A Graph Theoretical Approach for the Analysis of Cost in Thermal Power Plant

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Abstract: ***Power crisis has been a long clamour in India and this seems to persist for the coming decade too or so. Cost analysis of power plant can help in improving the efficiency as well as reducing the power plant running cost. The present study puts forward the cost based analysis of the coal based power plant as the way to approach the analysis of a power plant. This thesis present a methodology to evaluate the cost analysis using diagraph and matrix method for Operation and Maintenance cost and Fuel cost in a coal based power plant .Variable Performance Function (VPF) or Performance index is obtained for the Operation and Maintenance and Fuel cost from the attributed matrix. Factors affecting the Operation & Maintenance Cost and Fuel Cost and their interactions are analyzed. For a energy deficient country like India it is important to carry on cost analysis of the coal based power plant which account more the electric power produced than other type of power plant so that their efficiency can be improved to meet the energy requirement in future in India.***

Keywords: Graph theoretical approach, Thermal power plant, cost analysis, variable performance function

1. Introduction

The Power generation in India has registered remarkable growth since it gained independence in 1947. Power generation increased from 1362 MW in 1947 to about 104917 MW in 2002. Thermal power plant and hydro – sector are the major power producer in India. The major portion of power demand in India is met by thermal power plant due to availability of fossil fuel (coal, oil and gas). Around 72 per cent of total installed capacity is met by thermal power plant and 25 – 30 per cent is met by hydro – electric power generation, while rest account for other source of power generation. Among the conventional means of power generation fossil fuel based power plant are very significant in the energy scenario of India.

1.1 Thermal Power Plant

A coal-fired power station produces electricity, usually for public consumption, by burning coal to boil water, producing steam which drives a steam turbine which turns an electrical generator. After steam is passed through the turbine, the steam is condensed in a condenser and recycled to where it was heated; this is known as Rankine cycle. The variation in the design of thermal power station is due to different of fossil fuel resources generally used to heat the water. Certain power plant is also designed to produced heat energy for industrial process in addition to producing the electrical energy.

Coal is a relatively cheap fuel with some of the largest deposits in politically stable regions (China, India and the US) thus generally offering a more stable supply than natural gas and oil, the largest deposits of which are located in the more politically volatile Persian Gulf.

1.2 Historical Background of Thermal Power Plant

The initially developed reciprocating steam engine has been used to produce mechanical power since the 18th century, with notable improvement carried by James Watt. The first commercially developed central electrical power station was established in 1882 in New York and in London where steam engine were used. The development of the steam turbine in 1884 provide larger and more efficient machine designs for central generating stations. By 1892 the turbine was considered a better alternative to reciprocating engines [2] turbines offered higher speed, more compact machinery and stable speed regulation allowing for parallel synchronous operation of generators. After 1905, turbine entirely replaced reciprocating engine in large central power stations.

The largest reciprocating engine – generator set ever built were completed in 1901 for the Manhattan Elevated Railway. Each of seventeen units weighed about 500 tons and was rated 6000 kilowatts; a contemporary turbine set of similar rating would have weighed about 20 % as much.

The power sector in India has shown progress after independence. When India became independent in 1947, the country had a power generating capacity of 1,362 MW. Hydro power and coal based thermal power plant has been the main source of electrical energy. Generation and distribution of electrical power was carried out primarily by private utility companies. Power was only available in rural areas and villages did not have electricity. After 1947, all new power generation, transmission and distribution in the rural sector and the urban centers (which was not served by private utilities) came under the purview of State and Central government agencies. State Electricity Boards (SEBs) were formed in all the states. The concept of operating power systems on a regional basis crossing the political boundaries of states was introduced in the early sixties. In spite of the overall development that has taken place, the power supply industry has been under constant pressure to bridge the gap between supply and demand.

1.3 Why a Coal-fired power plant

Coal-fired power plants are a proven, reliable and efficient way to generate electricity, and are critical to meeting power-grid demand. The basic construction of single reheat large steam turbines for coal-fired power plants was established over 30 years ago. This construction, designed originally for operating at conventional steam conditions, has achieved very high standards of reliability and operability through continuing development and feedback of operating experience. The same basic design therefore provides a very sound reference base for high output applications at supercritical operating conditions taking advantage of advanced materials and design refinements. Advanced pulverized-coal-fired power plants are well suited for mid-range power supply and support the grid system to avoid blackouts. Coal's value as a power plant fuel is greatly enhanced by its ability to supply power during peak power demand -- as base power -- and off-peak power demand.

1.4 Site Selection for Thermal Power Stations

The selection of site for thermal power plant compared to hydro-plant is more difficult as it involves number of factors to be considered for its economic justification. The following considerations are taken into account for site selection:

Availability of Coal: The major source of energy which is available in India for thermal power plants is coal. The huge quantity of coal is required for large thermal power station. A thermal power station of 400 MW capacity requires 5000 to 6000 tons of coal per day. Therefore it is necessary to install the power station near coal mine. In this case, the power generation must be transported to the long distance. Therefore it is necessary to find the location which will give the lowest cost considering the coal transport and power transmission charges.

Ash Disposal Facilities: the ash removal problem has become more serious particularly in India because the coal used for power generation contains large percentage of ash 20% to 40%. The quantity of ash to be handled is as large as 1500 to 2000 tons per day. The ash handling problem is more serious than coal handling because it comes out in hot condition and it is highly corrosive. Therefore, there must be sufficient space to dispose of large quantity of ash. A 400 MW power station requires nearly 10 hectares area per year if the ash is dumped to a height of 6.5 meters.

The disposal of large quantities of ash from the power station if the site for its disposal at the plant is not available also becomes a problem. In addition to the mounting problem of ash disposal at these power stations in the large cities like Delhi, Bombay and Madras there is also a serious problem of pollution arising from fly ash.

The ash can be easily disposed off to river, sea or lake economically if such facilities are available at plant site.

Space Requirement: The space and building requirement by the power station is another point to be considered. The average land requirement is 3 to 5 acres per MW capacity which includes the space required for coal storage, ash disposal, staff colony, market facilities and the space required for whole machinery. Generally the space occupied in 10% for building, 33% for coal storage, 27% for cooling tower, 7% for switch yard and remaining 23% for other purpose. The cost of land is adds in the final cost of the plant therefore it should be available at cheap rates.

Nature of Land: The selected site for the power plant should have good bearing capacity as it has to withstand the dead load of the plant and forces transmitted to the foundation due to the machine questions. There are number of cases where the plants have failed due to weak foundations. The minimum bearing capacity of the land should be 10 bar.

Availability of Water: Large quantities of water are required for condenser, for disposal of ash and feed water to the boiler and drinking water for the working staff. The quantity of cooling water required in the condenser condensing the steam coming out from the turbine of 60 MW capacity plants is of the order of 20 to 30 thousand tons per hour if it is discharge to the lower side of the river. If the cooling water are used, then the makeup water required is also 500 to 600 tons per hour. The water required to feed the boiler owing to the losses in the system is also as large as 6 to 10 tons per hour for 60 MW capacity power plant.

It is therefore necessary to locate the power plat near the water source which will be able to supply the required quantity of water throughout the year.

Transport Facilities: This is another important consideration in locating the thermal power station. It is always necessary to have a railway line available near the power station for bringing in heavy machinery for installation and for bringing the coal.

Availability of Labour: Cheap labour should be available at the proposed site as enough labour is required during construction of the plant.

Public Problems: The proposed site should be far away from the towns to avoid the nuisance from the smoke, fly ash and heat discharged from the power plant.

1.5 Different Material Required For Thermal Power Plant

The thermal power plant presently are designed for 200 MW capacity of a single unit. The quantities of coal, air, water are considered the basic need of the thermal power plant.

Feed Water: The feed water is the water circulated through a closed circuit of the power plant which is converted into steam in the boiler. Generally steam consumption in such big plant is 5 kg/kWh. Therefore a plant of 100 MW capacity requires nearly 500 tons of water per hour to be circulated through the system. As this passes through the boiler, turbine, condenser, pump and piping, there is always 2% loss of this water, therefore 10 ton of pure water/hr must be feed in pure form from outside to a plant of 100 MW capacity.

Coal: The quantity of coal required must be sufficient to generate the steam in the boiler for the power plant.

Considering 5 kg/kWh of steam generation and 500 kcal of heat per kg of steam supplied in the boiler the quantity of coal required for 100 MW capacity plant is given by

$$W_c = \frac{(100 \times 1000) \times 5 \times 500}{5000 \times 0.8 \times 1000}$$

W_c = 6 tons/hr = 1500 tons/day

Where calorific value of the Indian coals containing 30% ash is taken as 20, 000 kJ/kg and overall boiler efficiency as 80%. Generally the power plant located away from the coal pit-heads needs to store the coal at least for one month. The quantity of coal to be stored for a plant of 100 MW capacity requires a storage space for 50,000 tons of coal, a huge coal yard and all required facilities for the coal storage, transport, fire protection and many others.

Cooling Water: The quantity of cooling water required for condensing the steam is nearly 50 kg/kg of steam. Therefore, the quantity of cooling water requirement for a 100 MW plant is

$$\frac{5 \times 100 \times 1000 \times 50}{1000}$$
$$= 25,000 \text{ tons/hr.}$$

Such a huge quantity of water must be available throughout the year which is very uncommon at most of the place. The water used once is used again and again by the evaporative cooling, so nearly 2% of the cooling water circulated is evaporated in the cooling water. The water carried by air is 500 tons/hr for a 100 MW plant. At least this quantity of cooling water must be available at the site throughout the year.

Ash: The ash formed with the Indian coal is also considerably large as it contains 20% to 30% ash or even 40%. The quantity of ash formed per hour is 20 tons/hr. Out of this, nearly 2 tons comes out as hot ash at 500° C to 600° C from the bottom and 18 tons come out in the form of fly ash. The ash contain many harmful contents, therefore is must be disposed off away from the power station and for a considerable time. A 100 MW plant can collect 5 million tons of ash during its life time of 20 years.

The quantity of water required to carry out this ash away from the plant in the form of slurry is also 100 tons/hr.

SO_2 **:** We are lucky to have coal with low sulphur content (1 to 1.5%) but even then the emission of SO_2 formed in the combustion chamber during the burning of the coal should be prevented as it is highly poisonous to the human and animal health as well as for the crops. The amount of SO2 coming out with burned gases is 1.8 ton/hr. For a plant of 100 MW requires 60 tons of coal which contains 1.5% sulphur and 1 kg of sulphur forms 2 kg of SO_2. A 100 MW plant will emit 50 tons of SO_2 into the atmosphere per day if not removed from the exhaust gases.

Air: A very large quantity of air is required for the combustion of the fuel. A 100 MW plant requires nearly = 60 X 20 = 1200 tons of air per hour as 20 kg of air is required per kg of coal burned.

In addition to this, the quantity of air to be circulated in the cooling tower is 25000 tons/hr as one kg of water requires one kg of air for effective cooling.

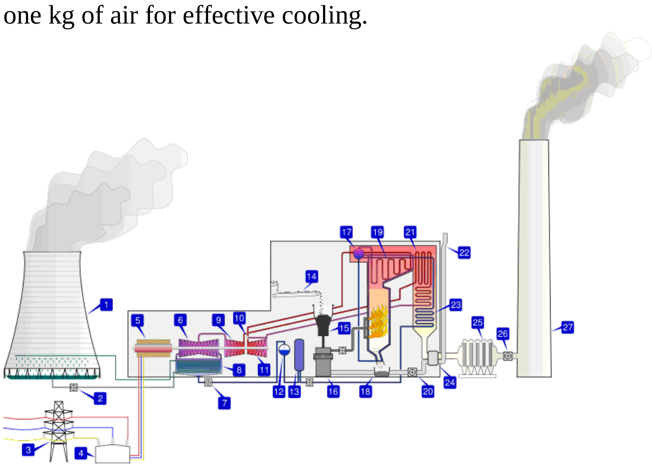

Figure 1: A typical coal Power Plant

1.6 Components of Thermal Power Plant

The main components which are used for the operation and safe functioning of thermal power plants are

Cooling Tower: A cooling tower is a heat rejection device which extracts heat to the atmosphere through cooling of water steam to a lower temperature. Cooling tower may either use the evaporation of water to remove the process heat and cool the working fluid to near wet bulb air temperature. Cooling tower vary in size from small roof – top unit to very large hyperboloid structures that can be up to 200 m tall and 100 m in diameter or rectangular structures that can be over 40 m tall and 80 m long.

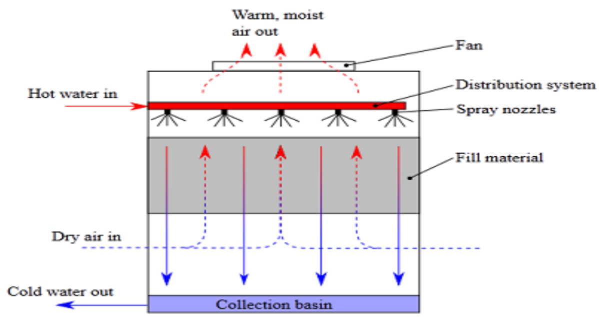

Figure 2: Cooling Tower

Boiler: A boiler or Steam generator is a device used for the generation of steam by applying heat energy to water. A boiler or steam generator is also used as a source of steam required in electric power generation as well as other industrial purpose. The form and size of boiler depends upon the application: Mobile steam engine such as steam locomotives, portable engines and steam powered road vehicles typically use a smaller boiler that form an integral part of vehicle; stationary steam engines, industrial installations and power stations will usually have a larger separate steam generating facility connected to the point of use by piping.

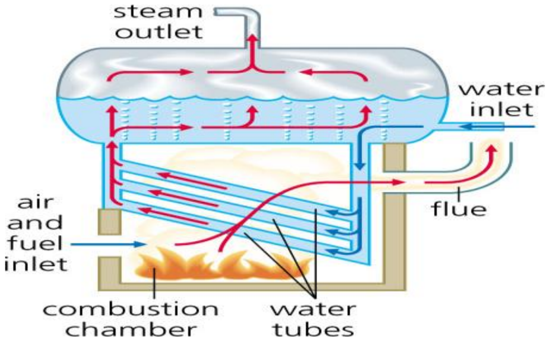

Figure 3: Cooling Tower

Steam Turbine: A steam turbine is a device that extracts thermal energy from pressurized steam and use it to do mechanical work on a rotating output shaft. As the turbine generate the rotary motion, it is particularly suited to be used to drive an electrical generator. Steam turbine may be made in a variety of size ranging from small 0.75 kW used as mechanical drives for pumps, compressor and other shaft driven equipment to 1,500,000 kW turbine used to generate electricity.

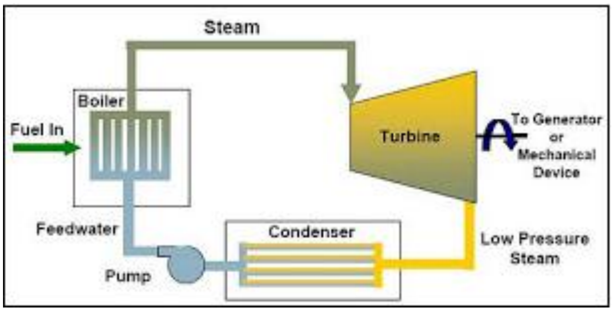

Figure 5: Steam Turbine

Boiler Feed Pump: A boiler feed pump is a specific type of pump used to pump feed water into a steam boiler. The water may be freshly supplied or returning condensate produced as a result of the condensation of the steam produced by the boiler. These pumps are normally high pressure units that take suction from a condensate return system and can be of centrifugal pump type or positive displacement type. Boiler feed pump range in size up to many horse power and the electric motor is usually separated from the pump body by some kind of mechanical coupling. Large industrial condensate pump may also serve as the feed water pump. To force the water in to the boiler, the pump must generate sufficient pressure to overcome the steam pressure developed by the boiler. This is usually accomplished by using the centrifugal pump. Another common form of feed water pump run constantly and are provided with a minimum flow device to stop over pressuring the pump on low flows. The minimum flow usually return to the tank

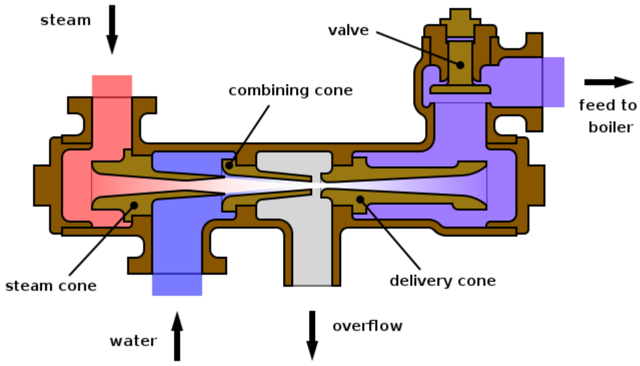

Figure 4: Boiler Feed Pump

Surface Condenser: A surface condenser is a commonly used term for a water cooled shell and tube heat exchanger installed on the exhaust steam from a steam turbine in thermal power stations. A surface condenser is a heat exchanger which convert heat from its gaseous form to liquid state at a pressure below the atmospheric. Where cooling water is in short supply, an air cooled condenser is often used. An air cooled condenser is more costly and can not achieve as a steam turbine exhaust pressure as a water cooled surface condenser. In thermal power plant, the primary purpose of a steam condenser is to condense the exhaust steam from a steam turbine to obtain the maximum efficiency and convert the turbine exhaust steam in to pure water so that it may be reused in the steam generator or boiler as boiler feed water.

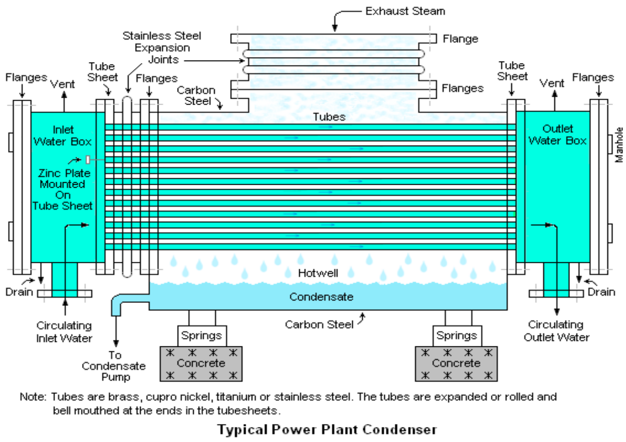

Figure 6: Power plant condenser

Feed Water Heater: A feed water heater is a power plant component used to pre – heat water delivered to a steam generating boiler. Preheating the feed water reduce the irreversibility involved in steam generation and therefore improve the thermodynamic efficiency of the system. This reduce the plant operating cost and also help to avoid thermal shock to the boiler metal when the feed water is introduced back into the steam cycle.

In a steam power plant, feed heater allow the feed water to be brought up to the saturation temperature very gradually. These minimize the inevitable irreversibility associated with the heat transfer to the working fluid.

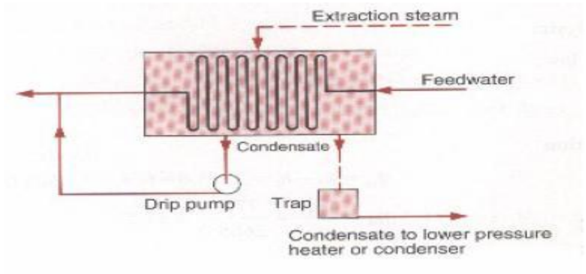

Figure 7: Feed Water Heater

Super Heater: A super heater is a device used to convert saturated steam or wet steam into dry steam used in steam engine. There are three types of super heater: radiant, convection and separately fired. A super heater can vary in size from a few meters to some hundred meters. A radiant super heater is placed directly in the combustion chamber. A convection super heater is located in the path of the hot gases. A separately fired super heater is totally separated from the boiler.

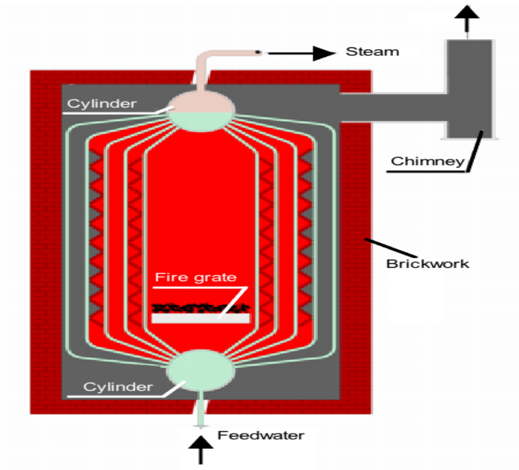

Figure 8: Super Heater

Air Pre-Heater: An air preheater is a general term to describe any device designed to heat air before combustion in a boiler with primary objective of increasing the thermal efficiency of the process. The purpose of air pre – heater is to recover the heat from the boiler flue gases which increase the thermal efficiency of the boiler by reducing the useful heat lost in the flue gas. As a consequence, the flue gases are also conveyed to the flue gas stack at a lower temperature, allowing simplified design of conveyance system and the flue gas stack. It also allow to control over the temperature of gases leaving the chimney.There are two type of air pre-heater for use in steam generators in thermal power stations: one is a tubular type built into the boiler flue gas ducting and other is regenerative air pre-heater. These may be arranged so the gas flows horizontally or vertically across the axis of rotation.

Chimney Stack: A Chimney is a structure which provide ventilation for hot flue gases or smoke from a boiler, stove and furnace to the outside atmosphere. Chimneys are typically vertical to ensure that gases flow smoothly. The space inside the chimney is called flue. The height of chimney influences its ability to transfer flue gases to the external environment via stack effect. Additionally the height of chimney reduce the immediate impact of dispersion of pollutants to surrounding.

1.7 Cost

Cost is divided into two parts:
1) Total Investment Capital
2) Variable Cost

Total Investment Capital is further divided into two parts:
Direct Cost (DC) Direct cost is further divided into following Parts:
a) Purchased-equipment cost (15-40% of cost)
b) Purchased equipment installation (20-90% of PEC)
c) Piping (10-70% pf PEC)
d) Electricity equipment and material (10-15% of PEC)
e) Land cost (0-10% of PEC)
f) Civil, Structural and architectural work (15-90% of PEC)

Indirect Cost (IC)
a) Engineering and Supervision (25-75% of PEC)
b) Construction cost including contractor's profit (15% of DC)

Variable Cost:
a) Cost of fuel including its handling and ash handling
b) Repair and Maintenance.
c) Transmission & Distribution cost.

2. Graph Theory

Graph theory is a approach which can be effectively used to access the performance of a coal based power plant. Factors affecting the performance of different parts of the plant can be evaluated using the diagraph and matrix method. Variable performance function or Performance index is obtained for different parts (Boiler, Turbine, Condenser etc.) from the attributed matrix.

3. Problem Identification & Formulation

To analyze the Operation and Maintenance cost and Fuel Cost for a coal based thermal power plant and ascertain the scope of improvement

4. Methodology

4.1 Cost Analysis

The cost analysis of supplying electrical energy from a thermal station is split into the following items:
1) Fixed Cost
2) Operating and Maintenance cost
3) Profit on the investment

4.1.1 Fixed Cost The fixed cost depend upon the total investment of the plant. The break - down of Total capital investment is as:

4.1.2Direct Cost (DC) Direct cost is further divided into following Parts:

a) Purchased-equipment cost (15-40% of total cost)
b) Purchased equipment installation (20-90% of PEC)
c) Piping (10-70% of PEC)
d) Electricity equipment and material (10-15% of PEC)
e) Land cost (0-10% of PEC)
f) Civil, Structural and architectural work (15-90% of PEC)

4.1.3 Indirect Cost (IC)
a) Engineering and Supervision (25-75% of PEC)
b) Construction cost including contractor's profit (15% of DC)

4.2 Operating and Maintenance cost

These costs are based on the energy output as measured in kWhr and these are directly proportional to the station load. These include:
a) Cost of fuel including its handling and ash handling.
b) Technology
c) Repair and Maintenance.
d) Oil, waste, Stores and other supplies.
e) Transmission and distribution costs.

Noted: The cost of coal is made up of two components a small fixed part and a large running part. The small fixed quantity is that which is needed to keep the station in readiness to meet the demand for power and its independent of whether any energy is sent out or not. The running component is the cost of coal equivalent of the heat converted into electrical power plus heat rejected in the condensers.

4.2.1 Investor's Profit If the power plant is the public property, as is the case in India, then the customers will be the taxpayers to share the burden of the government. For this purpose, there is an item in the rates to cover taxes in place of the investor's profit.

5. Result Evaluation

5.1 Results

The result we obtained by analysis of quantification factor for Operation & Maintenance cost are the value of B_1, B_2, B_3 and B_4
$B_1 = 24$ (Technology effect on O&M cost)
$B_2 = 96$ (Location effect on O&M cost)
$B_3 = 39$ (Spares parts effect on O&M cost)
$B_4 = 70$ (Transmission & Distribution effect on O&M cost)
Location > Transmission & Distribution > Spare Parts > Technology

The Final Matrix for Calculating the Variable Performance Factor for O&M cost with the assigned values is

$$(VPF)_{O\&M} = [B] = \begin{bmatrix} 24 & 0 & 4 & 2 \\ 0 & 96 & 4 & 4 \\ 3 & 4 & 39 & 0 \\ 0 & 4 & 0 & 70 \end{bmatrix}$$

The calculated value of [B] is 6382752.

The result we obtained by analysis of quantification factor for Fuel cost are the value of F_1, F_2, F_3 and F_4
$F_1 = 8$ (Location effect on Fuel cost)
$F_2 = 24$ (Quality effect on Fuel cost)
$F_3 = 40$ (Import effect on Fuel cost)
$F_4 = 18$ (Other miscellaneous factors effect on Fuel cost)
Import > Quality > Other miscellaneous factors > Location

The Final Matrix for Calculating the Variable Performance Factor for Fuel cost with the assigned values is

$$(VPF)_{Fuel} = [F] = \begin{bmatrix} 8 & 0 & 3 & 2 \\ 0 & 24 & 4 & 4 \\ 0 & 2 & 40 & 3 \\ 1 & 4 & 3 & 18 \end{bmatrix}$$

The calculated value of [F] is 130176.

6. Conclusions

1) Graph Theory Approach provides a very strong tool to analyze the factor which effect the Operation and Maintenance cost and Fuel cost for coal fired Thermal power plant.
2) It enable us rank the factor in the term of their relative importance and provide us with a mean to determine where the maximum scope to save the operation and maintenance cost and Fuel cost that exist.

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