1 (minimum normalized value as 0.05 for non-acceptable threshold values) such that the attributes with better or equal performance as that of benchmark gas turbine system are to be assigned maximum value and minimum for worse performance of the attributes.

3. Develop a variable permanent function matrix at the system level on the basis of digraph developed in step 2.

4. Using the logical values of the quality measure[s as] well as their interdependencies, obtain the permanent functions at the system. The log[ical] values of the interdependencies are specified on the basis of expert opinions after the effect of attributes are critically analyzed at the subsystem or sub-subsystem level. The off- diagonal elements of the matrix representation may also be obtained from the graphs, knowledge database interpretation.

5. The normalized relative importance matrix mentioned in section 4.4.2 may also be considered as reference for developing the Permanent function for the gas turbine systems. The attribute rating for the given gas turbine system with respect to the benchmark gas turbine system is used to calculate the inheritance functions in the above matrix.

6. Evaluate the permanent of the variable permanent function at the macro system level, i.e., Gas turbine system using the permanent functions developed at system level as this permanent has been obtained by analyzing, retrieving and processing the qualitative data of the gas turbine systems without losing any information as per the combinatorial practices of graph theory.

7. Various gas turbine systems can be compared on the basis of permanent system quality index thus obtained.

5. ILLUSTRATIVE EXAMPLE

Consider the selection of gas turbine system for a power generation application, wherein the attributes for different gas turbine systems have been identified. The preferred attributes benchmark values for this particular application as identified are placed in Table 5 given below.

Table 5. Preferred attributes ranges for gas turbine system

Power (MW)	150
Thermal efficiency (%)	35
Pressure ratio	14.6
Turbine inlet temperature (K)	1520
Air Flow (kg/s)	425
Exhaust gas temperature (OC)	580

From the list of identified attributes available in the database, the mini database is generated for preferred attributes sufficient to analyse the performance of the alternative gas turbine systems from macroscopic point

Table 6. Attributes for the short-listed gas turbine systems

	Power (MW)	Thermal efficiency (%)	Pressure ratio	Turbine inlet temperature (K)	Air flow (kg/s)	Exhaust gas temperature (°C)
GASTURB1	135	31	16	1525	410	570
GASTURB2	125	35	13.5	1500	415	575
GASTURB3	154	34	14	1480	435	540
GASTURB4	155	30	15	1520	425	490
GASTURB5	160	32	15.5	1510	420	500
GASTURB6	150	35	16.5	1515	430	560
GASTURB7	145	30	12	1530	437	575

of view. In the present paper, seven gas turbine systems with nomenclature GASTURB(N) have been short-listed which are eligible candidate for selection for the power generation application. Table 6 gives the detailed information about the preferred attributes of these candidate gas turbine systems.

Here, the exhaust gas temperature is a type of attribute for which lower magnitudes are desirable. Hence the reciprocal of the values in column representing exhaust gas temperature should be used to form the decision matrix, D.

The procedure for the evaluation and selection of the gas turbine system is as follows:

Step 1. Formulate the decision matrix, D, the matrix which will contain all the magnitudes of the preferred attributes. The element, d_{ij}, of this matrix represents the jth attribute value for the ith candidate gas turbine system and the corresponding decision matrix, D is represented as below:

$$D=\begin{bmatrix} 135 & 31 & 16 & 1525 & 410 & 0.001754386 \\ 125 & 35 & 13.5 & 1500 & 415 & 0.001739130 \\ 154 & 34 & 14 & 1480 & 435 & 0.001851852 \\ 155 & 30 & 15 & 1520 & 425 & 0.002040816 \\ 160 & 32 & 15.5 & 1510 & 420 & 0.002000000 \\ 150 & 35 & 16.5 & 1515 & 430 & 0.001785714 \\ 145 & 30 & 12 & 1530 & 437 & 0.001739130 \end{bmatrix} \quad \ldots (9)$$

Step 2. Construct the relative importance matrix A.

The relative importance of each attribute with respect to each other is determined through expert opinions and the symmetric terms will be equal to inverse scale value $(l-a_{ij})$ as stated in the methodology.

$$A=\begin{bmatrix} 1 & 0.6 & 0.2 & 0.3 & 0.65 & 0.55 \\ 0.4 & 1 & 0.4 & 0.4 & 0.6 & 0.5 \\ 0.8 & 0.6 & 1 & 0.5 & 0.7 & 0.75 \\ 0.7 & 0.6 & 0.5 & 1 & 0.75 & 0.8 \\ 0.35 & 0.4 & 0.3 & 0.25 & 1 & 0.35 \\ 0.45 & 0.5 & 0.25 & 0.2 & 0.65 & 1 \end{bmatrix} \quad \ldots\ldots (10)$$

Step 3. Find out the maximum eigen value of the relative importance matrix A.

$$(A - \lambda max . I) = \begin{bmatrix} 1-\lambda & 0.6 & 0.2 & 0.3 & 0.65 & 0.55 \\ 0.4 & 1-\lambda & 0.4 & 0.4 & 0.6 & 0.5 \\ 0.8 & 0.6 & 1-\lambda & 0.5 & 0.7 & 0.75 \\ 0.7 & 0.6 & 0.5 & 1-\lambda & 0.75 & 0.8 \\ 0.35 & 0.4 & 0.3 & 0.25 & 1-\lambda & 0.35 \\ 0.45 & 0.5 & 0.25 & 0.2 & 0.65 & 1-\lambda \end{bmatrix} = 0 \ldots (11)$$

The values of λ as calculated from the above equation are $\lambda_1 = 3.3580$; $\lambda_2 = 0.5604 + 0.2274i$; $\lambda_3 = 0.5604 - 0.22.74i$ $\lambda_4 = 0.5095 + 0.0922i$; $\lambda_s = 0.5095 + 0.0922i$; $\lambda_6 = 0.5023$ hence $\lambda_{max} = 3.3580$

Step 4. Calculate weights for each attribute using the eigen vector associated with minimum eigen value.

$$(A-\lambda_{max} I) = \begin{bmatrix} -2.358 & 0.6 & 0.2 & 0.3 & 0.65 & 0.55 \\ 0.4 & -2.358 & 0.4 & 0.4 & 0.6 & 0.5 \\ 0.8 & 0.6 & -2.358 & 0.5 & 0.7 & 0.75 \\ 0.7 & 0.6 & 0.5 & -2.358 & 0.75 & 0.8 \\ 0.35 & 0.4 & 0.3 & 0.25 & -2.358 & 0.35 \\ 0.45 & 0.5 & 0.25 & 0.2 & 0.65 & -2.358 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \end{bmatrix} = 0 \ldots (12)$$

we get the weights of the attributes as $w_1 + w_2 + w_3 + w_4 + w_5 + w_6 = 1.0$ and $w_1 = 0.151336454$; $w_2 = 0.1587115796$; $w_3 = 0.216780367$; $w_4 = 0.21598453$; $w_5 = 0.120198788$; $w_6 = 0.136984065$

Step 5. Calculate the normalized attribute matrix. This normalization helps to provide non-dimensional nature of the matrix.

Using $n_{ij} = \dfrac{d_{ij}}{\left(\sum_{i=j}^{m} d^2_{ij}\right)^{1/2}}$, we get

$$N = \begin{bmatrix} 0.347770 & 0.360587 & 0.410966285 & 0.381338 & 0.364903 & 0.35878528 \\ 0.321981 & 0.407114 & 0.346752803 & 0.375086 & 0.369353 & 0.35566541 \\ 0.396681 & 0.395483 & 0.359594499 & 0.370085 & 0.387154 & 0.37871780 \\ 0.399257 & 0.348955 & 0.385280892 & 0.380087 & 0.378253 & 0.41736247 \\ 0.412136 & 0.372219 & 0.398123588 & 0.377587 & 0.373803 & 0.40901522 \\ 0.386377 & 0.407114 & 0.423808981 & 0.378837 & 0.382703 & 0.36519216 \\ 0.373498 & 0.348955 & 0.308224714 & 0.382588 & 0.388934 & 0.35566407 \end{bmatrix} \quad ...(13)$$

Step 6. Calculate the weighted normalized attribute matrix. Here we incorporate the relative importance of the attributes with their normalized value to create unique parameter for the candidate gas turbine system

$$V = \begin{bmatrix} 0.052626 & 0.058231 & 0.089089422 & 0.082363 & 0.043861 & 0.049147866 \\ 0.048727 & 0.064615 & 0.075169200 & 0.081013 & 0.04396 & 0.048720493 \\ 0.060032 & 0.062769 & 0.077953244 & 0.079933 & 0.046535 & 0.051878303 \\ 0.060422 & 0.055385 & 0.083521333 & 0.082093 & 0.045466 & 0.057172007 \\ 0.062371 & 0.059077 & 0.086305378 & 0.081553 & 0.044931 & 0.056028567 \\ 0.058473 & 0.064615 & 0.091873467 & 0.081823 & 0.046000 & 0.050025507 \\ 0.056524 & 0.055385 & 0.066817067 & 0.082633 & 0.046749 & 0.048720493 \end{bmatrix} \quad ...(14)$$

This matrix takes care of all the preferred attribute values as well as their relative importance. So this matrix provides a reasonable base for comparison of gas turbine systems with respect to each other and the benchmark gas turbine system.

Step 7.1 TOPSIS method for ranking

The weighted normalized attributes for the +ve and -ve benchmark gas turbine systems can be obtained as

$V^* = (0.062371, 0.064615, 0.091873467, 0.082633, 0.046749, 0.057172007)$

$V'' = (0.048727, 0.055385, 0.066817067, 0.079933, 0.043861, 0.048720493)$

Simiarly using equations (6) and (7), the separation measures S^*_i and S'_i as calculated from +ve benchmark and -ve benchmark gas turbine systems are given as below:

$S^*_1 = 0.01517$, $S'_1 = 0.02282$
$S^*_2 = 0.02334$, $S'_2 = 0.01251$
$S^*_3 = 0.0154277$, $S'_3 = 0.0179853$
$S^*_4 = 0.1268$, $S'_4 = 0.02224$
$S^*_5 = 0.00821$, $S'_5 = 0.02523$
$S^*_6 = 0.00821496$, $S'_6 = 0.02859824$
$S^*_7 = 0.0286$, $S'_7 = 0.0087$

Now, the relative closeness to the ideal solution is calculated as

$C^*_1 = 0.60072$ (Ranking IV)
$C^*_2 = 0.34889$ (Ranking VI)
$C^*_3 = 0.53827$ (Ranking V)
$C^*_4 = 0.63691$ (Ranking III)
$C^*_5 = 0.75444$ (Ranking II)
$C^*_6 = 0.77685$ (Ranking I)
$C^*_7 = 0.23400$ (Ranking VII)

Step 7.2 Graph theoretic approach (GT) for ranking evaluation.

On the basis of identified interdependency level of the attributes for the candidate gas turbine system, a graphical representation, termed as digraph of the candidate gas turbine system is developed. The digraph representation of the gas turbine system for the preferred attributes is given in Fig. 1 below.

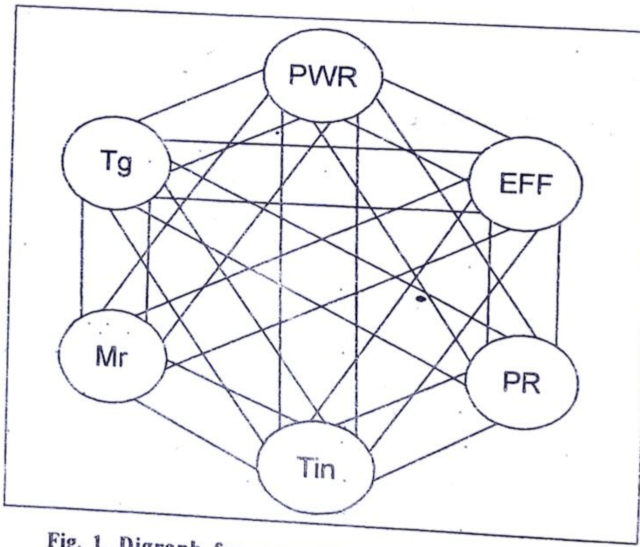

Fig. 1. Digraph for gas turbine system based on its preferred attributes

It has been observed that for some of the gas turbine systems, some of the attributes have negative magnitudes. It means that the attribute value does not fall in acceptable limits. Since, during the calculation of permanents of the variable permanent matrices developed for different gas turbine systems, priority is to have all positive values in the matrix database so that no information is lost during processing. Therefore, such negative values are discarded and a positive equivalent of magnitude 0.05 is assigned for these attribute inheritance. Similarly, values are assigned appropriately on higher side of the scale (i.e. 0.95 or so) for higher positive magnitudes obtained during calculations. Therefore, the various inheritance factors of the attributes in the candidate gas turbine systems are calculated in Table 7.

Table 7. Inheritance factors of the preferred attributes

GASTURBI	T^1_{11}=0.05	T^1_{22}=0.05	T^1_{33}=0.7368	T^1_{44}=0.5	T^1_{55}=0.05	T^1_{66}=0.0955
GASTURB2	$T.^2_{11}$=0.05	T^2_{22}=0.95	T^2_{33}= 0.05	T^2_{44}=0.05	T^1_{55}=0.05	T^2_{66}=0.04734
GASTURB3	T^3_{11}= 0.4	T^3_{22}=0.05	T^3_{33}= 0.05	T^3_{44}=0.05	T^3_{55}=0.8333	T^3_{66}= 0.4033
GASTURB4	T^4_{11}= 0.5	T^4_{22}=0.05	T^4_{33}=0.2105	T^4_{44}=0.01	T^4_{55}=0.01	T^4_{66}= 0.95
GASTURB5	T^5_{11}=0.95	T^5_{22}=0.05	T^5_{33}=0.4737	T^5_{44}=0.05	T^5_{55}=0.05	T^5_{66}= 0.8711
GASTURB6	T^6_{11}=0.1	T^6_{22}=0.1	T^6_{33} = 0.95	T^6_{44}=0.05	T^6_{55}=0.4167	T^6_{66}= 0.1944
GASTURB7	T^7_{11}=0.05	T^7_{22}=0.05	T^7_{33}= 0.05	T^7_{44}=0.95	T^7_{55}=0.95	T^7_{66}=0.04734

On the basis of inheritance factors and the logically quantified interdependencies of the attributes, the variable permanent matrix for each of the system is developed. The negative values are discarded and to minimize the probability of information loss during calculation for the permanents or qualitative index due to presence of negative terms in the matrix, the minimum value equal to 0.05 is assigned for the inheritances of such attributes. An example of the variable permanent function matrix of the GASTURB3 is represented by equation (16) as below:

$$V3 = \begin{bmatrix} 0.4 & 0.6 & 0.2 & 0.3 & 0.65 & 0.55 \\ 0.4 & 0.05 & 0.4 & 0.4 & 0.6 & 0.5 \\ 0.8 & 0.6 & 0.05 & 0.5 & 0.7 & 0.75 \\ 0.7 & 0.6 & 0.5 & 0.05 & 0.75 & 0.8 \\ 0.35 & 0.4 & 0.3 & 0.25 & 0.8333 & 0.35 \\ 0.45 & 0.5 & 0.25 & 0.2 & 0.65 & 0.4033 \end{bmatrix} \quad \ldots (16)$$

Similarly, the variable permanent function matrix for the other gas turbine systems may be developed. Now, the permanent function of the above matrix is given as

$$\begin{aligned} \text{Per}(A) = \prod_{1}^{6} T_i &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{ji}).T_k.T_l.T_m.T_n \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{jk}).(T_{ki}.T_{lj}).T_l.Tm.T_n \\ &+ \{\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{ji}).(T_{ki}.T_{lk}).Tm.T_n \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{jk}).(T_{ki}.T_{lj}).Tm.T_n\} \\ &+ \{\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{kl}.T_{lm}).(T_{mk}.T_{ij}.T_{ji}).T_n \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{jk}.T_{kl}.T_{lm}.T_{mi}).T_n\} \\ &+ \{\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{ji}).(T_{kl}.T_{lk}.(T_{mn}.T_{nm}) \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{ji}.T_{kl}.T_{lm}.T_{mi}.T_{nk}) \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{jk}.T_{ki}.T_{lm}.T_{mn}).T_{nt}) \\ &+ \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n (T_{ij}.T_{jk}.T_{kl}.T_{lm}.T_{mn}.T_{ni}\} \end{aligned}$$

Using attribute values for inheritance and interdependencies in the above matrix developed for each candidate gas turbine system, the calculated values of the permanents or the quality index responsible for meeting the benchmark standards of gas turbine attributes placed in ascending order are as given below:

Per(GASTURB1) = 4.89349
Per(GASTURB2) = 4.16716
Per(GASTURB3) = 5.36701
Per(GASTURB4) = 5.20351
Per(GASTURB5) = 7.86002
Per(GASTURB6) = 5.39901
Per(GASTURB7) = 5.81740

Step 8. Comparison of ranking preferences using TOPSIS and Graph Theoretic approach. The different candidate gas turbine systems have been evaluated for the set of preferred attributes and the priorities of the selection of short-listed gas turbine systems have been calculated by using the TOPSIS and graph theoretic approach. The results have been indicated in Table 8.

Table 8. preference ranking of Gas turbine systems

Candidate gas turbine system	Ranking preference order using TOPSIS	Ranking preference order using GT approach
GASTURBI	4	6
GASTURB2	6	7
GASTURB3	5	4
GASTURB4	3	5
GASTURB5	2	1
GASTURB6	1	3
GASTURB7	7	2

From the above, it is clear that the ranking order calculated by using TOPSIS and the graph theoretic approach differ from each other. This is due to a limited exercise for the expert's opinion related to interdependency level calculations for the attributes. Further, the weights (inheritance factors) of the attributes may not be wisely specified due to involvement of number of assumptions as the attribute which are not considered as preferred attribute may affect the overall performance of the gas turbine systems drastically due to sudden variation in any of the preferred attributes of the gas turbine system. Therefore, it is desirable, that detailed analysis of the effect of all the attributes within their operational limits may be critically examined prior to coding of the attributes and the evaluation of the gas turbine system

CONCLUSION

This paper presents a coding, evaluation and selection procedure for the gas turbine systems which is a concept used not so frequently for this purpose. The various attributes have been identified for the gas turbine system representation at the subsystem levels as well as for its performance for typical applications. The procedure of coding and evaluation of the candidate gas turbine systems on the basis of preferred attributes have been implemented. The preference order of the short-listed gas turbine systems have been calculated by using TOPSIS and graph theoretic approach. The deviations in the ranking orders obtained by two approaches have also been justified. Further, the database of the attributes can be improved from time to time and the preferred attributes may also be varied depending upon the type of application or system constraints. It can be summarily suggested that the method is quite helpful in creating the database, improving the data base, data retrieval for instant decision making related to selection of such systems.

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