FEASIBILITY STUDY OF OPTIONS FOR AGING HYDRO-POWER GENERATION FACILITY

by

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ABSTRACT

FEASIBILITY STUDY FOR AGING HYDRO-POWER

GENERATION FACILITY

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Most of the hydro generation facilities are operating under derated capacity due to various factors. The availability of generation facilities is decreasing, the cost for maintenance is going up and plants are crippled with severe faults leading to outages. The feasibility study for aging hydro-power plant is carried out with an objective to find out the best possible alternative both with respect to reliability of operation and benefit to cost ratio.

The multi-criterion weighted average condition evaluation of hydro-electric generator is carried out. A Visual Basic and Microsoft Excel based condition evaluation program is implemented for possible condition decision making of the generator. The result of evaluation is depicted as range. The reliability analysis of generator is carried

out. The Weibull distribution approximation of engineering reliability for base line data is estimated by finding the Weibull parameters using straight line method. Using Baye's theorem of conditional probability, reliability and failure rate for generator is calculated using condition index. The condition index (CI) is score from 0 to 100, which are used to represent the present condition of the generator.

The Francis turbine's main components are discussed with sole aim of identifying the existing problems and availability of newer technology. The critical issues in each component are briefly described to evaluate the condition of the turbine. The turbine reliability analysis is carried out with very similar approach as for the generator.

Economic analysis is carried out for all the alternatives. The incrementing net operating benefits are calculated for all the alternatives. The benefit to cost ratio (BCR) and breakeven analysis is done to choose the most economically viable alternative for the aging hydro-power facility.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The motivation for this thesis is a result of important awareness regarding clean renewable energy. With our dependence growing day by day on limited resources like oil and coal, billions of dollars is spent everyday to import oil, our dependence on oil is so much that any shortage could bring the single nation to standstill, some have even stated this dependence as a threat to national security. In the U.S, in 2005 where congress was successful in passing the bill with the clause authorizing the automobile makers, to increase the efficiency of their engine. It failed to pass the bill that would have made mandatory, for all the utilities to generate at least 20% of their future energy generation from renewable resources. Around twenty states has set their own renewable energy standard for utilities.

Our dependence on limited resources(fossil fuels) cannot be completely answered but we can work on formulating policies and laws that will help us to limit the use of fossil fuels and provide extra incentives for alternate sources of energy like renewable resources, fuel cells etc. We must look forward to a day when all the oil reserves will be exhausted, the temporary solution could be to try and stabilize our demand as much as possible and address the increasing demand by alternate sources.

Around 99% of total renewable energy produced in the United States comes from hydro power which has an average age of around 45 years. Due strict federal regulations regarding new hydropower plant and other environmental concerns the project for any new hydropower facility is hardly in the pipeline. Based on National Hydro Association analysis there will be no new hydro power plant before 2020. The generation of extra power by upgrading and uprating of aging hydro power plant is considered to be the best way to produce extra clean energy without having to go through any formalities.

1.2 Hydropower at Present

Of the alternate sources of energy that we talk today the fuel cells and wind farming is relatively new topics. Hydropower is the largest source of alternate energy accounting 7% [1] of total energy generated in the United States. Hydro-power accounts for more than 80,000 MW of installed capacity and including the pumped storage facilities it amounts to nearly 95,000 MW of renewable energy. Figure 1.1 shows the break down of the power generation based on the type of source in the United States.

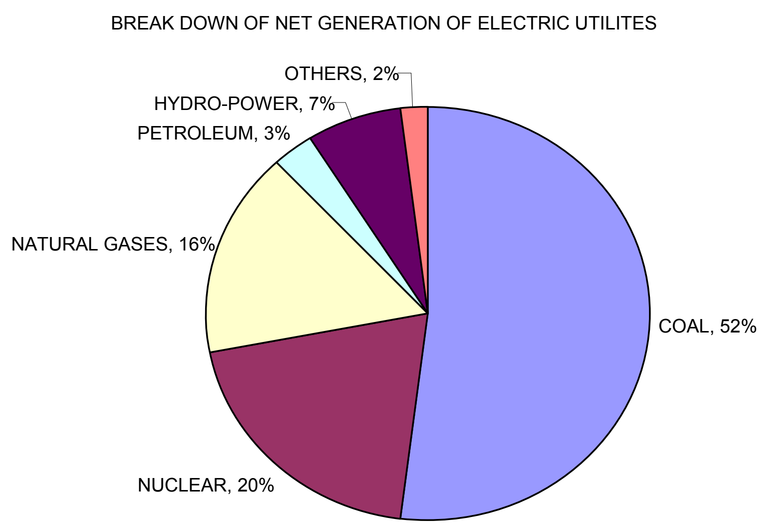

Figure 1.1 Breakdown of Generation of Electrical Energy in the USA [1]

Hydro-power has been the largest renewable source of energy with 99% of renewable energy being generated by hydro. Of the total 75,187 dams [2] in the United States, only 3% of these have been used to harness electricity. Hydro-power supplies energy to more than 28 million households which is roughly equivalent to 500 million barrels of oil. At present based on the river basin analysis, the United States has more than 70,000 MW of hydro energy in undeveloped form. [2] Of this undeveloped potential more than 29,780 MW [2] of electricity can be generated without constructing a single dam. One of the main obstacles in the development of hydropower in the United States has been strict environmental concerns regarding new hydropower plant; issues regarding federal licensing process, because of these many utilities have shown less concern towards hydro power. With present burden and delay associated with the licensing process, it is anticipated that none of the new generation site will be developed by 2020.

On top of the total installed capacity in the United States, more than 4316 MW has been identified as capacity that can be added easily by uprating of existing hydro-generation facility, i.e. without going over to build the new facility. The emphasis here is to increase the hydro-electric capacity without constructing any new facilities because of strict environmental and licensing formalities for new units. Besides adding installed capacity by upgrading older units or replacing them with modern units is the cheapest method of generating electricity which is at one tenth of the cost of generation from a new plant. Compared to any other generation hydro is the cheapest and adding new capacity by upgrading is even cheaper.

1.3 Economic Advantage of Hydro-power

The economic advantage of hydropower are immense, the capital cost of hydropower for construction of infrastructure is more compared to other kind of generation facility but in the long run hydropower is the cheapest and cleanliest form of renewable source of energy produced in large scale. Hydropower plant has least expense on maintenance and operation, cheap technology and zero cost for procurement of fuel, which are the reason for the low cost of generation. The Table 1.1 shows the breakdown of the cost of hydropower generation plant for construction, maintenance and operation.

Table 1.1 Economic Benefits of Hydropower Generation [3]

Cost Type	Amount
Capital Cost $/kW	$1700 – 2300/kW
Operation Cost/kWh	4.05 mills
Maintenance Cost/kWh	2.62 mills
Total Cost/kWh	23.57 mills
Operating Life	50+ Years
Capacity Factor	40 – 50 %

One of the main advantages of hydropower generation is price stabilization of energy, the energy produced from thermal generating plant or diesel power plant is expensive, had there been no contribution of energy from hydropower generation the energy price would have been much higher than its present cost. The vast difference in electricity pricing between Canada and the United States is because of the fact that Canada generates 68% of its electricity from hydropower, while the United States generates only 7% of electricity from hydropower.

Table 1.2 Comparisons of Electricity Prices between the USA and Canada [4]

Average Prices on April 1, 2005					
American Cities	Residential (in ¢/kWh)				
Consumption	625 kWh	750 kWh	1000 kWh	2000 kWh	3000 kWh
Boston, MA	15.65124	15.47835	14.93496	14.61386	14.50683
Chicago, IL	9.591635	9.245842	7.821505	6.833525	6.446567
Detroit, MI	8.949448	9.138811	9.377573	9.739832	9.863329
Houston, TX	11.83929	12.00395	11.93809	11.68286	11.60053
Miami, FL	8.982381	8.842417	8.900049	8.990614	9.015314
Nashville, TN	7.508645	7.343982	7.146386	6.849992	6.742961
New York, NY	17.46254	20.85	16.78742	16.22756	16.04644
Portland, OR	6.537132	6.537132	6.537132	6.932323	7.072287
San Francisco, CA	17.73	15.74181	14.99259	18.08826	19.2162
Seattle, WA	6.29837	6.668862	7.129919	7.829738	8.0685
AVERAGE	11.05507	11.18512	10.55656	10.77886	10.8579
Residential (in ¢/kWh)					
Consumption	625 kWh	750 kWh	1000 kWh	2000 kWh	3000 kWh
Canadian Cities					
Montréal, QC *	5.738515	5.475054	5.244525	5.228059	5.219825
Charlottetown, PE	11.1971	10.73604	10.15149	8.529557	7.870904
Edmonton. AB	8.052034	7.739173	7.360448	6.784126	6.586531
Halifax, NS	9.015314	8.776552	8.480158	8.035567	7.88737
Moncton, NB	8.957682	8.587189	8.109666	6.915857	6.380701
Ottawa, ON	8.513091	8.38136	8.315495	8.348427	8.356661
Regina, SK	8.776552	8.463692	8.0685	7.475712	7.278116
St. John’s,	8.513091	8.175531	7.747407	7.113453	6.899391
Toronto, ON	9.748065	9.459904	9.18821	8.891816	8.801251
Vancouver, BC *	5.458587	5.376256	5.277458	5.129261	5.079862
Winnipeg, MB *	5.507986	5.368022	5.186893	4.923432	4.832867
AVERAGE	8.134365	7.867162	7.557295	7.034115	6.835771
* Hydropower rich Province.					

Electricity prices in Canada are the lowest in the world because it is the largest producer of hydropower and the share of hydropower is more than half of the total electricity generated, the other leading nations in hydropower generation are the United States, Brazil, China, Russia etc. Table 1.2 shows the electricity pricing in major cities of the United States and Canada, comparing the prices in Table 1.2 will depict the importance of hydropower in price stabilization.

1.4 Other Advantages

Besides, generating cheap form of electricity, helping in price stabilization and being proven technology, there are many other aspects of hydropower which makes it the most popular form of power generation. Some of the important features as well as advantages of hydropower are:

- Hydropower operational flexibility is unique, its ability to change the output quickly with respect to the load, voltage control, load following and operation as both base load unit as well as peaking unit helps to maintain the stability of the grid.
- Research and development has lead to increase in turbine efficiency, better insulation and efficient generator, which accounts for efficiency of hydropower today converting 90% of available energy into electricity, while the efficiency of thermal power plant stands at around 50%.

- Development of infrastructure for hydropower brings other developments like, in the area of irrigation, recreation (picnic, boating, camping etc) and distribution of water resources.
- Hydropower generates electricity that is carbon-free; it avoids burning fossil fuels and releasing carbon dioxide into atmosphere. The present installed capacity of hydropower generation by thermal plants would release exhaust equal to 62.2 million passenger cars per year. [2]
- The statistics of 1999, shows hydropower avoided the release of additional 77 million metric tons of carbon equivalent into atmosphere, in absence of hydropower, the United States would have to burn and additional 121 million tons of coals, plus 27 million barrels of oils and 741 billion cubic feet of natural gas combined per year.[2]

1.5 Thesis Structure

The thesis has been presented with a sole aim of first introducing the present benefits of hydropower then moving on to the aging hydropower generation facility and their present condition and options available based on condition of generating plant and its component with full consideration of cost/benefit analysis. The thesis shows how federal regulations impede any investment on new hydropower project because of federal laws and environmental concerns, which leaves upgrading and uprating as the only way to generate extra energy.

Chapter1 discusses mainly about the present energy situation in the United States, then there is a description of present condition of hydropower in the United

States, how hydropower could help the present situation partially and in brief it presents factors that have been behind, lack of interest on any significant investment in hydropower while on the other hand new benefits of generating energy by upgrading has been introduced. The economic advantage of hydropower in price stabilization of electricity prices and other advantages have been briefly discussed with sole aim of introducing benefits of hydropower generation.

Chapter 2 introduces the hydroelectric generation facility in general and important components of generator and turbine, responsible for efficiency and reliability of the plant. In general it discusses the present problems associated with the aging plants and available options which are discussed in form of alternatives. The rehabilitation of aging plants is discussed. The strategy for aging plants is discussed in steps.

Chapter 3 discusses the multi-criterion analysis of generator to verify the present condition of the generator. The scoring system for analyzing the condition of generator briefly discussed which is, based on design and fabrication, maintenance and repair history, visual inspection and tests and measurements with the sole aim to make decision stating condition of generator based on its important component to component evaluation. The weighted average decision making method is used based on the scoring provided by the inspection personnel with due weightage calculated for each criterion. Method for reliability analysis is discussed initially using baseline data of similar kind of generators then approximating baseline reliability by Weibull distribution to estimate the failure rate and reliability with present condition of generator integrated. A case study is carried out on the generator at Whitney hydropower plant, to verify the results.

Chapter 4 firstly, introduces the hydraulic turbines which are the next important unit of hydropower plant. The present technology in turbine is discussed and the increase in efficiency of hydraulic (Francis) turbine is noted, other development in the area of turbine is considered with increase in safety for the fish passage and dissolved oxygen down the stream. The chapter discusses about important components of turbine and possible type of deterioration together with guidance on probable critical issues that needs to be addressed as soon as possible. The reliability analysis using the baseline data for similar type of Francis turbine is carried out for estimation of failure rate and reliability. The baseline reliability is estimated using Weibull distribution approximation. A case study is undertaken to show the results based on the condition of Francis turbine at Whitney Hydropower facility.

Chapter 5 presents the cost/benefit analysis of the alternatives available to the aging hydropower plant. At the end cost/benefit ratio is calculated as a tool to assess the feasibility of the implementation of alternatives. The advantages of with project alternatives are discussed and how reliability increases after upgrading is explained.

Chapter 6 includes important remarks and the major conclusions of the thesis. The conclusion discusses how after monitoring of operational parameters increases the reliability of the plant. It also makes suggestions for further scope of development and study in this area.

CHAPTER 2

STRATEGY FOR AGING HYDRO-POWER GENERATION FACILITY

2.1 Introduction

The concept behind the generation of electricity from water is based on conversion of potential energy of water at head to rotate the turbine runner which in turn is coupled to the rotor of the generator. Two key points in case of generation by hydro are volume of water flowing and head, where volume means flow rate available and head is the difference in elevation between the upstream and downstream of the river. Hydroelectric is a renewable source of energy and cheapest form of energy. Besides being emission free source of energy hydropower infrastructure has been instrumental in supporting wetlands, flood mitigation, navigation, irrigation and recreation etc.

The hydroelectric generating facilities and the components, are one of the most robust, durable and reliable structures ever produced by the engineers. The robustness of these plants allows the owner to operate these even beyond their optimum economic life, without any major investment on upgrading. The conversion of electricity from water is almost more than 90% efficient way of converting the available energy into electricity, which is higher than thermal which constitute the major source of electricity. Besides, the ability of hydropower facility to operate both as base load unit as well as peaking unit and its load following characteristics makes it unique. The Figure 2.1 shows a typical layout of the hydroelectric power plant with important components.

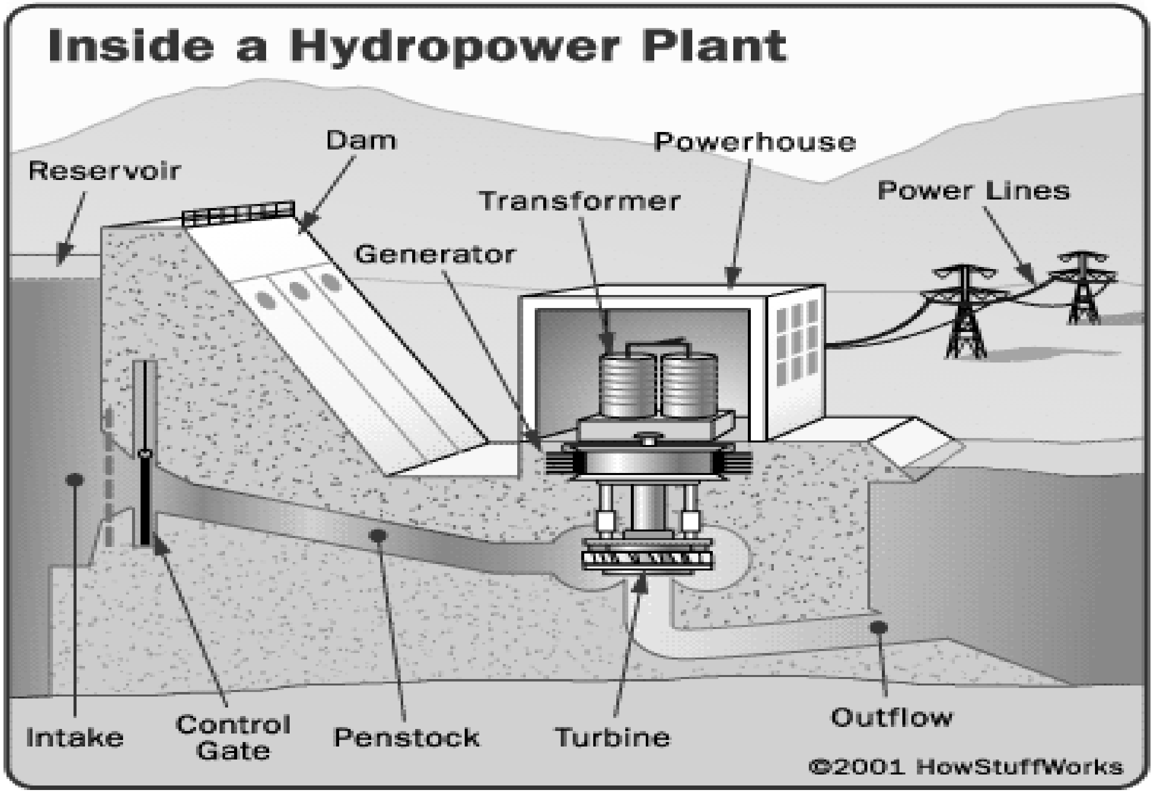

Figure 2.1 Hydro-Power Generation Plant [5]

Besides the civil infrastructure, Turbine and Generator are the most important components responsible for generation of electricity from the water.

2.2 Hydro Electric Generator

The Generator is the main component used to convert the mechanical energy of turbine shaft into electrical energy. It is based on the Faraday's laws of electromagnetic induction which states that:

- Moving conductor which cuts the lines of magnetic flux of a constant magnetic field has voltage induced in it.
- The change in magnetic flux inside a loop made from conductor material will induce the voltage in the loop.

The synchronous generator which has revolving or rotating magnetic field-winding wound on the rotor and the armature wound on the stationary stator, the voltage will be induced across the armature or stator windings. D.C current is used to energize the rotating magnetic field on the rotor. The above explains the basic operation of synchronous generator, incase of three phase machines, the armature windings or stator windings are placed at 120^o apart.

The generator like any other electrical component is subjected under different operating condition, due which deterioration and wearing takes place resulting in premature aging as a result of this, the reliability of the component decreases. The Table 2.1 shows the percentage of failure of generator with respect to the component.

Table 2.1 Percentage of Failure of Generator's Components [6]

Components	Percentage of Failure
Stator	70%
Rotor	12%
Bearing	12%
Excitation	3%
Others	3%

From the operational and efficiency point of view the most important components of the generator are:

2.2.1 Stator Winding

The stator windings are most important component of the generator, failures related to stator windings are the main reasons for majority of failures in the generator.[Table 2.1] Basically, stator windings are copper conductors which are equally distributed in the stator core slots, to engage symmetrical linkage with the flux produced by the rotor. To minimize the effect of any eddy currents these stator windings are made up of many number of copper strands which are insulated from each other. Most of the failures in stator windings are related to insulation failures, which could be due to ineffective cooling system, thermal cycling, thermal strength of insulating material, operation under abnormal conditions etc.

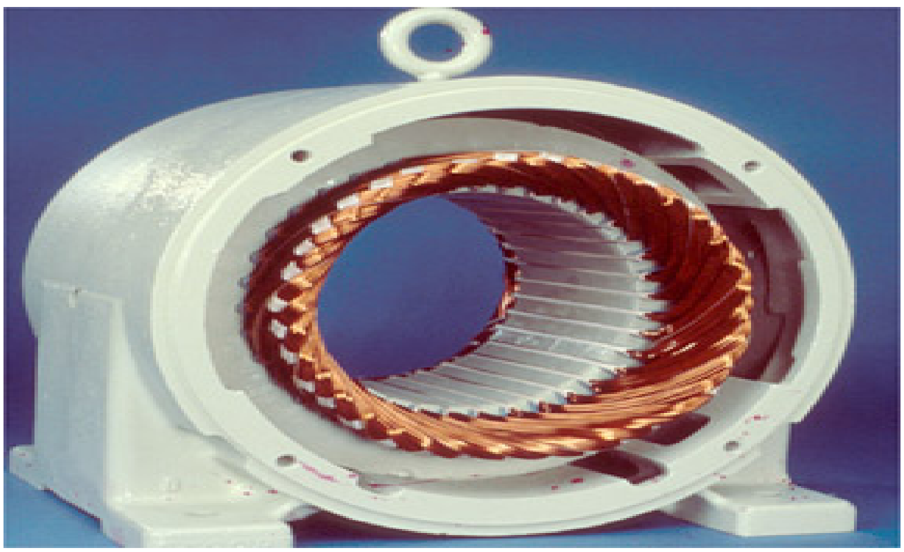

Figure 2.2 Generator Stator Winding [24]

2.2.2 Stator Core

The basic function of stator core in a generator is to house the stationary stator winding and provide path for electromagnetic flux or carry electromagnetic flux. The stator core is built of thin laminations insulated from each other to reduce eddy current losses; the dimension of these sheets varies from electrical grade, 3% to 4% silicon or grain oriented, and 0.3555 mm to 0.483 mm thick steel [7]. These, thin plates are called by various names like, laminates or core plate or sheets etc. The stator core of a generator contains tens of thousands of sheets, stacked in group of 10 to 24 and tightened using key bars. The core handles magnetic flux densities in the stator teeth and core-back or yoke area.

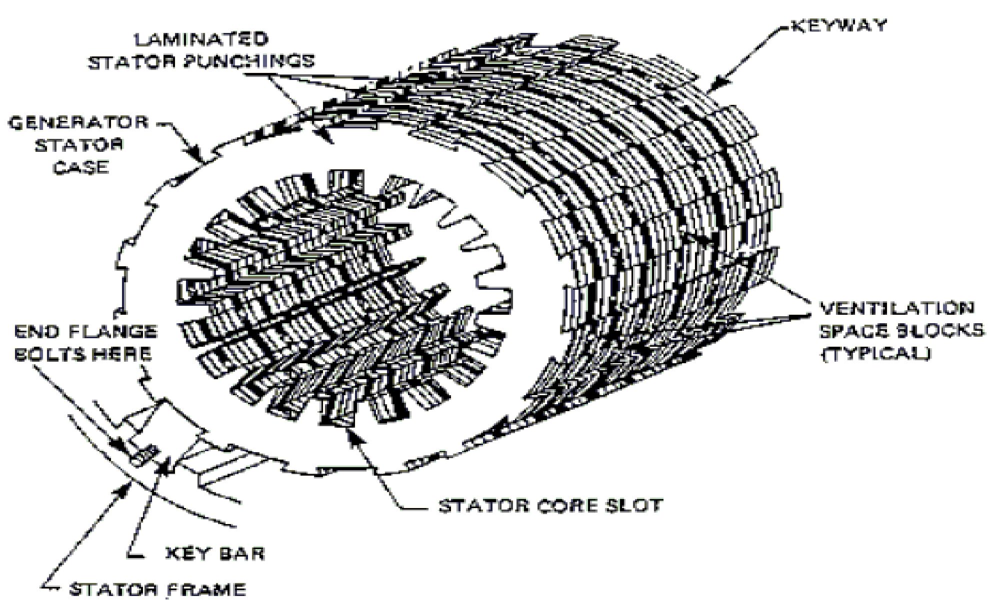

Figure 2.3 Generator Stator Core [25]

The alternating magnetic field produces changing voltages and currents, which are sources of core losses, besides losses the alternating effect leads to vibration which is one of the main reasons for core failures. Besides vibration, the inter-laminar insulation breakdown can also bring down the core. Based on design imperfection and operational condition, potential reasons for core failures could be summarized as below:

- Application of inadequate pressure during the piling of core plates.
- Use of resilient material excessively, which will relax later leading to imperfection in design.
- Over heating of stator core, which will eventually lead to thermal aging of the generator.
- Excessive eddy current flow and consequently leading to breakdown of inter-laminar insulation due to over heating by eddy currents.

2.2.3 Rotor

The rotor is the dynamic component of generator, it rotates at very high speed, rotor should be highly stressed out and hence should have good amount of strength to carry copper windings and operate under mechanical and thermal loading. A rotor generally consist of spider attached to the shaft, a rim constructed of solid steel or laminated rings and field poles attached to the rim. Rotor is the most susceptible to operating incident such as motoring or negative sequence currents etc; it is also subjected to very high centrifugal forces during normal operation. The rotor winding has slots around its circumference placed symmetrically; in these slots are placed rotor windings between the poles.

The rotor is made of essentially one piece steel forging, now days two piece rotor are no more common. The material used in rotor forging is usually, high permeable magnetic steel to carry the flux produced by the rotor winding. Under operation, very high stresses occur; if these stresses are not properly compensated then performance of rotor is slowly derated leading to major failure finally.

Figure 2.4 Generator Rotor [26]

The rotor is coupled to prime mover which in turn rotates the rotor. In hydro generation facility the prime mover is the turbine, which is coupled to the generator, the turbine in turn is rotated by the energy of falling water. While inspecting the rotor, we have to check the condition of rotor winding insulation, pole impedance, rotor vibration and whether coupling with the turbine is tight enough or not.

2.2.4 Mechanical Components

Besides the stator and rotor, the integrity of mechanical components mentioned below is important for optimal performance of the generator. The mechanical components like stator frame, bearings, brake etc, are essential for reliable operation of generator as envisaged by designers, any malfunction can be risky for the safety of personnel as well as, could lead to complete outage of the unit with loss of revenue and extra cost of repair and replacement. One of most important mechanical component of the generator is the bearing, which should be in good condition for mechanical integrity of the generator.

2.3 Hydraulic Turbine (Francis)

The main function of turbine is to work as prime mover for the generator i.e., rotating the rotor of the generator. The turbine shaft and the rotor are coupled together to generate electricity. After many years of continuous operation the runner of Francis turbine deteriorates, severe corrosion problems is visible in most cases, looses efficiency, besides these the it does very little to correct low level of oxygen levels in the discharged water. The important components of hydraulic turbine are:

- Runner
- Turbine Shaft
- Wicket Gates
- Discharge Rings
- Turbine Guide Bearing
- Draft Tube
- Stay Vane
- Spiral Casing

The proper function of above components of turbine is necessary for desired results, any critical condition with respect to above components that needs immediate attention has been discussed in Section 4.3

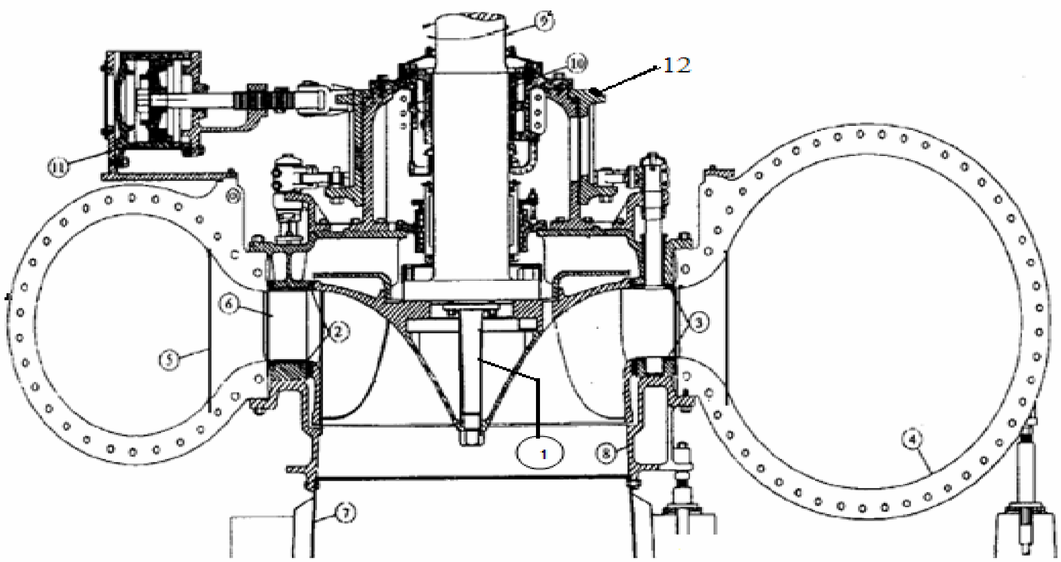

Figure 2.5 Francis Turbine [19]

Table 2.2 Components of Francis Turbine

Number	Component
1	Runner
2	Wearing Rings or Seal Rings
3	Facing Plate or Curve Plate
4	Spiral Case
5	Stay Vane
6	Wicket Gate
7	Draft Tube
8	Discharge Ring
9	Turbine Shaft
10	Turbine Guide Bearing
11	Wicket Gate Servomotors
12	Shit Ring or Wicket Gate Operating Ring

2.4 Strategy for Aging Generator/Turbine

The robustness of hydropower equipments, allow the operation of these equipment beyond the optimum economic viability age. Many of these are still in service and have suffered major degradation and are currently operating at derating capacity. The federal regulations and other legal formalities associated with the construction of new hydropower facility has opened the new are of upgrading and uprating of aging hydropower plant. Rehabilitation of old hydro generation unit has been widely popular as a source of extra clean and renewable source of electricity. The government's incentive in increasing the electricity generation by hydropower plants have been widely applauded. The Energy Policy Act of 2005 added two forms of hydropower to renewable resources eligible for Tax Credit under Section 45, of IRS code. The objective is to emphasize, for increasing generation of the renewable sources of electricity. The "incremental hydropower" i.e. uprating in capacity of existing plant after rehabilitation and the new hydropower at non-hydropower dam that already has FERC license, both of these qualify for tax credit up to $150 million. The Tax rebate based on Section 45 is 0.9 cents/kWh, considering capacity factor of plant to be 45%, for each mega-watt of generation the hydropower plant is eligible of around $35,000 tax credit for up to 10 years for all the capacity generated between August 8th 2005 and January 1st 2008. [8]

The objective before deciding action on these aging components should be taken after carefully analyzing the trend of revenue generated, expenditure on operation and maintenance, performance of equipment for last few years. The best time to carry out the overall assessment of the plant is before the plant is crippled by frequent failures leading to outages. This type of condition is indicated by severe problems like:

- Generator winding failures
- Major runner cracking
- Severe cavitation or erosion damage
- Bearing failures or Problems related to alignment.

When even one or more of the above conditions are met, then it is usually late to carry out feasibility study based on economic analysis as emergency remedies are required.

The remaining life of the hydropower plant is dependent on the collective residual lives of each individual component and its sub-component and therefore, the remaining life can only be determined by assessing the remaining life of each component. The economic lives of hydropower plants are usually shorter than the collective residual life of the generating facility. The Table 2.2 shows the economical and technical life of hydropower facility and its sub-component. Having carried out normal maintenance and repair work the economic life of these components might turn out to be more than what we see below.

Table 2.3 Economic and Technical Lifetime of Hydropower Plant and its Sub-Component [9]

Plant Subsystem	Economical Lifetime in Yrs	Technical lifetime in Yrs
Generator /Transformer	25 – 40	30 – 60
Electrical Control and Auxiliary Equipment	25 – 40	30 – 60
Francis Turbine and Kaplan Turbine	30 – 40	30 – 60
Pelton Wheel	40 – 50	40 – 70
Gates, Butterfly Valves, Special Valves, Cranes and Auxiliary Mechanical Equipment	25 – 40	25 – 50
Dams, Canals, Tunnels, Reservoirs etc.	60 – 800	80 – 150

2.4.1 Criterion Undertaken While Deciding for Upgrading of Aging Hydropower Plant

The utility has to constantly review the generating performance and expenditure on maintenance and operation of the aging power plant. Once a trend of drop in performance starts, the utility has to try and reach to the main reason behind the drop in performance, which could be due to number of causes like drop in flow rate of water, falling of turbine efficiency, generator's deteriorating condition etc. The utility has to investigate to know the cause of the problem. Based on the cause the utility has to make one of the choices out of the following:

- Retirement from the service
- Continue Operation with repair and maintenance for breakdowns

- Continue operation with full surveillance, planned maintenance, inspections for faults and their repair
- Upgrading and uprating of existing hydropower plant
- Replacing new generator, new turbine and new control system
- Construction of new generation plant.

Out of the above few alternatives only few can be economically realizable and pragmatic approach to the problem. The first option to retire from the service would not be a practical approach as on one hand it would lead to loss of revenue and on the other hand the utility has to incur all the expenses of maintaining the hydropower plant site, the second option of maintenance and repair for failures is highly unsuitable in present market scenario where credibility as a reliable source of electricity is important and also the expenses for repair and loss of revenue could be higher than total expenditure on upgrading and uprating, the third option of economically optimum decision but its only matter of time before which the utility has to undertake the project. The fourth option of upgrading and uprating is best with respect to reliability but a through cost/benefit analysis has to be undertaken to justify the project. The option related to new generator and turbine is associated with considerable amount of investment, if the Market looks promising and cost/benefit analysis shows positive trends then this option will give utility considerable revenue while the operation and maintenance cost will be drastically reduced. The fifth option is considered only where there is no scope of upgrading and uprating, before choosing this option one has to be aware of federal regulations for construction of new site.

2.4.2 Why Upgrading and Uprating an Option?

The few reasons for which upgrading and up-rating are considered an option are summarized below:

1. A Generation Unit running under de-rated capacity due to removal of coils after previous winding failures, insulation break down and ineffective cooling systems.
2. Analysis of Generation unit over last few years together with its operation and maintenance records proving deteriorating trend of the equipment with respect to unit availability, cost of maintenance and operation, forced outages and loss of revenue due to forced outages.
3. Availability of modern insulation material that are thinner and have higher thermal strength, can withstand higher voltages and occupy less space could be best for upgrading as well as up-rating to a higher capacity.
4. The use of wear resistant material like Nitronic 60 or Aluminum Bronze could be considered wherever superior galling and cavitation resistance runner is required. This runner will ensure improved performance as well as longer period of performance. The upgraded turbine is capable of better level of dissolved oxygen in the discharged water.
5. Over the years the demand for energy has increased, issues related with federal licensing and environmental awareness have been the main obstacle behind for tough federal regulations for new generation units,

hence uprating of generation unit, is by far the cheapest and easy way for producing additional energy.

6. Making use of modern core design that can reduce the losses greatly, modern turbine system and insulating material will greatly add to the reliability of the generation facility, add extra power at lower cost and go for remote monitoring by upgrading the control systems.
7. Changes in operating conditions like water usage could lead to availability for generation of more power, this will in fact require higher rated generator, turbines and other component thus triggering upgrading study.
8. One of the main considerations behind upgrading could be issues related to seismic standard of construction of structures supporting generator and turbine, which is the capacity of the generation facility to respond to effects of earthquakes and other natural disaster.
9. Installation of complete new online monitoring system which record and trend key parameters for the generator/turbine operation, like turbine discharge, generator vibration, power, partial discharge activity in the windings, guide vane position, shaft run out and bearing temperatures, shaft seal lubricating water flow rates.

CHAPTER 3

MULTI CRITERION EVALUATION OF HYDRO-ELECTRIC GENERATOR

3.1 Introduction

Under multi criterion based analysis of hydro-electric generator's condition, each of the generator's components, are analyzed, where each component have sub-components. The weighting of each component in the final analysis depends on the weightage or score it receives by visual inspection, failure and maintenance history and electrical tests and measurements to determine soundness of each component. This analysis could start after it is determined that the decision to upgrade or uprate completely depends on condition of generator. It is economically beneficial to do multi criterion analysis for running unit during major overhaul of the generator, so that we avoid any outages particularly for the upgrading feasibility study. Incase, the generator is out of service the decision to restore it back to service, by whether repairing or upgrading and uprating should be taken after carefully studying the trend of generator for past few years. The service reliability, cost of maintenance and operation in past against the economic benefits of upgrading and up rating should be analyzed before taking any major decisions, in short a cost/benefit analysis of all the alternatives available should be done to show that, implementation of alternatives are economically viable.

3.1.1 Different Criterions Undertaken During Analysis

In this analysis, each component is analyzed on four different platforms, under each kind the present condition of component compared to its designed specifications, will have major weightage on the analysis. The weightage or scoring on analysis of each component is based on importance of the component and its present condition, for reliable service of the generator and cost to the owner incase of failure of the component leading to both outage and repair. The scores or the weightage for upgrading each component, could increase incase there is a better technology available compared to the technology and material used in the component under analysis. The four major criterions [6] that will be studied incase of hydro electric generator are:

1. Design and specification of each component as provided by the manufacturer.
2. Operation and maintenance history giving insight into major failures and repairs of each component and maintenance records during major overhauls.
3. Visual inspections of each component with set of guidelines for each sub-component.
4. Electrical tests and measurements to assess and verify the condition of each component.

Analyze each component of generator with respect to four different criterions and based on the scoring system given in the Table 3.1, the valid scores are entered based on condition of the criterions. The major component of generator that will be analyzed in our analysis of the generator are respectively, stator winding, stator core, rotor and mechanical components. Besides, the sub-components of the generator the evaluation will also focus on external factors that will give any meaningful objective for upgrading and uprating project.

The design and fabrication provides us the information regarding the technology used while manufacturing, the material used and their tolerances and other important data regarding component type and its physical dimension. These are very important for feasibility study for upgrading and uprating as sometime constraint in design and physical dimension impedes the upgrading project. Hence, it becomes imperative to know at the very beginning whether design consideration and physical dimensions allows any upgrading and uprating activity or not.

The maintenance and operation history of any equipment tells us about the health of the component under investigation. It is a fact that with age, these components will require more maintenance and supervision but records of maintenance can give us information, which can be used to trend the degradation of that component for example, if the result of polarization index test is decreasing for last few years then it’s a situation which warrants immediate attention. The estimation of cost of maintenance and history can be used for justification for any rehabilitation to be undertaken.

The visual inspection is the best method for experienced eyes to quickly identify the condition of the windings, stator core, rotor, stator frame, bearings and insulation system. The accumulation of dirt on the windings, white discharge and bulging or shifting of insulation will be enough to give us the information about the current condition of the component.

The electrical tests and measurement are done to support to verify the information obtained from visual inspection, besides the extent of damage may not be assessed correctly, hence electrical tests like high voltage test for examining the insulation condition, polarization test for finding the resistance of insulation and comparing it with result during commissioning, and other test gives us information regarding the amount of degradation of the component.

Besides four major criterions, the external factors which can directly affect the upgrading decision of the power plant are also considered while deciding on the generator. This is because the reason to go for upgrading may be more attractive after there is more demand of power and increase in flow rate or else the turbine is undergoing major overhaul. Few factors considered, which might have influence in the upgrading decision are:

- Run-of-the-river powerhouse
- Need of Turbine overhaul
- Relative importance to the grid
- Frequency of start-ups

3.2 Major Components of Generator

For optimal operation of any unit the major components should be without defects otherwise the output capacity is de-rated and performance falls below the designed specifications. Due to the present cost of energy, it isn’t a very wise decision economically, to run the generation unit with de-rated capacity when there are options available for producing extra energy or uprating the generation capacity without much of the formality and at least cost of generation per unit. The major components of generator which are responsible for its optimal performance are following:

1. Stator Winding
2. Stator Core
3. Rotor
4. Mechanical components

Based on the fact that the turbine coupled to the generator is performing as designed, the drop in performance can be attributed to one or more flaws in the above component. To check the current condition of these component and decide on upgrading and uprating its capacity, each component have to be examined by looking for operation and maintenance work done, past failures and repairs, visual inspection and perform tests and measurement which will gives us an insight into the condition of these components. It is very important to cover all the aspects in order to estimate the useful life left of the generator so that information regarding time period available before major failure or outage occurs. The Table 3.1 provides us with a tool to analyze each component of the generator using four different criterions discussed in the section 3.1.1. The weightage [6] provided in the Table 3.1 is used in the final evaluation of the component. Based on the criterions discussed above score is given to each sub-attributes based on its presents condition, the scoring is done during condition evaluation based on the weightage provided in third column of Table 3.1.

3.3 Condition Evaluation of Hydro-Generator

Table 3.1 Generator Condition Evaluation [6]

Attribute/Sub-Attribute	**STATOR WINDING** (G_1)		
1	**DESIGN AND FABRICATION**		
1.A	***TYPE OF INSULATION***	**Weightage**	**Evaluation**
	EPOXY MICA " b-stage"	0	
	FLAKED EPOXY MICA	1	
	POLYSTER MICA	2	
	ASPHALT MICA	3	
	MICAFOLIUM	4	
	CAMBRIC	5	
		SUB ATTRIBUTE1	
1.B	***TYPE OF WINDING***		
	1 TURN	0	
	MULTI - TURNS	5	
		SUB ATTRIBUTE2	
1.C	***NUMBER OF TURNS/COIL***		
	1 TURN	1	
	2 TURNS	2	
	3 TURNS	3	
	4 TURNS	4	
	5 TURNS	5	
		SUB ATTRIBUTE3	
1.D	***RATED VOLTAGE (PHASE TO PHASE)***		
	2 TO 2.4 KV	0	
	4 TO 4.4 KV	1	

Table 3.1 - continued

	6.6 TO 6.9 KV	2	
	11 TO 12 KV	3	
	13.8 KV	4	
	GTEATER THAN 13.8 KV	5	
		SUB ATTRIBUTE4	
1.E	***FIRE PROTECTION SYSTEM***		
		EPOXY ASPHA	
	AUTOMATIC PROTECTION	0 0	
	MANUAL PROTECTION & AUT DETECTION	1 2	
	MANUAL PROTECION	2 4	
	ONLY DETECTION	3 6	
	NOTHING	6 8	
		SUB ATTRIBUTE5	
2	**MAINTENANCE AND OPERATION HISTORY**		
2.A	***NUMBER AND TYPES OF COIL FAULTS***	**Weightage**	**Evaluation**
	NONE	0	
	CONNECTION	(# x 2)	
	OUTSIDE OF SLOT	(# x 4)	
	FOREIGN OBJECT	(# x 5)	
	IN SLOT, PHASE TO GND	(# x 6)	
	IN SLOT, PHASE TO PHASE	(# x 10)	
		SUB ATTRIBUTE6	
2.B	***FAULT IN LAST 5 TO 7 YRS***		

Table 3.1 - continued

	NO FAULTS	0	
	YES	(# X 5)	
	BYPASSED COILS PER CIRCUIT	(# X 5)	
		SUB ATTRIBUTE7	
2.C	***FAULT ON SIMILAR GENERATORS***		
	NO	0	
	YES	(# x 5)	
		SUB ATTRIBUTE8	
2.D	***WINDING AGE***		
	LESS THAN 10 YRS	0	
	10 TO 20 YRS	1	
	20 TO 30 YRS	3	
	30 TO 40 YRS	7	
	40 TO 50 YRS	10	
	50 TO 60 YRS	13	
	60 TO 70 YRS	16	
	GREATER THAN 70 YRS	20	
		SUB ATTRIBUTE9	
3	**VISUAL INSPECTION**		
3.A	***PRESENCE OF DUST***	**Weightage**	**Evaluation**
	NEGLIGABLE (CLEAN)	0	
	LESS THAN 1 mm	1	
	MORE THAN 1 AND LESS THAN 5 mm	3	
	MORE THAN 5 mm (VERY DIRTY)	5	

Table 3.1 - continued

		SUB ATTRIBUTE10	
3.B	***RADIAL WEDGING OF COILS***		
		EP/M ASP/M	
	60 TO 80 %	0 0	
	MORE THAN 80 %	1 1	
	50 TO 60 %	2 4	
	25 TO 50 %	3 6	
	LESS THAN 25 %	4 8	
	WEDGES/STRIPS OUT	5 10	
		SUB ATTRIBUTE11	
3.C	***BLOCKS AND TIES***		
	TIGHT	0	
	AVERAGE	2	
	LOOSE	5	
		SUB ATTRIBUTE12	
3.D	***PARTIAL DISCHARGES (WHITE POWDER)***		
	NONE	0	
	ON SHOULDERS	(2 TO 6)	
	SLOT	(3 TO 9)	
	SLOT AND SHOULDERS	(5 TO 15)	
		SUB ATTRIBUTE13	
3.E	***ASPHALT RUN***		
	N/A OR NONE	0	
	LITTLE	2	
	SOME	5	
	MORE	10	
		SUB ATTRIBUTE14	

Table 3.1 - continued

3.F	***CONDITION OF INSULATION***		
	FIRM	0	
	CRACKS	(5 TO 10)	
	CRUMBLING LITTLE	5	
	CRUMBLING AVERAGE	10	
	CRUMBLING MORE OR MUCH	20	
		SUB ATTRIBUTE15	
4	**TESTS**		
4.A	***MEGGER***	**Weightage**	**Evaluation**
	GREATER THAN 500 MEGA OHMS PER PHASE	0	
	100 TO 500 MEGA OHMS PER PHASE	2	
	50 TO 100 MEGA OHMS PER PHASE	4	
	30 TO 50 MEGA OHMS PER PHASE	8	
	LESS THAN 30 MEGA OHMS PER PHASE	15	
		SUB ATTRIBUTE16	
4.B	***PLOARISATION INDEX***		
	4 TO 7	0	
	3 TO 4	2	
	2 TO 3	5	
	1 TO 2	10	
	LESS THAN 1	15	
		SUB ATTRIBUTE17	
4.C	***HI - POT(s) STANDARD***		
	PASSED	0	

Table 3.1 - continued

	PASSED BY(# OF BYPASSED COILS)	(# x 5)	
	FAILED	20	
		SUB ATTRIBUTE18	
4.D	***RESISTANCE OF FARADAY SHIELD***		
	2 TO 5 K OHM	0	
	5 TO 10 K OHM	2	
	10 TO 20 K OHM	4	
	20 TO 50 K OHM	6	
	GREATER THAN 50 K OHM	10	
		SUB ATTRIBUTE19	
4.E	***FULL LOAD TEMPERATURE RISE***		
	CLASS F CLASS B (OLD)		
	LESS THAN 40˚ C LESS THAN 35˚ C	0	
	40˚ C TO 60˚ C 35˚ C TO 45˚ C	1	
	60˚ C TO 80˚ C 45˚ C TO 55˚ C	3	
	80˚ C TO 90˚ C 55˚ C TO 60˚ C	7	
	GREATER THAN 90˚ C GREATER THAN 60˚ C	15	
		SUB ATTRIBUTE20	
	TOTAL OF ATTRIBUTE STATOR WINDING	**ATTRIBUTE G_1 *TOTAL***	
	STATOR CORE (G_2)		
5	**DESIGN AND FABRICATION**		
5A	***LAMINATION QUALITY***	**Weightage**	**Evaluation**

Table 3.1 - continued

	AFTER 1980	1	
	1960 TO 1980	3	
	1940 TO 1960	6	
	1920 TO 1940	8	
	BEFORE 1920	10	
		SUB ATTRIBUTE21	
5B	***STACKING METHOD***		
	CONTINOUS	0	
	2 - SECTIONS	6	
	4 - SECTIONS	8	
	6 - SECTIONS	10	
		SUB ATTRIBUTE22	
5C	***RADIAL KEYS***		
	YES	0	
	(external diameter < 7m)	1	
	(7m > external diameter < 10 m)	3	
	(external diameter > 10 m)	5	
		SUB ATTRIBUTE23	
5D	***HEIGHT***		
	< 1 M	2	
	1 to 2 m	4	
	> 2 m	5	
		SUB ATTRIBUTE24	
5E	***OUTPUT COEFFICENT***		
	< 5	0	
	5 TO 6	1	
	6 TO 7	2	
	7 TO 8	3	

Table 3.1 - continued

	8 TO 9	4	
	> 9	5	
		SUB ATTRIBUTE25	
5F	***STATOR CORE FLANGES***		
	5 TO 10 FINGERS	1	
	1 TO 5 FINGERS	4	
	> 10 FINGERS	5	
		SUB ATTRIBUTE26	
6	**HISTORY**		
6.A	***FAULTS IN SLOT***	**Weightage**	**Evaluation**
	NO FAULTS	0	
	PHASE TO GROUND	(# x 3)	
	PHASE TO PHASE	(# x 10)	
		SUB ATTRIBUTE27	
6B	***DAMAGES BY FOREIGN OBJECT***	**Weightage**	**Evaluation**
	NONE	0	
	LITTLE	(# x 2)	
	AVERAGE	(# x 6)	
	MUCH	(# x 10)	
		SUB ATTRIBUTE28	
6C	***DISPLACEMENT AT JOINTS***	**Weightage**	**Evaluation**
	NONE	0	
	< 3 mm	1	
	3 TO 5 mm	3	

Table 3.1 - continued

	5 TO 8 mm	5	
	> 8 mm	10	
		SUB ATTRIBUTE29	
6D	***SLIDING OF LAMINATIONS***		
	NONE	0	
	LITTLE	2	
	AVERAGE	4	
	MUCH	6	
		SUB ATTRIBUTE30	
6E	***CORE AGE***		
	< 20 YEARS	0	
	20 TO 40 YEARS	3	
	40 TO 60 YEARS	6	
	60 TO 80 YEARS	9	
	> 80 YEARS	12	
		SUB ATTRIBUTE31	
7	**VISUAL INSPECTION**		
7A	***DUST AND DIRT***	**Weightage**	**Evaluation**
	DUCTS BLOCKED < 3 %	0	
	3 TO 10 %	1	
	10 TO 30 %	3	
	30 TO 50 %	6	
	> 50 %	10	
		SUB ATTRIBUTE32	
7B	***CORE WAVINESS***	**Weightage**	**Evaluation**

Table 3.1 - continued

	NONE	0	
	< 3 mm	1	
	3 TO 5 mm	3	
	5 TO 8 mm	5	
	> 8 mm	10	
		SUB ATTRIBUTE33	
7C	***SLIDING OF LAMINATIONS***		
	NONE	0	
	LITTLE	1	
	AVERAGE	3	
	MUCH	5	
		SUB ATTRIBUTE34	
7D	***LAMINATION VIBRATIONS (RED POWDER)***		
	NONE	0	
	LITTLE	1	
	AVERAGE	3	
	MUCH	5	
		SUB ATTRIBUTE35	
7E	***MEHCANICAL DAMAGE***		
	NONE	0	
	LITTLE	(# x 2)	
	AVERAGE	(# x 6)	
	MUCH	(# x 10)	
		SUB ATTRIBUTE36	
8	**TESTS**		
8A	***MAGNETISATION (RING) TEST***		

Table 3.1 - continued

	NO HOT SPOT	0	
	HOT SPOTS < 5° C	(# x 2)	
	HOT SPOTS 5° C TO 10° C	(# x 4)	
	HOT SPOTS > 10° C	(# x 6)	
		SUB ATTRIBUTE37	
8B	***BOLT TIGHTNESS***		
	RATED VALUE	0	
	80 TO 100 %	3	
	60 TO 80 %	5	
	40 TO 60 %	7	
	< 40 %	9	
		SUB ATTRIBUTE38	
8C	***TOLERANCES***		
8C.A	***CIRCULARITY(OF NOMINAL AIR GAP) :***	**Weightage**	**Evaluation**
	< 8 %	0	
	8 TO 16 %	1	
	16 TO 24 %	3	
	24 TO 32 %	5	
	32 TO 40 %	8	
	> 40 %	10	
		SUB ATTRIBUTE39	
8C.B	***VERTICALITY :***		
	< 6 %	0	
	6 TO 12 %	2	
	12 TO 18 %	5	
	18 TO 24 %	7	
	24 TO 30 %	10	

Table 3.1 - continued

		SUB ATTRIBUTE40	
8C.C	***AIR GAP:***		
	< 7 %	0	
	7 TO 14 %	2	
	14 TO 21 %	4	
	21 TO 28 %	6	
	28 TO 35 %	8	
	> 35 %	10	
		SUB ATTRIBUTE41	
8D	ELCID TEST		
	NO READINGS ABOVE 50 mA	0	
	READING BETWEEN (50-100)mA	4	
	READING BETWEEN (100 – 200) mA	8	
	TWO OR MORE READINGS (100-200) mA	12	
	ONE OR MORE ABOVE 200 mA	15	
		SUB ATTRIBUTE42	
8E	***FRAME VIBRATION***		
	0 TO 0.025 mm	0	
	0.025 TO 0.075 mm	2	
	0.075 TO 0.0125 mm	4	
	0.125 TO 0.250 mm	7	
	> 0.250 mm	10	
		SUB ATTRIBUTE43	
	ATTRIBUTE STATOR CORE (G_2)	***ATTRIBUTE G_2 TOTAL***	
	ROTAR (G_3)		
9	**DESIGN AND FABRICATION**		
		Weightage	**Evaluation**

Table 3.1 - continued

9A	***TYPE OF GROUND INSULATION***		
	ROLLED MICA	0	
	MICAL SHEETS	2	
	ASBESTOS	3	
	PAPER	5	
		SUB ATTRIBUTE44	
9B	***TYPES OF INSULATION BETWEEN TURNS***		
	NOMEX	0	
	MICA SHEETS	2	
	ASBESTOS	3	
	PAPER	5	
		SUB ATTRIBUTE45	
9C	***FIELD LEADS***		
	COPPER BAR	2	
	CABLE	4	
		SUB ATTRIBUTE46	
9D	***POLE CONNECTIONS***		
	"I" SOLDERED WITH TIN	1	
	HORSE SHOE	2	
	THIN STRIP FLEXIBLES	5	
		SUB ATTRIBUTE47	
9E	***POLE COLLARS***		
	GLASS-EPOXY	0	
	PHENOLIC, TEXTOLITE	3	
	ASBESTOS, PERMALI	3	
	MICARTA	4	
	WOOD	5	

Table 3.1 - continued

		SUB ATTRIBUTE48	
9F	***STATIC EXCITER***		
	NOT PLANNED	0	
	PLANNED : CEILING VOLTAGE = 6.0 p.u	10	
	PLANNED : CEILING VOLTAGE = 10.0 p.u	20	
		SUB ATTRIBUTE49	
10	**HISTORY**		
10A	***AGE OF INSULATION***	**Weightage**	**Evaluation**
	AFTER 1980	1	
	1960 TO 1980	3	
	1940 TO 1960	7	
	1920 TO 1940	13	
	BEFOR 1920	20	
		SUB ATTRIBUTE50	
10B	***NO. OF GROUND FAULTS***		
	0 FAULTS	0	
	1 FAULTS	2	
	2 FAULTS	5	
	3 TO 5 FAULTS	10	
	> 5 FAULTS	20	
		SUB ATTRIBUTE51	
10C	***NO. OF SHORT-CIRCUITED POLES***		
	0	0	
	1	2	
	2	5	
	3 TO 5	10	
	> 5	20	

Table 3.1 - continued

		SUB ATTRIBUTE52	
10D	***INTER POLE CONNECTION BREAK***		
	0 BREAK	0	
	1 BREAK	3	
	2 BREAKS	5	
	3 TO 5 BREAKS	10	
	> 5 BREAKS	15	
		SUB ATTRIBUTE53	
10E	***ROTATING EXCITERS***		
	N/A	0	
	STATOR RUBS	2	
	REWINDING REQUIRED	2+	
	> 50 YEARS OLD	2+	
		SUB ATTRIBUTE54	
11	**VISUAL INSPECTION**		
11A	***PRESENCE OF DIRT***	**Weightage**	**Evaluation**
	NONE	0	
	< 1 mm	1	
	1 TO 5 mm	3	
	> 5 mm	5	
		SUB ATTRIBUTE55	
11B	***INSULATION CONDITION***		
	FIRM	0	
	SEPERATED TURNS	(3 TO 6)	
	BROKEN COLLARS	(4 TO 8)	
	CRUMBLING	(6 T 10)	

Table 3.1 - continued

		SUB ATTRIBUTE56	
11C	***RIM***		
	KEYS TIGHT	0	
	LOOSE KEYS	(3 TO 5)	
	KEYS VIBRATION (RED POWDER VISIBLE)	(6 TO 10)	
	FLOATING RIM	5+	
		SUB ATTRIBUTE57	
11D	***SPIDER***		
	NO CRACKS	0	
	CRACKED WELDS	(# x 4)	
	CRACKED PLATES	(# x 10)	
	INSUFFICENT STIFFNESS	(5 TO 25)	
		SUB ATTRIBUTE58	
11E	***BRAKE TRACK***		
	GOOD CONDITION	0	
	USED OR DAMAGED	(1 TO 5)	
	PLATES NOT ALIGNED	2+	
		SUB ATTRIBUTE59	
11F	***AMORTISSEUR WINDING***		
	GOOD CONDITIONS OR N/A	0	
	VIBRATIONS	(1 TO 3)	
	DAMAGED WELDS	(1 TO 3)+	
	BARS/SLOTS	(1 TO 3)+	
	DAMAGES	(6 TO 10)+	
		SUB ATTRIBUTE60	
11G	***SHAFT***		

Table 3.1 - continued

	GOOD	0	
	CRACKED (REPAIRABLE)	(1 TO 7)	
	TO REPLACE	10	
		SUB ATTRIBUTE61	
12	**TEST AND MEASUREMENTS**		
12A	***MEGGER AT 500 V dc***	**Weightage**	**Evaluation**
	> 100	0	
	50 TO 100	2	
	5 TO 50	5	
	2 TO 5	8	
	< 2 Meg	10	
		SUB ATTRIBUTE62	
12B	***POLE IMPEDANCE***		
	VARIATION OF < 10 %	0	
	VARIATION OF 10 TO 20 %	5	
	VARIATION OF > 20 %	10	
		SUB ATTRIBUTE63	
12C	***TOLERANCES***		
12C.A	***CIRCULARITY***		
	< 6 %	0	
	6 TO 12 %	3	
	12 TO 18 %	6	
	18 TO 24 %	10	
	24 TO 30 %	15	
	> 30 %	20	
		SUB	

Table 3.1 - continued

		ATTRIBUTE64	
12C.B	***CONCENTRICITY***		
	< 1.2 %	0	
	1.2 TO 2.4 %	3	
	2.4 TO 3.6 %	6	
	3.6 TO 4.8 %	10	
	4.8 TO 6.0 %	15	
	> 6.0 %	20	
		SUB ATTRIBUTE65	
12D	***GUIDE BEARING VIBRATION***		
	< 25 MICRONS	0	
	25 TO 100 MICRONS	2	
	100 TO 300 MICRONS	4	
	300 TO 500 MICRONS	7	
	> 500 MICRONS	10	
		SUB ATTRIBUTE 66	
12E	***COLLECTOR***		
	FULL LOAD TEMP RISE		
	< 75˚ C	0	
	75˚ C TO 85˚ C	1	
	> 85˚ C	2	
		SUB ATTRIBUTE 67	
	SUB-TOTAL TESTS AND MEASUREMENT OF ROTOR	*SUB-TOTAL 12*	
	ATTRIBUTE ROTOR (G_3)	**ATTRIBUTE G_3 TOTAL**	

Table 3.1 - continued

	MECHANICAL COMPONENTS (G_4)		
13A	***STATOR FRAME***	**Weightage**	**Evaluation**
	NO CRACKS	0	
	CRACKED WELDS	(1 TO 6)	
	CRACKED PLATES	(3 TO 15)	
	DEFICIENT SOLEPLATES	(5 TO 15)	
	CONCRETE MOVEMENT	(5 TO 25)	
	INSUFFICIENT RIGIDITY	(5 TO 25)	
		SUB ATTRIBUTE 68	
13B	***UPPER BRACKET***		
	NO CRACK OR N/A	0	
	CRACKED WELDS	(1 TO 6)	
	CRACKED PLATES	(3 TO 15)	
	DEFICIENT SOLEPLATES	(3 TO 15)	
	INSUFFICIENT RIGIDITY	(6 TO 24)	
		SUB ATTRIBUTE 69	
13C	***UPPER GUIDE BEARING***		
	N/A	0	
	INSULATION TO REPLACE	1	
	BABBITT DAMAGED OR TO REPLACE	1 OR 3	
	DEFICIENT DESIGN	(1 TO 5)	
		SUB ATTRIBUTE 70	
13D	***LOWER BRACKET (OR CONE)***		
	NO CRACKS	0	
	CRACKED WELDS	(0.3 TO 2)	
	CRACKED PLATES	(1 TO 5)	
	DEFICIENT SOLEPLATES	(1 TO 5)	
	CONCRETE MOVEMENT	(2 TO 8)	

Table 3.1 - continued

	INSUFFICIENT RIGIDITY	(2 TO 8)	
		SUB ATTRIBUTE 71	
13E	***LOWER GUIDE BEARING***		
	N/A	0	
	BABBITT DAMAGED OR TO REPLACE	1	
	INSULATION TO REPLACE	1 OR 3	
	DEFICIENT DESIGN	(1 TO 5)	
		SUB ATTRIBUTE 72	
13F	***THRUST BEARING***		
	INSULATION TO REPLACE	1	
	BABBITT DAMAGED OR TO REPLACE	1 OR 3	
	OIL INJECTION REQUIRED	5	
	DEFICIENT DESIGN	(1 TO 8)	
		SUB ATTRIBUTE 73	
13G	***COOLERS***		
13G.A	***STATOR COOLERS***		
	GOOD CONDITION OR NONE	0	
	MAINTANENCE REQUIRED	(# x O TO 25)	
	REQUIRED OVERHAUL	(# x 0 TO 5)	
	REPLACEMENT REQUIRED	(# x 1 TO 0)	
	PIPING TO REPLACE 3	3	
		SUB ATTRIBUTE 74	
13G.B	***GUIDE BEARING UPPER OR DOWNSTREAM***		
	GOOD CONDITION OR N/A	0	
	REQUIRED MAINTANECE	(0 TO 25)	
	REQUIRED OVERHAUL	(0 TO 5)	

Table 3.1 - continued

	REQUIRED REPLACEMENT	(1 TO 0)	
	PIPING TO REPLACE	(0 TO 5)	
		SUB ATTRIBUTE 75	
13G.C	***GUIDE BEARING LOWER OR UPSTREAM***		
	GOOD CONDITION OR N/A	0	
	REQUIRED MAINTANECE	(0 TO 25)	
	REQUIRED OVERHAUL	(0 TO 5)	
	REQUIRED REPLACEMENT	(1 TO 0)	
	PIPING TO REPLACE	(0 TO 5)	
		SUB ATTRIBUTE 76	
13G.D	***THRUST BEARING (ALONE OR COMBINED)***		
	GOOD CONDITION OR N/A	0	
	REQUIRED MAINTANECE	(0 TO 75)	
	REQUIRED OVERHAUL	(1 TO 5)	
	REQUIRED REPLACEMENT	(3 TO 0)	
	PIPING TO REPLACE	(1 TO 0)	
		SUB ATTRIBUTE 77	
13H	***BRAKES AND JACKS***		
	GOOD CONDITION	0	
	MINOR REPAIR	1	
	MAJOR REPAIR	2	
	REPLACEMENT REQUIRED	4	
		SUB ATTRIBUTE 78	
	ATTRIBUTE MECHANICAL COMPONENTS (G_4)	***ATTRIBUTE G_4 TOTAL***	
	EXTERNAL FACTORS (G_5)		

Table 3.1 - continued

14A	***RUN-OF-THE-RIVER POWER HOUSE***	**Weightage**	**Evaluation**
	NO	0	
	YES	10	
		SUB ATTRIBUTE 79	
14B	***RELATIVE IMPORTANCE TO THE NETWORK***		
	< 50 MW	0	
	>= 50 MW	(1Pt/ 50 MW)	
		SUB ATTRIBUTE 80	
14C	***NEED OF TURBINE OVERHAUL***		
	NO	0	
	YES #NOTE	(1 TO 40)	
		SUB ATTRIBUTE 81	
14D	***ABNORMAL OPERATING CONDITIONS***		
14D.A	***POWER STATION***		
	N/A	0	
	< 5 %	5	
	5 TO 10 %	10	
	10 TO 20 %	15	
	> 20 %	20	
		SUB ATTRIBUTE 82	
14D.B	***TERMINAL VOLTAGE***		
	95 TO 105 %	0	
	< 95 %	4	
	105 TO 110 %	7	
	> 110 %	10	

Table 3.1 - continued

		SUB ATTRIBUTE 83	
14E	FREQUENCY OF START-UPS		
	< 10 PER YEAR	*1*	
	10 TO 49 PER YEAR	*2*	
	50 TO 99 PER YEAR	*3*	
	100 TO 199 PER YEAR	*4*	
	200 TO 300 PER YEAR	*6*	
	> 300 PER YEAR	*10*	
		SUB ATTRIBUTE 84	
14F	PLANT UTILISATION FACTOR		
	< 25 %	*2*	
	25 % TO 50 %	*4*	
	50 % TO 75 %	*6*	
	75 % TO 90 %	*8*	
	> 90 %	*10*	
		SUB ATTRIBUTE 85	
	ATTRIBUTE EXTERNAL FACTORS CONTRIBUTIONS (G5)	*ATTRIBUTE G5TOTAL*	

3.3.1 Threshold Scores for Conditional Analysis

The possible conditions of generator which are set of outcome of multi-criterion study for conditional analysis of generator is based on the threshold score for each component analyzed independently. These threshold scores provide a basic criterion for choosing possible condition based on the score provided for each of the component or attributes of the generator in Table 3.1. Once the criterion for the possible conditions are framed then we evaluate the scoring of each component based on the present condition of the component, the scoring in this case is would be provided in the Table 3.1. Comparing these to the framed criterions helps us to make a decision regarding the possible conditions of the generator, to decide whether to go for upgrading or not. The Table 3.2 below shows the possible conditions of the generator and the threshold score corresponding to the possible conditions.

Table 3.2 Threshold Scores for Possible Conditions [6]

Attributes(→) Possible Conditions	Stator Winding(G_1)	Stator Core (G_2)	Rotor (G_3)	Mechanical (G_4)	External Factors (G_5)
Excellent Condition (X_1)	< 35	< 35	< 30	< 5	< 20
Good/Average Condition (X_2)	35 – 60	35 – 60	30 – 55	5 – 15	20 – 40
Poor Condition (X_3)	60 – 85	60 – 85	55 – 80	15 – 40	40 – 60
Mediocre Condition (X_4)	> 85	> 85	> 80	> 40	> 60

3.3.2 Program Based Analysis

The Visual Basic is first used with Excel to frame the decision criterion using the weightage for each sub-attribute shown in Table 3.1 and subsequently analyze the scoring for the evaluation of each sub-attribute of the generator by engineers and technician and come up with the one of the possible conditions of the generator. The Visual Basic is used to read the Table 3.1 and make the decision on relevant possible conditions within the framed criterions. Some of the highlights of the Visual Basic and Excel base program for evaluation of possible conditions of generator are:

- Analysis of Each Component or Attribute is done separately to know the condition of each component.
- The over all outcome of the evaluation does not depend on just anyone attribute. This would possibly remove the over influence of any single attribute for decision making.
- The program analyzes the input evaluation and compares it with the numerical range of possible conditions, once the evaluation falls within that range; the generator present condition is given in form of one of the possible condition.

3.4 Multi-Criterion Weighted Average Evaluation Based Decision Making

The objective behind using multi-criterion weighted average evaluation based decision making for generator upgrading is to develop a tool that could be used by engineers for evaluation of generator's condition. The term evaluation could have different meaning based on situation and type of people who use it. In practical situation decision are mostly taken considering more than one feature or attributes with different weightage on the decision alternatives, and how much weight each attribute carries on the type of decision one takes, depends on the importance attribute itself.

For example if you plan to buy a laptop, price range or weight or type of processor or looks or brand could be many goals you will be definitely looking for and your decision to buy the laptop will be weighed based on ratings each goal is assigned. The decision you can take could be, buy the laptop or not to buy or look in different store or don't buy at present.

Multi-criterion weighted average evaluation based decision making deals with decision making with evaluation based on multiple criterions discussed in Section 3.1.1, that is when the decision has to be taken considering multiple analysis. As required in our upgrading study, weighted average evaluation will be useful tool in deciding whether an upgrading study is desirable or not based on the analysis of the different components or attributes of the generators. The decision making process using weighted average method will utilize the weightage given to each component in "International Energy Association's Guidelines for Rehabilitation of Hydro Generator" as shown in Table 3.1. Based on the present condition of the sub-component or sub-attribute, score is given as shown in the Table 3.1, after analyzing the score with respect to the formulated decision criterion based on weighted average; the decision will be taken out of given four possible conditions.

3.4.1 General Outline of the Theory

Faced with the decision problem where decision has to be taken after evaluating the different attributes of the generator, the section focuses on weighted average decision making process. Let us consider a decision involving multiple possible conditions given by set X such that, $X = \{X_i \,/\, i = 1, 2, \ldots\ldots n\}$ and while making decision, consider multiple attributes of the generator given by set $G = \{G_j \,/\, j = 1,$

2,…… m}. Total of each attributes based on scoring provided according to the guidelines can be calculated.

$$\text{TOTAL ATTRIBUTE}(G_1) = \sum_{j=1,.....20} \text{Sub - Attribute}(j) \qquad (3.1)$$

$$\text{TOTAL ATTRIBUTE}(G_2) = \sum_{j=21,.....43} \text{Sub - Attribute}(j) \qquad (3.2)$$

$$\text{TOTAL ATTRIBUTE}(G_3) = \sum_{j=44,.....66} \text{Sub - Attribute}(j) \qquad (3.3)$$

$$\text{TOTAL ATTRIBUTE}(G_4) = \sum_{j=67,.....78} \text{Sub - Attribute}(j) \qquad (3.4)$$

$$\text{TOTAL ATTRIBUTE}(G_5) = \sum_{j=79,.....85} \text{Sub - Attribute}(j) \qquad (3.5)$$

$$TOTAL(G) = \sum_{j=1,.....5} G_j \qquad (3.6)$$

The weightage of G_i defined as W_i is calculated using Equation 3.6 and the data provided in the Table 3.1. The relative importance of the possible condition X_i with respect to the attribute G_j, given by weighting X_{wij}, which is provided in the Table 3.3, is calculated for the threshold for each possible condition discussed in Section 3.3.1. The relative importance or weightage of goals is given by:

$$W_i = \frac{(\text{Sum of max scores for all sub - attributes of Attribute 'i'})}{\sum_{i=1.....5} \text{Sum of Max Score for all Attributes}} \qquad (3.6)$$

Where:

W_1 = Weightage of Stator Winding in the analysis.

W_2 = Weightage of Stator Core in the analysis.

W_3 = Weightage of Rotor in the analysis.

W_4 = Weightage of Mechanical Components in the analysis.

W_5 = Weightage of External Factors in the analysis.

and:

G_1 = Stator Winding

G_2 = Stator Core

G_3 = Rotor

G_4 = Mechanical Components

G_5 = External Factors

Let X_i be the set of possible condition of the generator.

$X = \{X_i / i = 1, 2, \ldots\ldots n\}$

X_1 = *the condition of Generator is **EXCELLENT**, **Upgrading** could be an option if **Uprating** of installed capacity is **DESIRED**.*

X_2 = *the condition of Generator is **Good/Average**, **Upgrading** could be an option for modernization as well as **Uprating** capacity and reliability of generation. A **CONSTANT AND CAREFUL SUPERVISION*** is *required.*

X_3 = *the condition of Generator is **POOR**, the **installed capacity of Generation unit is derated, Upgrading** is best option for **reliable operation** of generator, besides that **Uprating** the installed capacity can be done together at **minimum cost.***

X_4 = *the condition of the Generator is **<u>WORST</u>**, to bring the Generator **<u>back to Service Upgrading</u>** would be best option together with **Uprating installed capacity**.*

G = {G_1, G_2, G3, G_4, G_5} be the set of component or attributes, with respect to the Generator and X = {X_i / i = 1,2….n} be the possible conditions available based on the present condition of the component or attribute 'G'. The weightage of each alternative is give by set X_w, such that X_w = {X_{wi} / i = 1,2…4} is given by Equation 3.7 , the maximum for each attributes comes from Table 3.1 and the weightage for possible condition is given as per the guidelines.

$$X_{wij} = \frac{X_i(\textit{threshold score}) \text{ of Possible Conditions}}{\underset{j=1....5}{G} \text{jMAX}} \qquad (3.7)$$

The values of X_{wij} for 'i' possible conditions with respect to 'j' goal or attribute is given in the Table 3.3 in form of 4×5 matrix, rows designating possible conditions and column, the attributes of the generator.

Table 3.3 Weightage of Possible Condition w.r.t Attributes

X_{wij}	Stator Winding (G_{1MAX})	Stator Core (G_{2MAX})	Rotor Winding (G_{3MAX})	Mechanical Components (G_{4MAX})	External Factors (G_{5MAX})
X_1	0.15152	0.132075	0.11719	0.05682	0.19418
X_2	0.25974	0.22642	0.21485	0.1705	0.38835
X_3	0.36797	0.32076	0.3125	0.4546	0.58252
X_4	> 0.36797	> 0.32076	> 0.3125	> 0.4546	> 0.58252

R_{ij} is defined as the relative weightage of possible condition 'X_i' with respect to goal 'G_j', this is especially important while analyzing each goal individually, R_{ij} gives the range for each possible conditions based on the weightage of possible condition with respect weightage of the goal, R_{ij} is given by Equation 3.8.

$$R_{ij} = X_{wij} \times W_j \qquad (3.8)$$

Where: i = 1 to 4 and j = 1 to 5

The Table 3.3 shows the relative weightage of the possible condition with respect to the weightage of attributes for the generator condition analysis. Based on these standard ratings and the input data of Table 3.1, decision making based on condition of five different components of the generator and their weightage.

Table 3.4 Ratings of Possible Conditions w.r.t the Attributes

Attributes → ***Decision*** ***Possible conditions ↓***	Stator Winding (G_1)	Stator Core (G_2)	Rotor (G_3)	Mechanical Components (G_4)	External Factors (G_5)	Range for Possible conditions
Excellent Condition (X_1)	0.037116	0.037116	0.031813	0.0053022	0.02121	0.13256
Good/Average Condition (X_3)	0.063627	0. 063627	0.058325	0.015907	0.04242	0.24390
Poor Condition (X_3)	0.09014	0.09014	0.084836	0.042418	0.06363	0.37116
Mediocre Condition (X_4)	> 0.0901	> 0.0901	> 0.08484	> 0.042418	>0.0636	> 0.37116

Based on the above rating and weightage given to each attributes as shown below in the set, a threshold for each decision making is fixed. Set W depicts weightage of each sub-component in the multi-criterion weighted average decision making analysis.

$W = \{W_{1,} W_{2,} W_{3,} W_{4,} W_5\}$

$W_1 = 0.24496$

$W_2 = 0.28102$

$W_3 = 0.27147$

$W_4 = 0.09332$

$W_5 = 0.10923$

Hence, W = {0.24496, 0.28102, 0.27147, 0.09332, 0.10923}; for the multi-criterion analysis of hydroelectric generator for upgrading study. In Table 3.4, the range for the decision criterion is calculated, based on relative weightings of attribute with respect to the possible conditions. The range for formulating the decision criterion based on Table 3.5 is given by Equation 3.8.

$$\text{Range for } X_i = \sum_{j=1}^{5} R_{ij} \tag{3.8}$$

The Table 3.4 shows the decision and the corresponding range of values for decision making guidelines.

Table 3.5 Possible Conditions and Their Range

Decision/Possible conditions (X_i)	Range of values
Excellent Condition (X_1)	0 – 0.13256
Good/Average Condition (X_3)	0.13256– 0.24390
Poor Condition (X_3)	0.24390 – 0.37116
Very Poor/Mediocre Condition (X_4)	> 0.37116

3.5 Estimation of Useful Life of Generators

After preliminary inspection and testing, it is necessary to estimate the remaining life of the generator, so that final decision can be taken regarding upgrading or uprating. The outcome of testing, measurement, visual inspection and other analysis, is used in this section to estimate the useful life of the generator and its reliability of operation. It is important to determine the approximate remaining life of the generator so that our decision can be implemented before any major failure occurs. Reliability of any hydropower equipment is defined as capability of equipment to perform as originally intended. Any unit plagued with component failure, lack of maintenance and improper operation leads to derated performance.

The basic procedure of estimating engineering reliability is development of the reliability curves. Statistical approach is used for development of reliability curves based on the service life of similar equipment together with past experience as well as service histories. The reliability analysis provides us the information about the availability of the generator under investigation, where availability 'A' is defined as:

$$A = \frac{MTFF}{MTFF + MTTR} \qquad (3.9)$$

Where:

A = Availability of the unit

MTFF = Mean time to failure

MTTR = Mean time to repair

The Mean time to failure and repair are estimated from the past data [10] available for similar kind of unit under investigation, the manufacturer or other research agency should have these data available. Using these data first develop the base line curve, which is fitted as shown in the next few sections with respect to the current condition for proper estimation. The failure rate of any electrical equipment is a function of time, provided other maintenance related issues are addressed, hence given any function h(t), such that at time, t = 0, h(0) = 0 and the function increases monotonically to infinity as 't' goes to infinity, can be defined by cumulative probability function shown below. The probability of failure is given by Equation 3.11.

$$F(t) = 1 - \exp(-h(t)) \tag{3.10}$$

P(t = 0) = 0, and at 't' approaching infinity $P(t \to \infty) = 1$ (3.11)

3.5.1 Reliability Analysis of the Generator

Reliability of any equipment is defined as probability that the equipment will continue to be in service till time't' with satisfactory performance as desired. In hydropower plant and incase of many other equipment, failure rate increases with time. Hence, the probability, that the equipment will be in service till time 't' is defined as reliability R (t).

$$R(t) = P(T > t) \tag{3.12}$$

Where:

T = Time to failure.

The Equation 3.12 states reliability as the probability of successful operation till time‘t’ such that time to failure, ‘T’ is greater than ‘t’. The engineering reliability R (t) is defined as:

$$R(t) = 1 - \frac{n_r(t)}{n_e(t)} \tag{3.13}$$

Where:

R (t) = Engineering reliability, t = age

n_e (t) = Number of generators exposed, including both in service as well as out out of service or retired.

n_r (t) = Number of generators retired.

The Weibull distribution is often used to model aging failure process of electrical and mechanical equipment, this distribution is characterized by parameters gamma also know as the shaping parameter and alpha the scale parameter. The Weibull distribution approximation of the engineering reliability defined above by Equation 3.14 is defined as:

$$\text{Reliability} = R(t) = e(-H(t)) = e^{-(\frac{t}{\theta})^{\lambda}} \tag{3.14}$$

Where:

H(t) = Cumulative Hazard function

θ = Characteristic age at which R = $\frac{1}{e}$ = 0.37

and λ = dimensionless shape parameter.

Similarly, the relation between cumulative hazard function and the hazard rate function, h(t) is defined below:

$h(t) = \frac{dH(t)}{dt}$; Where cumulative hazard rate function must satisfy the following condition:-

H(0) = 0; and

$$\lim_{t \to \infty} (H(t)) = \infty$$

Using Equation 3.9 for Weibull distribution approximation of hazard (failure) rate function applying the relationship above:

$$h(t) = H`(t) = \frac{d(H(t))}{dt} = \frac{d}{dt}(\frac{t}{\theta})^{\lambda}$$

$$h(t) = \left(\frac{\lambda}{\theta}\right) * \left(\frac{t}{\theta}\right)^{\lambda - 1} \qquad (3.15)$$

The equation for h(t), gives the hazard rate function by Weibull distribution approximation, and is widely used in evaluation of reliability of equipment whose failure rate increases with age. Now take an algebraic transformation of the Equation 3.14 [12] and use Weibull model to fit the reliability data. After the curve fitting, the Weibull parameters θ and λ can be estimated. Taking logarithm of Equation 3.14 twice to get:

$$\ln[R(t)] = -\left(\frac{t}{\theta}\right)^{\lambda}$$

Taking the logarithm again.

$$\ln\left[\ln\left(\frac{1}{R(t)}\right)\right] = \lambda \ln(t) - \lambda \ln(\theta) \tag{3.16}$$

Comparing Equation 3.16 with the equation of a straight line $y = mx + c$, Equation 3.16 is in the same form as linear equation of straight line. From the Equation 3.16, $y = \ln\left[\ln\left(\frac{1}{R(t)}\right)\right]$; slope $m = \lambda$ and X = ln(t) and the 'Y' axis intercept C $= \lambda \ln(\theta)$. A plot of $y = \ln\left[\ln\left(\frac{1}{R(t)}\right)\right]$ Versus X = ln(t) will give the equation of the best fit line for baseline data giving Weibull parameters. Besides, using straight line fitting method, a simple linear regression sequence with n = 100 will give us the parameters, since baseline data extends up to 100 yrs, and find the Weibull parameter λ and θ using Equation 3.17 [13].

$$\lambda = \left[\frac{n * \sum_{k=1}^{n} X_k Y_k - \left(\sum_{k=1}^{n} X_k\right)\left(\sum_{k=1}^{n} Y_k\right)}{n * \left(\sum_{k=1}^{n} X_k^2\right) - \left(\sum_{k=1}^{n} X_k\right)^2}\right] \tag{3.17a}$$

$$\theta = \exp\left[\frac{\left(\sum_{k=1}^{n} Y_k\right)\left(\sum_{k=1}^{n} X_k^2\right) - \left(\sum_{k=1}^{n} X_k\right)\left(\sum_{k=1}^{n} Y_k\right)}{\lambda * \left(n * \sum_{k=1}^{n} X_k^2 - \left(\sum_{k=1}^{n} X_k\right)^2\right)}\right] \tag{3.17b}$$

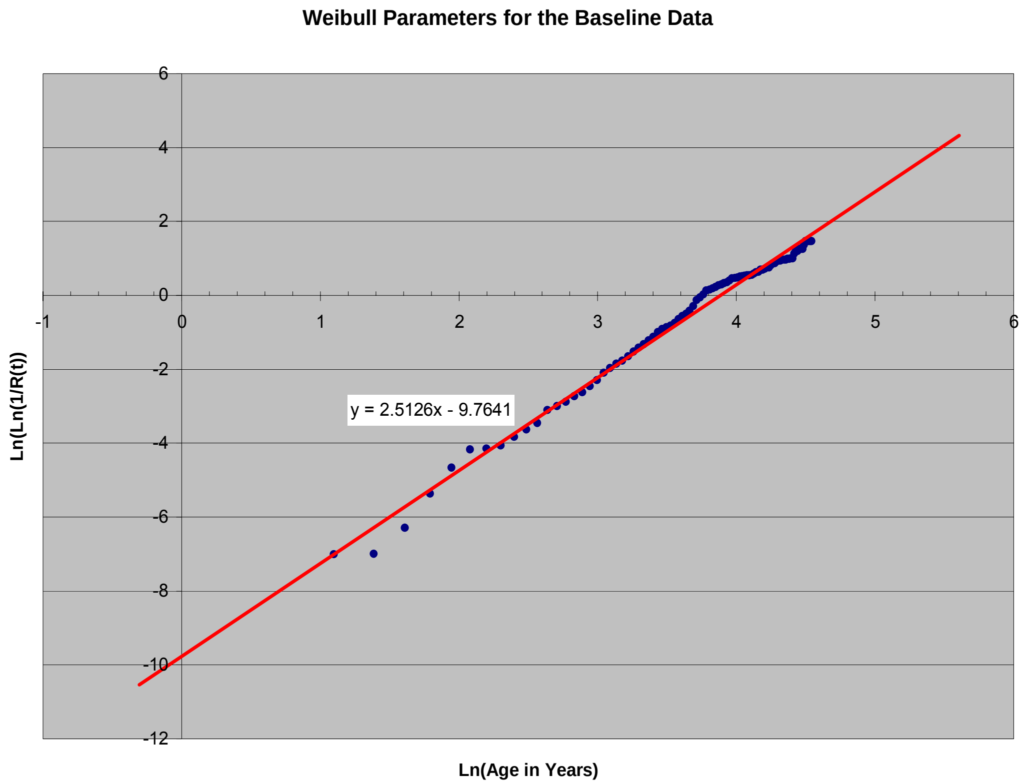

Figure 3.1 Weibull Parameter Estimation

Figure 3.1 above, shows the, $y = mx + c$, approximation of Equation 3.16 for baseline data, from which Weibull parameters can be estimated. The base line data plotted above represents average life of equipment and does not take into account the current condition of the equipment, whether maintenance and operation was carried out periodically and performance of generator as designed etc. Hence, from the baseline data one can interpret the average reliability of similar types of generator, which does not take into account the actual condition of the generator.

After calculating the Weibull parameters from the above mentioned technique, our aim now is to find the hazard rate function and then be able to estimate the hazard or failure rate for any equipment. In the section 3.5.2, discusses Bayes theorem, which takes into account current condition in form of condition indicator, which helps in assessment of equipment considering present condition.

3.5.2 Reliability Analysis by Integration of Present Physical Condition of the Equipment

Considering the above situation, Bayes theorem of probability provides the basic reason for integrating the qualitative condition indicators; widely know as the CI, the adjusted reliability of the equipment by integrating the current condition is give by the Equation 3.18.[10,12]

$$R_{CI} = \frac{P_s * R}{P_s * R + P_U (1 - R)} \tag{3.18}$$

Where:

R_{CI} = The reliability of equipment after taking present condition CI, into account.

R = The reliability from the survivor curve.

P_s = Condition indicator given satisfactory condition.

$= \frac{CI}{50}$

P_U = Condition indicator given unsatisfactory condition.

$= \frac{50}{CI}$.

Equation 3.18 shows the weighting of survivor function (Weibull reliability) and condition indicator, which directly reflects the present condition of the equipment. The fact that more credence or weightage is given to the present condition in the Equation 3.18, is reflected from the plot of Figure 3.2, where reliability (R_{CI}) is plotted versus age at different values of condition indicator, a plot for baseline reliability is also plotted. Equation 3.18, takes into account the present condition of the generator, based on the value of the condition indicator the reliability of the equipment changes with respect to age, comparing baseline curve with respect to the current condition integrated curve in Figure 3.2, giving the comparison between baseline reliability estimation given by Weibull distribution and reliability of equipment taking after integrating present condition.

At CI = 10, 30, 60, 80 and 95 plot of the reliability obtained by above Equation against the age, the Figure 3.2 clearly shows the effect of CI on reliability with respect to the age.

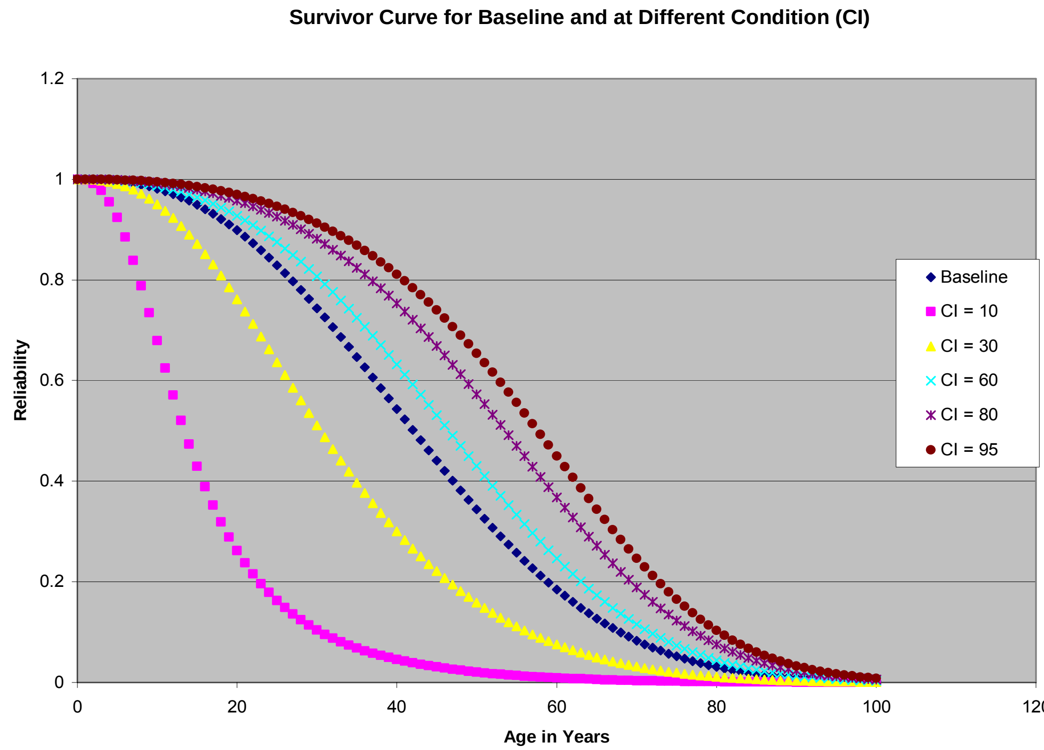

Figure 3.2 Showing Plot for Reliability versus CI

3.5.3 Condition Indicators [14]

The condition indicator is quantitative rating given after assessment of equipment thoroughly. Condition indicators are an outcome of Research, Evaluation, Maintenance and Reliability program (REMR) of Army Corps of Engineers. The condition indicator varies from 0 to 100, and scoring is done with respect to the present physical state of the equipment and its sub-component. The scoring after inspection and test are based on the deterioration of the sub-component, and study of operation and maintenance report. The CI provides a fair and uniform procedure of analyzing equipment through testing and visual inspection. Any equipment with CI values between 70 and 100 is considered to be in good to excellent condition, the range 40 to 69, is considered to be marginal, average or fair condition and the range from 0 to 39 is considered to be poor, very poor and failed based on the value of CI in the range. The Table 3.6 shows the condition index scaling together with general condition description and recommended action to be taken.

Table 3.6 Showing Condition Index Scaling [14]

Zone	Condition Index	Condition Description	Recommended Action
I	85 to 100	Excellent: no noticeable defects. Some wearing or aging may be visible.	Immediate action is not required.
	70 to 84	Good: only minor deterioration or defects are visible.	
II	55 to 69	Fair: Some deterioration or defects are evident, but operation is not affected significantly	Economic analysis of repair options is recommended to determine appropriate action.
	4 0 to 54	Marginal: Moderate deterioration, operation is still adequate.	

Table 3.6 - continued

III	25 to 39	Poor: Serious deterioration in at least some portion of sub-component operates at derated condition.	Detailed evaluation is required to determine the need for repair, rehabilitation or reconstruction. Safety evaluation is recommended.
	10 to 24	Very Poor: Extensive deterioration, barely functional.	
	0 to 10	Failed: No longer functions, general failure or complete failure of major component.	

3.5.4 Case Study

The Whitney power plant is located on the Brazos River, about 75 miles southeast of Dallas, Texas. The Whitney power house consists of two identical generating units with name plate capacity of 15,000kW each. These are erected in vertical position, installed by Allis Chalmers in 1953. Each unit has been operating since last 50 years, these generating units has undergone extensive wear and tear, and at present are operating at derated capacity. The base line data for the reliability analysis was provided from hydroelectric development center (HDC), [10] based on these data and following the Section 3.5.2, develop reliability curve both for baseline data as well as with the present condition indicator and estimate it to Weibull distribution. The

Figure 3.3 shows the estimation of baseline reliability curve (survivor curve) to Weibull distribution given by Equation 3.16 is shown below.

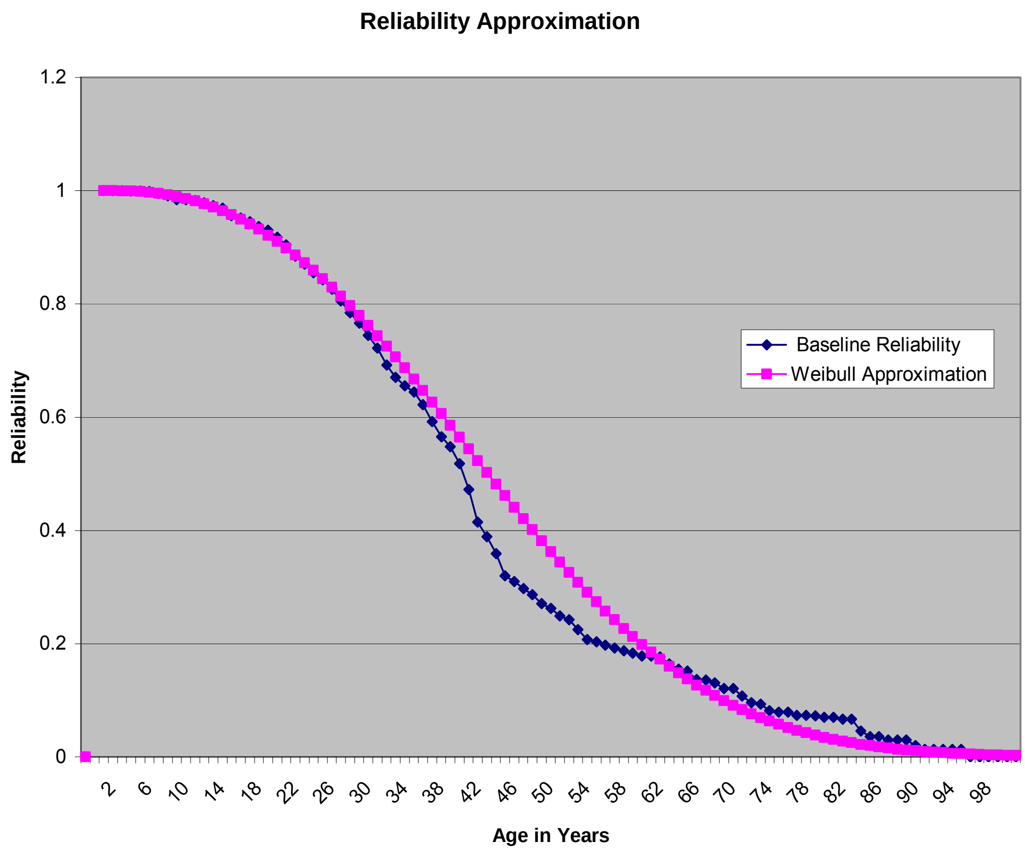

Figure 3.3 Weibull Distribution Estimation of Baseline Survivor Curve

After extensive study of maintenance and operation history, visual inspection and electrical testing of both the unit at Whitney Lake, the inspection team evaluated the present condition of both the unit. The CI score was awarded for both the unit as per their present condition. Using Equation 3.18, first calculate the reliability of the each unit considering present condition. Table 3.7 shows the CIs and other parameter of Whitney generator's for Equation 3.18.

Table 3.7 Showing Parameters for Both the Generators [10]

Parameter	Unit I	Unit II
Condition Indicator (CI)	17	12
Remark based on CI	Very Poor	Very Poor
Probability of satisfactory condition, Ps	0.34	0.24
Probability of unsatisfactory condition, Pu	2.9412	4.1667

Insert the above values in the Equation 3.13, and calculate adjusted reliability or reliability reflecting present condition, R_{CI}.

$$R_{CI} = \frac{P_s * R}{P_s * R + P_U (1 - R)} \qquad \text{3.18}$$

The R_{CI}, calculated is used in the Equation 3.16, a plot of $y = \ln\left[\ln\left(\frac{1}{R(t)}\right)\right]$; against X = ln(t), for the adjusted parameters is shown in the Figure 3.9 for Unit I and Figure 3.3 for Unit II. By approximating the best fit straight line for both the Figures mentioned above, Weibull parameters are evaluated; Table 3.7 shows the results of Weibull parameters from Figure 3.3 and 3.4.

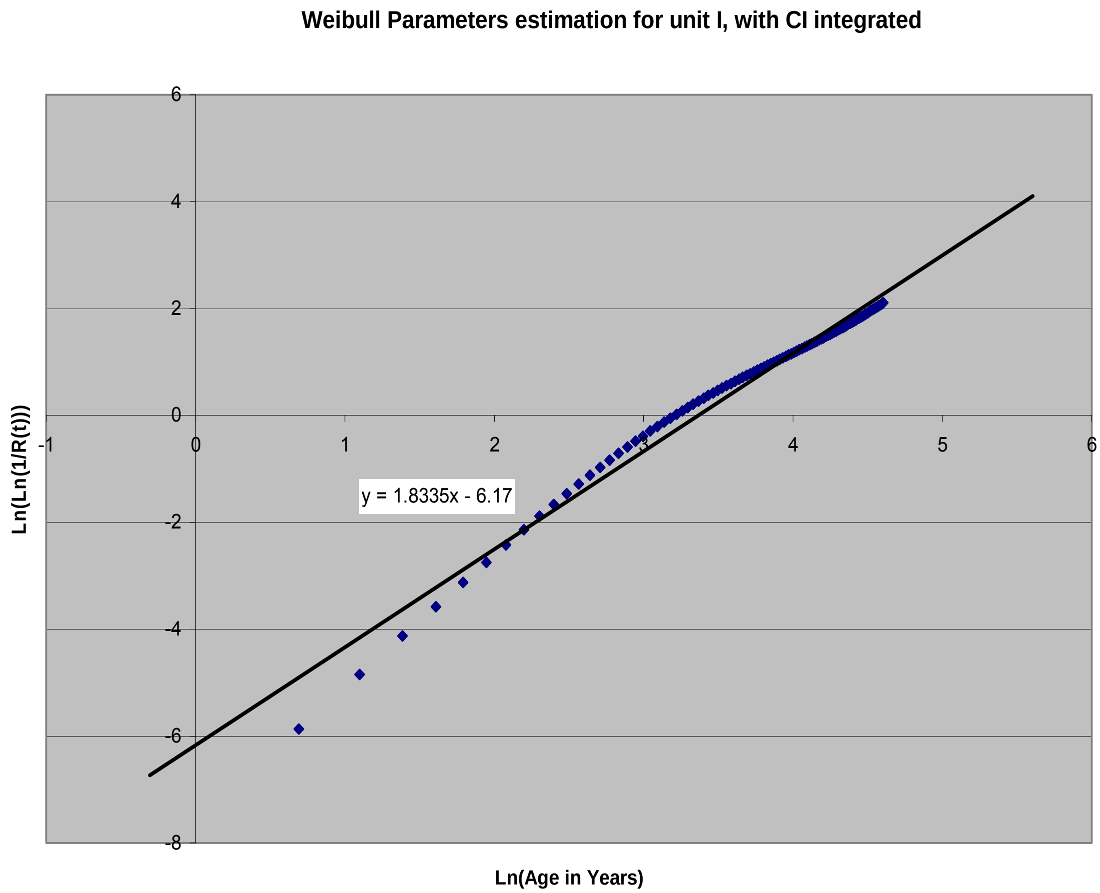

Figure 3.4 Weibull Parameter for Unit I

From the Figure 3.4, the Equation for the straight line with best fitting is given by, Y = 1.9319x - 6.4833, based on these values Weibull parameters like λ and θ are calculated, where λ is given by the slope of straight line in Figure 3.3:

λ *= 1.9319 and* θ *= Exp (6.4833/1.9319) = 23.7294 yrs.*

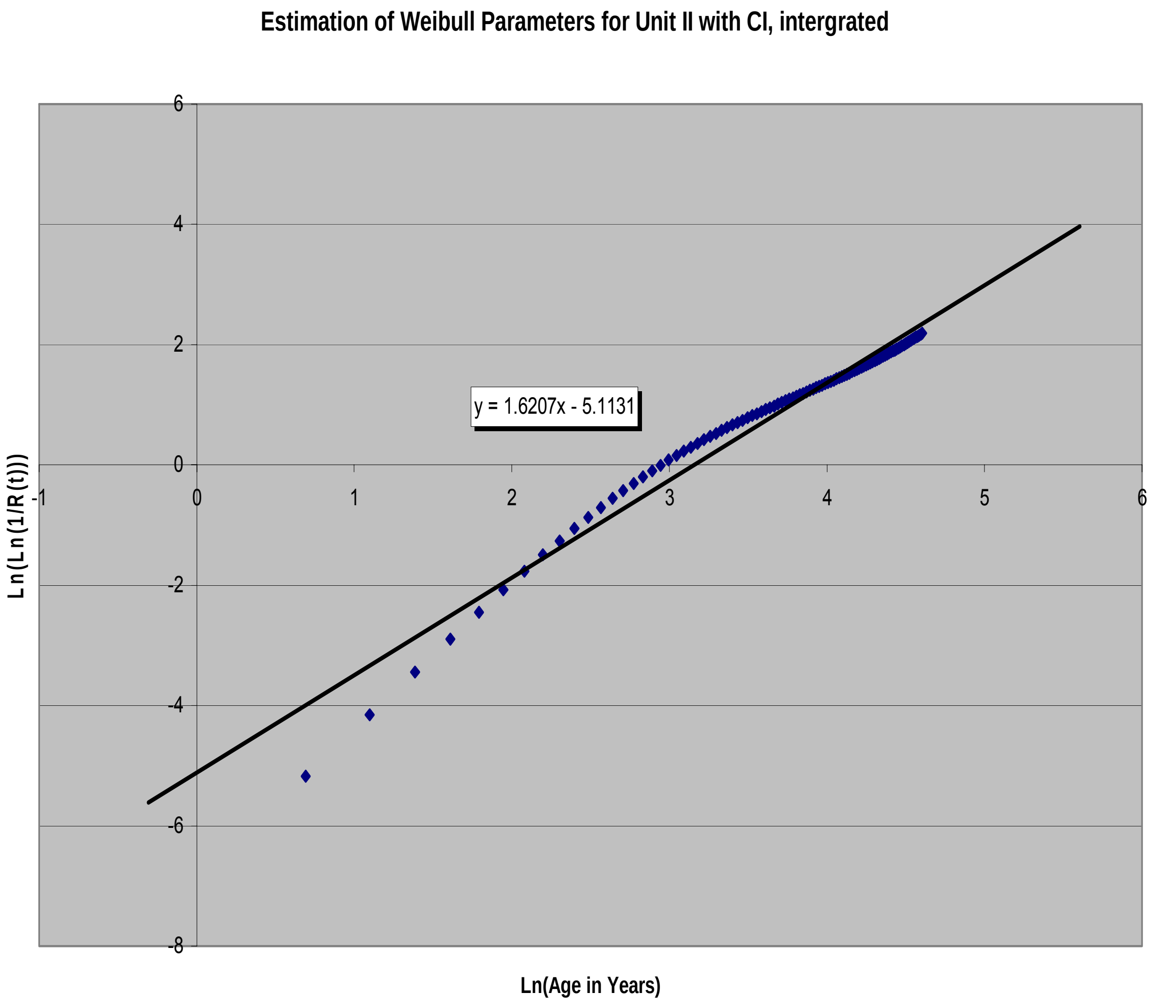

Figure 3.5 Weibull Parameters for Unit II

Similarly, for Figure 3.10 the equation of the best fitting straight line is given by, Y = 1.7317x - 5.4838, and based on these values Weibull parameters are shown below:

λ *= 1.7317 and* θ *= Exp (5.4838/1.7317) = 28.6719 yrs*

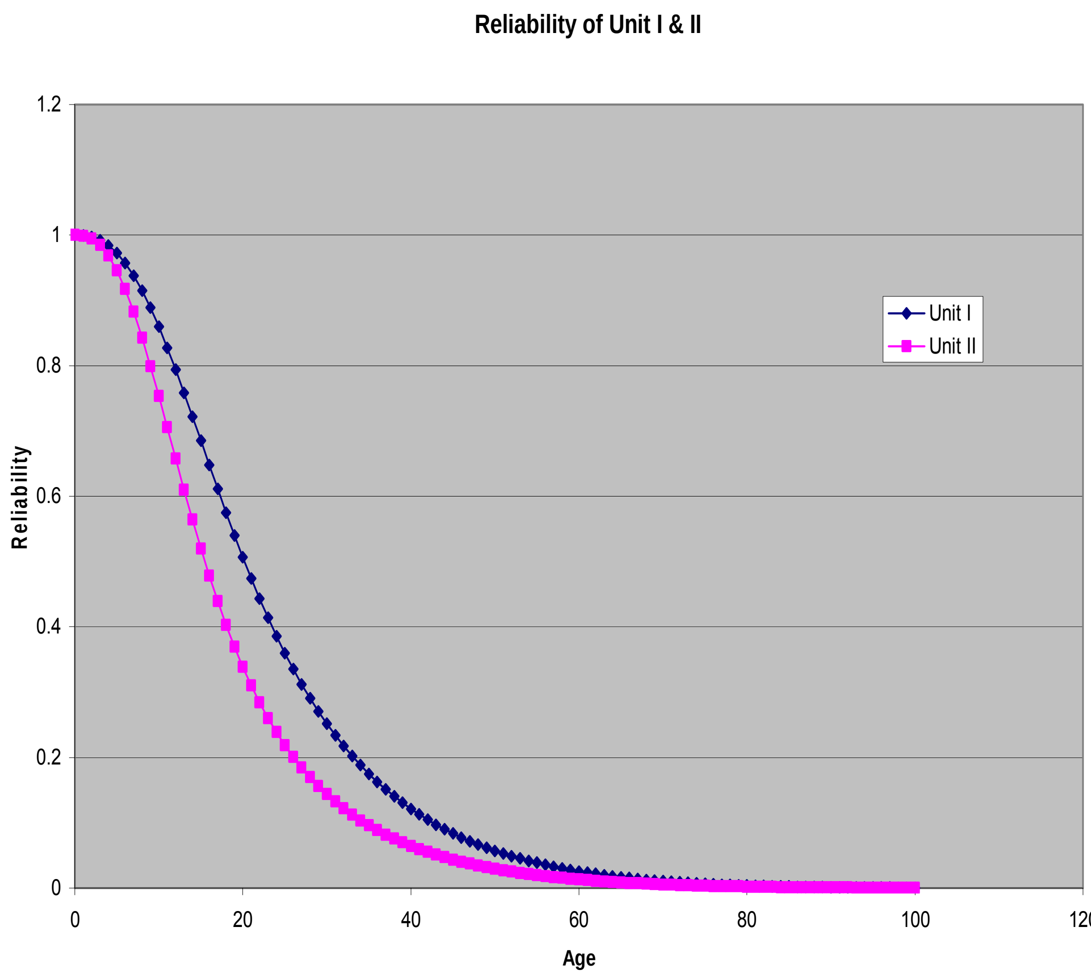

Figure 3.6 Plot of Generator Reliability for Unit I & II

Substitutions of values of λ and θ, in the hazard function with respect to the age of the equipment yields the hazard function or failure rate function of the equipment, given by the Equation 3.19.

$$h(t) = \left(\frac{r}{\theta}\right) * \left(\frac{t}{\theta}\right)^{\lambda - 1} \tag{3.19}$$

Table 3.8 Hazard Rate for Baseline Data, Unit I and Unit II

Age	Baseline Hazard rate	Unit I, Hazard rate with CI	Unit II, Hazard rate CI
0	0	0	0
10	0.00470	0.02613	0.04072
20	0.01341	0.04656	0.06261
30	0.02477	0.06530	0.08053
40	0.03827	0.08299	0.09627
50	0.05364	0.09999	0.11057
60	0.07067	0.11635	0.12382
70	0.08923	0.13230	0.13626
80	0.10920	0.14788	0.14803
90	0.13050	0.16313	0.15926
100	0.15305	0.17811	0.17002

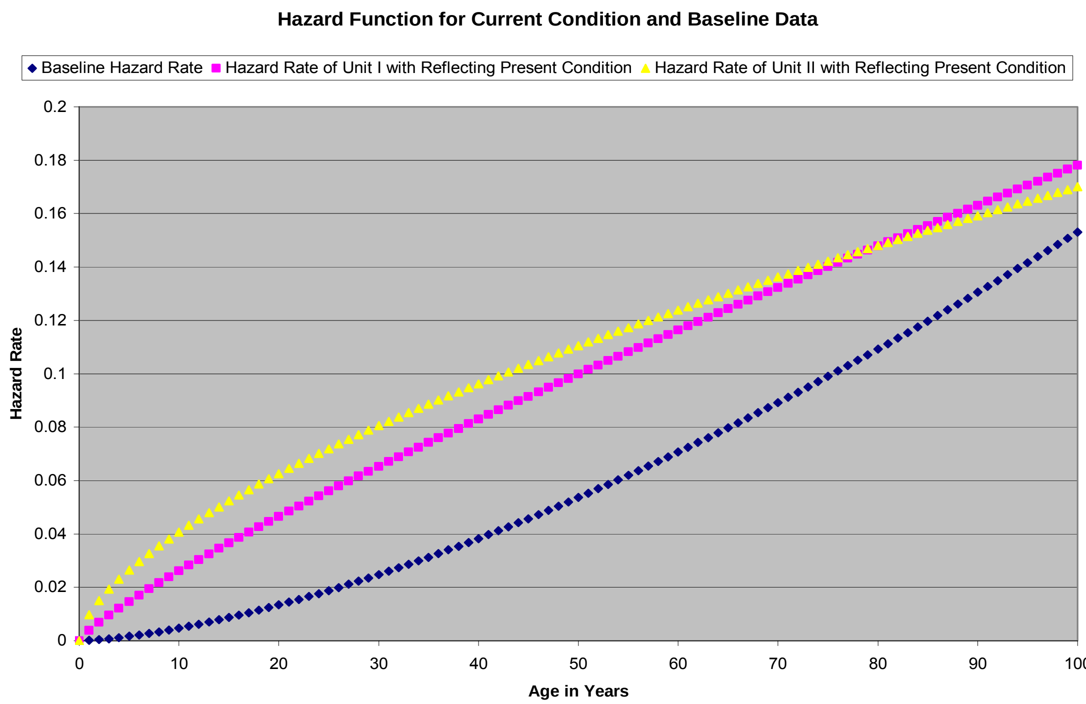

Figure 3.7 Plot of Hazard Rate for Baseline, Unit I and Unit II With CI.

Based on the reliability evaluation using present condition integrator and Weibull parameter estimation by straight line method, the present reliability and the hazard rate for the two generators has been approximately calculated assuming present age of the generator to be 53 years. The Table 3.9 shows the present reliability and failure rate of the generator at Whitney power plant while for baseline curve failure rate stands at 0.05366 and the reliability of the generator is 0.34389.

Table 3.9 Present Parameters for Whitney Generators

Parameter	Unit I	Unit II
Hazard Rate/Year	0.105	0.109
Reliability	0.0571	0.029

CHAPTER 4

FEASIBILITY STUDY FOR UPGRADING HYDRAULIC (FRANCIS) TURBINE

4.1 Introduction

Hydraulic turbines have a long history of development; water wheel is the oldest and simplest form of hydraulic turbine. Hydraulic turbines have been used since long time in hydro-electric power plant for harnessing electricity out of falling water. Based on the type of flow for rotating the runner, these have been categorized as impulse and reaction turbine. Pelton turbine is an example of impulse turbine while Francis and Kaplan belong to reaction type of hydraulic turbine.

Hydraulic turbine convert potential energy of the falling water into mechanical energy, by rotating the shaft coupled to the rotor of the generator producing electricity. The amount of energy that can be harnessed depends upon the available head, flow, efficiency of the hydraulic turbines and efficiency of generator coupled to the turbine. The turbine output in metric unit, Kw is given by Equation 4.1.[15]

$$Kw = \frac{HQw\eta}{102} = 9.8HQ\eta \qquad (4.1)$$

Where Kw = output in kilowatt.

H = Net head in meter.

Q = Turbine discharge in meter^3/sec

η = Turbine Efficiency.

4.2 Feasibility for Upgrading and Uprating Hydraulic Turbine

The fundamental fact of any equipment is that they will reach an age and a condition when major rehabilitation is inevitable, regardless of its performance. Most of the problems associated with hydraulic turbine are due to corrosion. The mineral-saline content of the rivers presents problems to turbines and corrosion could result due to non-operation of the generator also. It is a sound advice to perform major overhaul before revenues are affected, either due to failing or critical state of important component.

The average age of hydraulic turbine is around 50 to 60 years. Due to many years of operation, the turbine's mechanical component like any other machinery is prone to ageing, worn out component increases the risk of outage and turbine operates under reduced capacity. Replacement or refurbishment of old and aging components of turbine that has undergone deterioration, can lead either at least to restoration of original capacity or increase in capacity (uprating). Besides due to research and technological advancement the new components available are more efficient and less prone to cavitations and mechanical failure. Upgrading of old components can drastically see improvements in the following:

- Efficiency
- Turbine performance due to uprating
- Reduction in cavitations
- Reductions in noise and vibration

Figure 4.1 shows clearly the increase in efficiency of Francis turbine with respect to specific speed, throughout the last century due to research and development activities in the field of hydraulic turbine.

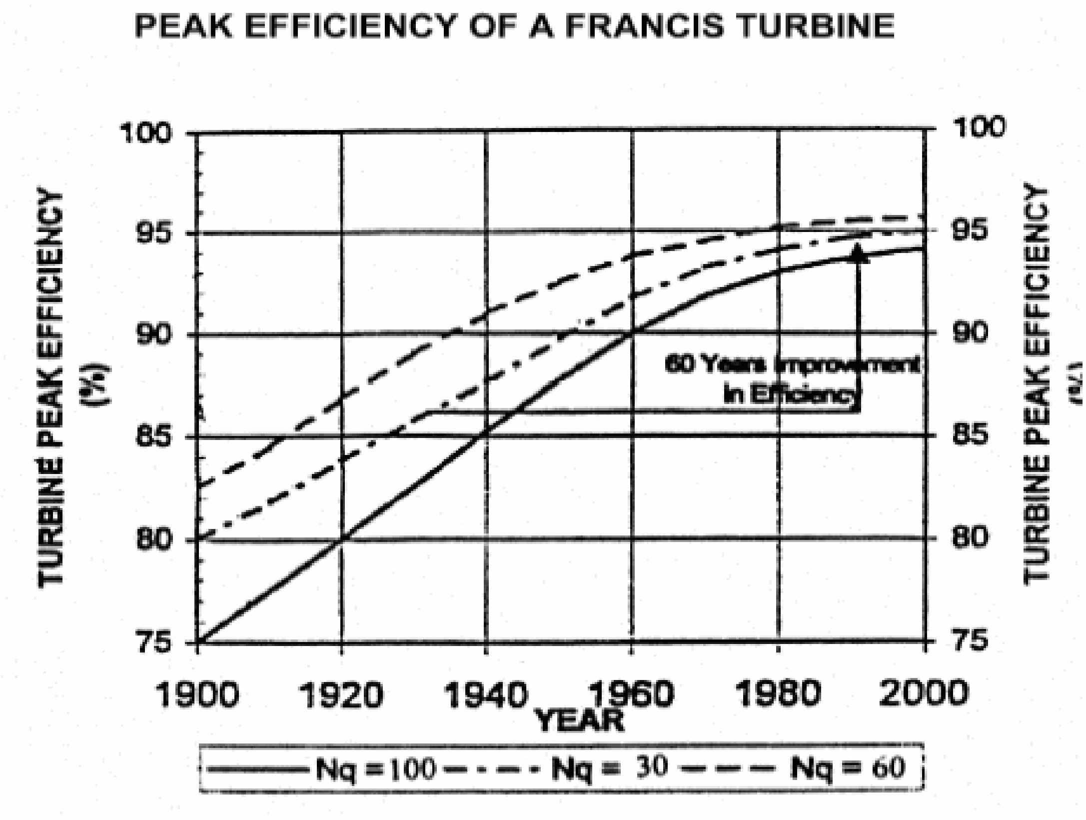

Figure 4.1 Showing Increase in Peak Efficiency of Francis Turbine [9]

The cost of lost in revenue due to derated capacity and scope of adding extra capacity by upgrading in most of the cases justifies upgrading and uprating project both with respect to cost/benefit and reliability of the unit. Under present deregulated market, reliability of the generation facility is important with respect to revenue as well as credibility in the market. The assessment of present condition and evaluation of available data will be centrally focused around the following to analyze if there is any possibility of upgrading or uprating:

- Turbine integrity
- Performance
- Operation and maintenance cost
- Turbine reliability and availability status
- Hydrology

The possibility for upgrading arises after through investigation of present condition of the turbine with respect to integrity, availability, generation, increase in maintenance and operations cost and drop in revenue possibly due to derated performance of the turbine. The decision to whether go for upgrading and uprating should be taken after careful analysis of energy production versus years , well based on the data available the theoretical energy can be calculated, the plot of energy production versus period will show us the degradation in performance of the hydropower plant. Other way to look at the degradation is to observe the change in gross revenue as a result of drop in turbine power or efficiency, from reduced unit availability or could be from reduced available discharge, the exact cause should be identified before any decision is taken.

Other ways to look at possible degradation of turbine is by trending the annual cost of maintenance and operation for past few years, any significant rise will mean reduced reliability, risk of outage due to failure and loss of revenue. The maintenance and operation cost can also be the basis for upgrading and uprating if trend for past few years shows significant economic burden on the plant. While conducting cost/benefit analysis for different possible conditions, the impact of increasing operation and maintenance cost is analyzed. The other way of looking at the degrading health of plant is to plot the plant load factor over a period of time; the decrease in load factor could be attributed to factors other than turbine efficiency degradation.

Hence, one of the main objectives of turbine condition analysis in Section 4.4 is to actually identify the physical condition of the turbine independently, perform field test to check the efficiency level, this could be done by independent laboratory. The possibility for upgrading and uprating could be the result of change in hydraulic conditions which could be, to better utilize the available discharge, the plant operating mode could demand more capacity which is possible only after upgrading and uprating, besides these any drop in efficiency of turbine by more than, 4% to 6% will be critical performance issue which needs to be addressed as soon as possible, in most of the plants.

The research and development in the area of hydraulic turbine has lead to increase in efficiency as well as capacity of these turbines, unlike the old turbines, the new hydraulic turbines are equipped with state of art technology. Environmental issues like content of dissolved oxygen has been better addressed, research have led to fish passage in modern turbine with lesser risk and modern governors are far superior compared to old mechanical governors, whose parts may no more be available in the market. The modern turbine system with advanced fish passage technology, with better aeration, environmentally friendly and compatible for remote monitoring makes and advance technology and availability of better material together with added power at least generation cost makes upgrading an attractive alternative. Based on the condition of existing turbine, the owner has to make a choice out of following alternatives:

A. *Retirement of generating plant*

This alternative means total cessation of any commercial operation, hence no more revenue while, on the other hand the owner is responsible for maintenance of civil structures, regulation of flows or any other issues agreed upon. This alternative has cumulative economic impact as on one hand after stopping of operation you don't have any revenue and on the other hand the utility has to incur all the expenses for the maintenance for the plant.

B. *Continued operation of plant with maintenance for failures*

This alternative is simply about repairing whenever there is failure, gradually with time the components start degrading, efficiency of plant decreases, reliability of the plant decreases, availability is affected and number of forced outages increases due to failure, revenue is lost and expense for repair and maintenance has to be undertaken by the owner of the plant.

C. *Continued operation of existing generating plant with careful supervision, scheduled inspection and maintenance and repair for any brake downs.*

This option is very similar to the last alternative but here the owner of the plant makes every possible bid to run the operation smoothly. This alternative is the best method to optimize revenues and profits over longer period of time, but with passage of time the turbine components deteriorates, reliability decreases and at any instant the turbine failure could lead to major outage. The repair cost and loss of revenue could cost more than upgrading project.

D. *Upgrading and uprating of existing generating plant*

This alternative is a proactive approach; the main objective of this alternative is to increase the reliability and availability by renewing the technical life of the turbine. It is the best way to optimize the potential revenue for another 25 to 40 years by upgrading, due to less expenditure on operation and maintenance, extra generation due to uprating and added reliability ensures security of revenue collection from the generation. Besides in today's deregulated environment, the reputation of reliable generating unit cannot be compromised.

E. *The new generating plant*

This alternative means construction of new modern plant with high efficiency, reliability and full utilization of potential available at the site. This alternative could be carried out in those sites where there is no scope of upgrading or hydrology of the site has changed with higher or lesser potential for generation. This alternative requires huge investment and the owner has to wait for revenue till the completion of the plant, a through cost/benefit analysis should be carried out before opting for this alternative.

The above five alternatives are available once the condition analysis study is completed, based on that study the alternatives are opted. Before final decision on the alternatives it is important to estimate the useful life left for the turbine so, that project implementation is done as per the plan. The alternatives should be compared with respect to cost/benefit analysis too.

4.3 Main Components of Hydraulic Turbine (Francis)

Hydraulic turbines have been broadly classified into two groups, impulse turbines (Pelton turbine) and reaction turbines (Francis and Kaplan turbines). The impulse turbines are driven by one or more water jets impinging the bucket tangentially where as the reaction turbines has continuous water column. The basic principle of reaction turbine is the fact that there is a change in pressure as water moves through the runner to the draft tube and finally to the tail race, converting the change in pressure to work, hence reaction turbines are either encased in the spiral casing called 'Volute' or are fully submerged. Here discussion will be mainly about the reaction turbines with emphasis on Francis turbine.

The flow of water in reaction turbine completely fills all of the passages in the runner, and most of the pressure drop takes place in the turbine itself. A Draft tube is used to connect the turbine to the tail race, the level of water at tailrace should be higher than the draft tube so that it is filled with water and guide vanes are used for controlling the direction of flow of water. In Francis turbine the pressure of water gradually decreases as it flows through the runner, the decrease in pressure results into work. The Figure 4.2 shows the important components of the Francis turbine, it is important for mechanical integrity of the turbine that these components perform according to their design specifications.

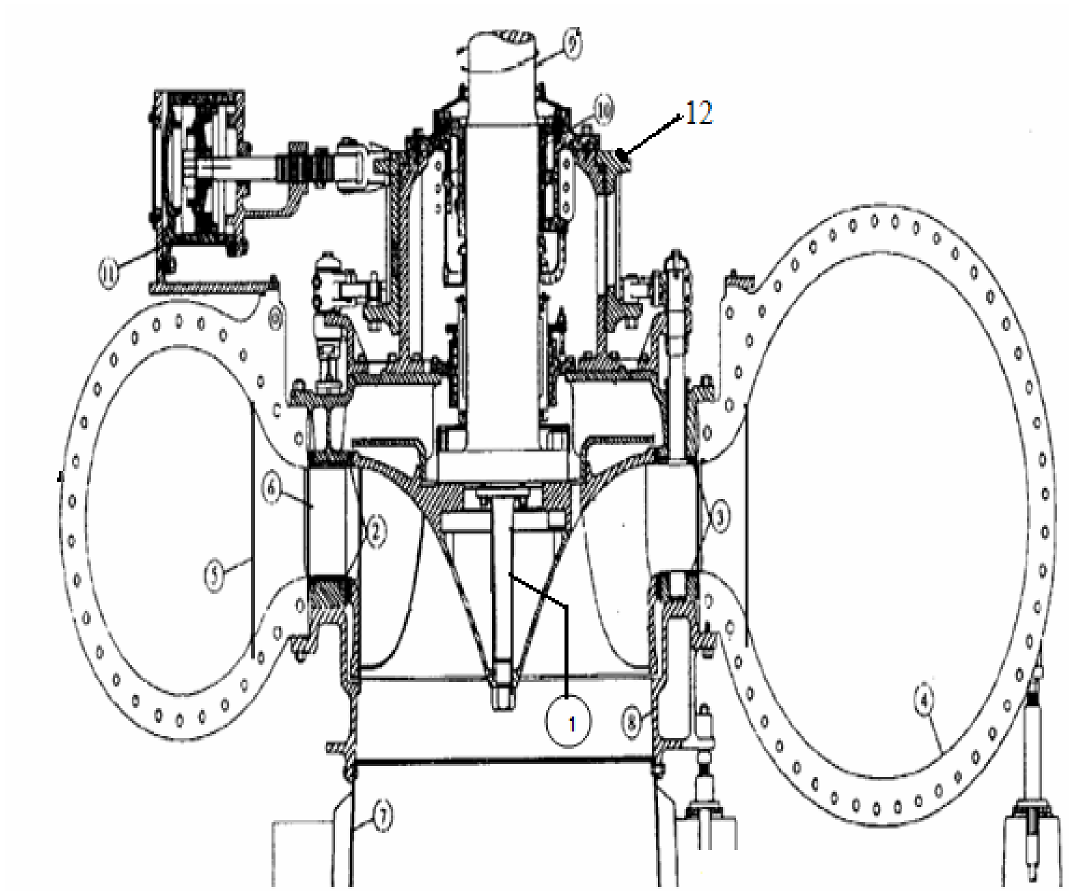

Figure 4.2 Vertical Position Francis Turbine with Important Parts Numbered [19]

Table 4.1 Important Components of Francis Turbine

Number	Component
1	Runner
2	Wearing Rings or Seal Rings
3	Facing Plate or Curve Plate
4	Spiral Case
5	Stay Vane
6	Wicket Gate
7	Draft Tube
8	Discharge Ring
9	Turbine Shaft
10	Turbine Guide Bearing
11	Wicket Gate Servomotors
12	Shit Ring or Wicket Gate Operating Ring

The Table 4.2 [9] shows the increase in efficiency of the Francis turbine after replacement of runner only. Similarly Table 4.3, shows increase in efficiency if other components like spiral casing, stay ring, guide vanes and draft tube are also upgraded together with the runner replacement. Table 4.4, shows improvements in efficiency if runner seal components are replaced or refurbished.

Table 4.2 Francis Turbine Efficiency Uprating (%) After Runner Replacement Only [9]

Rated Head (meter)	Francis Turbine Age (Years)					
	60		40		20	
	Peak	Weighted	Peak	Weighted	Peak	Weighted
25-99	2.2	2.7	1.0	1.3	0.5	0.7
100 - 199	2.0	2.5	1.0	1.3	0.5	0.7
> 200	2.0	2.6	1.0	1.3	0.5	0.7

Table 4.3 Efficiency Uprating (%) after Refurbishing Water Passage Components [9]

Water Passage Component	Surface Finish Improvements	Modifications Or Replacement
Spiral Case	0.3	0.3
Stay Ring	0.2	0.3 to 2.0
Guide Vanes	0.2 to 2.0	0.3 to 0.5
Draft Tube	0.3	0.3 to 1.0

Table 4.4 Efficiency Uprating after Refurbishing Runner Seal Components [9]

Runner Seal Component	Modification and/or Replacement
Crown	0.2 to 2.0 %
Band	0.2 to 2.0 %

4.4 Turbine (Francis) Present Condition Evaluations [9, 19]

The first hand information regarding the present condition of the hydraulic turbine is evaluated after physical inspection of the turbine components, field test and other non-destructive testing methods are implied. The objective behind turbine condition evaluation is to be able to exactly gain the first hand knowledge of the extent of deterioration in the turbine. During turbine present condition evaluation, look at those components whose deterioration leads to drop in performance and efficiency of the Francis turbine. Besides performance and efficiency issues, the material of component is also compared to the present technology, it is always advisable to change the component if more efficient, reliable and better technology is available at present compared to the one under investigation. Besides failure of old mechanical governor may not be repaired at all due to unavailability of the spare parts, as they may be out of production, replaced by modern governors.

To evaluate the present condition of an aging Francis turbine, inspect the important components and look at general symptoms of aging or deterioration and other defect associated with each of these components. Based on the analysis of each component, the condition of whole turbine can be easily evaluated. Under this Section Visual inspection and required test are performed to find the critical issues in the following components.

- Runner

The Runner is inspected for any damages by erosion, cracking and cavitations. The visual inspection as well as nondestructive examination for cracks should be focused particularly in all the junctions between crown, blades and bands. The average roughness of the water passage surfaces is measured and recorded with roughness gauge. The runner cone is inspected to check any defect in its connection to runner or the shaft; the bolts are also inspected for any mechanical defect.

The critical issues with respect to the condition of runner arise when there is visible crack particularly at the junction of crown and the band, any severe cavitation erosion or suspended particle erosion and any evidence of wrecked bolts or looseness. These critical issues are severe enough to affect the physical integrity of the runner.

- Spiral Casing

The spiral casing is inspected for any damage to plates resulting from cracking, usually in the area of stay ring. The roughnesses of the water passage surface finish to be checked and be measured using roughness gouge. Determine local and average plate thickness by ultrasonic measurements and record the variations in thickness with respect to the locations, and measure this with the original thickness. Check the spiral case design pressure, material and mechanical properties.

Critical issues that would warrant immediate upgrading or uprating would be, any cracks in plates or welded joints, severe erosion and corrosion damage beyond specified allowance, if the plates have lost more than 5% of thickness at critical locations and broken or severely damaged rivet heads.

- Discharge Ring

Measure and compare the axial clearance between the discharge ring and the runner and compare it to the original readings. Inspect and check the condition of bolts, studs, nuts, dowel pins and any cracking in discharge ring plates.

Here the critical issue would be cracks in the discharge ring, looseness of bolts and nuts and evidence of broken bolts.

- Bottom Ring

The bottom ring is inspected for any cracks, looseness, any wear and tear in the guide vane end seals and facing plates. The radial clearance of runner band to wearing ring at 8 equally spaced locations is measured and compared against the original design values. Inspect condition of all bolts, studs, nuts and dowel pins.

The critical issue in the bottom ring would be any proof of contact between the guide vanes and bottom ring, looseness of the bottom ring and any increase in clearance between bottom ring and the runner wearing rings with respect to the original manufacturer's recommended clearances.

- Stay Ring

Stay ring and stay vanes are inspected for cracks at the interface with the shroud plates, also the profile of the stay vane is inspected for any wear due to corrosion. The surface finish of the water passage is measured using roughness gouge and any roughness beyond permissible limit will be noted with the location. The condition of the bolts, nuts, studs and dowels pins are examined. The level of stay ring flange for the head cover is measured and compared to the original reading during commissioning.

Critical condition would be if there is cross-sectional area reduction in thickness of stay vane profile by more than 10% due corrosion, evidence of cracks in the stay ring particularly at the joints of stay vanes and shroud plates and variation of flange level exceeding the manufacturer's recommendation.

- Turbine Shaft

The turbine shaft is inspected both visually as well as by nondestructive examination to check for any corrosion, erosion and cracks. The high stressed areas like any welds joining the coupling flange with the shaft body, the cracks at bearing journal ball and connections with shaft body for solid forgings. Inspection of the coupling between runner and the turbine shaft and the tightness of bolts and nuts. To determine the tensile strength and other mechanical properties of the shaft material and check whether, runner and turbine shaft has been designed correctly.

The critical issue with respect to the turbine shaft that would warrant immediate attention for repair, upgrading or replacement would be any evidence of cracks at couplings or bearing journal bell and broken or loose bolts.

- Turbine Shaft Seal

The shaft seal is checked for any damage by corrosion, erosion and cracking. The wear in the seal is measured and compared with the manufacturer's recommendation. The seal material is identified to replace any banned material like asbestos in them.

High leakage water rates which cannot be corrected, chronic problems of bolt failures and seal elements at the end of their useful life are considered critical issues which needs to addressed as soon as possible.

- Turbine Guide Bearing

The guide bearing clearance is measure by jacking method or feller gauges. The measured values are compared against the original manufacturer's tolerances. Bearing operating parameters such as cooling water flow rates and pressure, Babbit metal and oil temperatures are measured and compared against the manufacturer's tolerances and amount of deterioration is compared.

The critical issues would be, the bearing clearance beyond the limit with misalignment will result in possible contact with the runner damaging runner seals and runner blade. The beading or oil temperatures exceeding the manufacturer's limit may result in permanent bearing damage or premature failure or wear of Babbit and shaft journal.

- Guide Vanes

The guide vanes are inspected for any cracks at the interface between the trunnion and vane body, wear of guide vanes profiles due to erosion and record the vane to vane contact line clearances with and without servomotor loads applied. The axial clearances between the guide vane bodies and the bottom ring and head cover is measured and compared with the original design values also using roughness gauge estimate the surface roughness of the water passage surface and compare it with the allowable tolerances.

The critical issues for guide vanes demanding immediate attention would be any evidence of contact between guide vane and bottom ring or the head cover, reduction in guide vane profile or loss of effective sealing on contact surfaces due wear as a result of excessive erosion and any cracks on the guide vanes usually, at the connection of guide vane body and torque delivery trunnion.

- Guide Vanes Operating Mechanism

The guide vanes operating mechanism is inspected for any cracks, looseness, wear and maladjustment. The operating rings, livers, links, shear pins, link pins and bushings are inspected to detect any defect in them. The operation of guide vane mechanism is verified binding or non-uniform movement and the opening and closing times are recorded and the value compared with the original manufacturer's requirements.

The critical issue with respect to operating mechanism for the guide vanes would be variation in closing time from manufacturer's values during commissioning, evidence of binding in the movement of the mechanism and any broken shear pins, link pins or evidence of distortion or cracks in the gate operating rings, livers and links.

- Draft Tube

The draft tube liner is inspected for cavitation or erosion damage. Inspection for damage plates resulting from cracking or detachment from external ribs or anchors and bolts, nuts, studs and dowel pins. The average roughness of the water passage surface is measured and locations of severe wear are marked and compared with the required surface finish to minimize any losses.

The critical condition of the draft tube would be, if the corrosion and erosion damage exceeds and reduces the thickness of the shell by more than 50% locally or 30% of the shell thickness throughout the circumference or if there is any evidence of cracking in the draft tube line region.

- Turbine Aeration System

  The best way to determine the condition of existing turbine would be by finding the amount of air consumption at high loads, more air consumption at high load means drop in efficiency of the turbine. The effectiveness of the aeration system is established by operating the unit through the entire power range and monitoring the stability of draft tube pressure, spiral casing pressure and power at the generator terminals.

  Critical issues with respect to the aeration system would be any evidence of unit instability with or without the aeration systems.

After performing the above inspection, measurements and tests, if there is any evidence of any restrictions to unit's operating range be it power or the guide vane opening mechanism or the reduction in excess of 4% to 6% of power production from the name plate value under careful and controlled testing condition, would be enough to justify early upgrading and uprating.

4.5 Estimation of Turbine Useful Life

The estimation of useful life of the turbine employs reliability analysis similar to the one done for the generator in chapter 3. The basic approach is same as in Section 3.5, except the data of number of retired and in-service Francis turbine is different this time. Start from the baseline data approach and calculate the Weibull parameters to estimate both the Weibull reliability as well as hazard rate. The present condition of the turbine is integrated in the reliability calculation using condition indicators score (CI), the reliability of the turbine as per its present condition is calculated using Equation 4.7.

4.5.1 Turbine Reliability Analysis

The hydraulic turbine reliability analysis criterion is formulated using data such as number of similar turbine that has been retired and the number still in service, the retirement age for each is noted and total number of exposed generator is calculated for each year which is basically using the end of life data of the similar type of turbine. These end of life data are insufficient to truly represent the reliability of the turbine as the retirement age of turbine is directly related to the operational condition and regular maintenance and repair, hence each turbine has different operational condition and maintenance and repair work, for example two same turbine operating under different utility might end up having different mean life, the reason is different operational condition and maintenance and repair work. Although, the end of life data would not be representing exact reliability of the turbine but it could be an essential step to start forward, as it closely resembles the turbine reliability also called the engineering reliability of the turbine. The Equation 4.2 shows the engineering reliability in terms of number of exposed and retired turbines against their age.

$$R(t) = 1 - \frac{n_r(t)}{n_e(t)} \tag{4.2}$$

Where:

$R(t)$ = Engineering reliability, t = age

$n_e(t)$ = Number of turbine exposed, including both in service as well as out of service or retired.

$n_r(t)$ = Number of turbines retired.

The Equation 4.2 is the first step of reliability analysis for estimation useful life of the hydraulic turbine. The Figure 4.3 shows the plot of engineering reliability against the age for the baseline data of similar kind of Francis turbine.

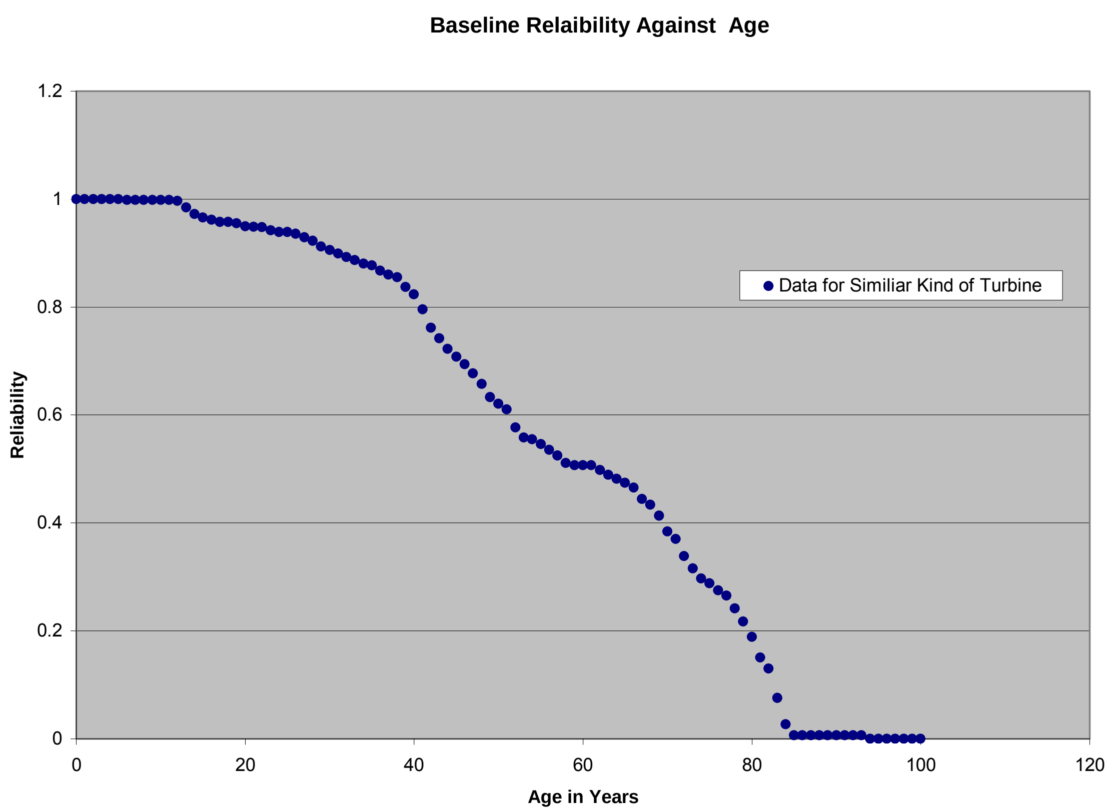

Figure 4.3 Plot of Baseline Reliability for Francis Turbine

The Weibull distribution is very often used to model reliability analysis for aging failure processes. The Weibull distribution is characterized by two parameters, gamma (γ) the shape parameter and theta (θ) as the scale parameter. The Weibull distribution approximation of the engineering reliability is defined as:

$$\text{Reliability} = R(t) = e(-H(t)) = e^{-(\frac{t}{\theta})^{\gamma}} \qquad (4.3)$$

Where:

H(t) = Cumulative Hazard function

θ = Characteristic age at which R = $\frac{1}{e}$ = 0.37

γ = dimensionless shape parameter.

And, t = Age

Similarly, the relation between cumulative hazard function and the hazard rate function, h(t) is defined below:

$h(t) = \frac{dH(t)}{dt}$; Where cumulative hazard rate function must satisfy the following condition:

- H(0) = 0; and
- $\lim_{t \to \infty} (H(t)) = \infty$

Using Equation 4.3, for Weibull distribution approximation of hazard (failure) rate function as given by Equation 3.15:

$$h(t) = \left(\frac{\gamma}{\theta}\right) * \left(\frac{t}{\theta}\right)^{\gamma - 1} \quad (4.4)$$

The Equation 4.4 for h(t), gives the hazard rate function by Weibull distribution approximation, and is widely used in evaluation of reliability of equipment whose failure rate increases with age. Now take an algebraic transformation as shown in Equation 3.16 and comparing with a equation of a straight line $y = mx + c$. The comparison gives $y = \ln\left[\ln\left(\frac{1}{R(t)}\right)\right]$; slope $m = \gamma$ and X = ln(t) and the 'Y' axis intercept C = $\gamma \ln(\theta)$. A plot of $y = \ln\left[\ln\left(\frac{1}{R(t)}\right)\right]$ Versus X = ln(t) will give the equation of the best fit line for baseline data giving Weibull parameters. The Figure 4.4 shows the straight line fitting of the baseline data.

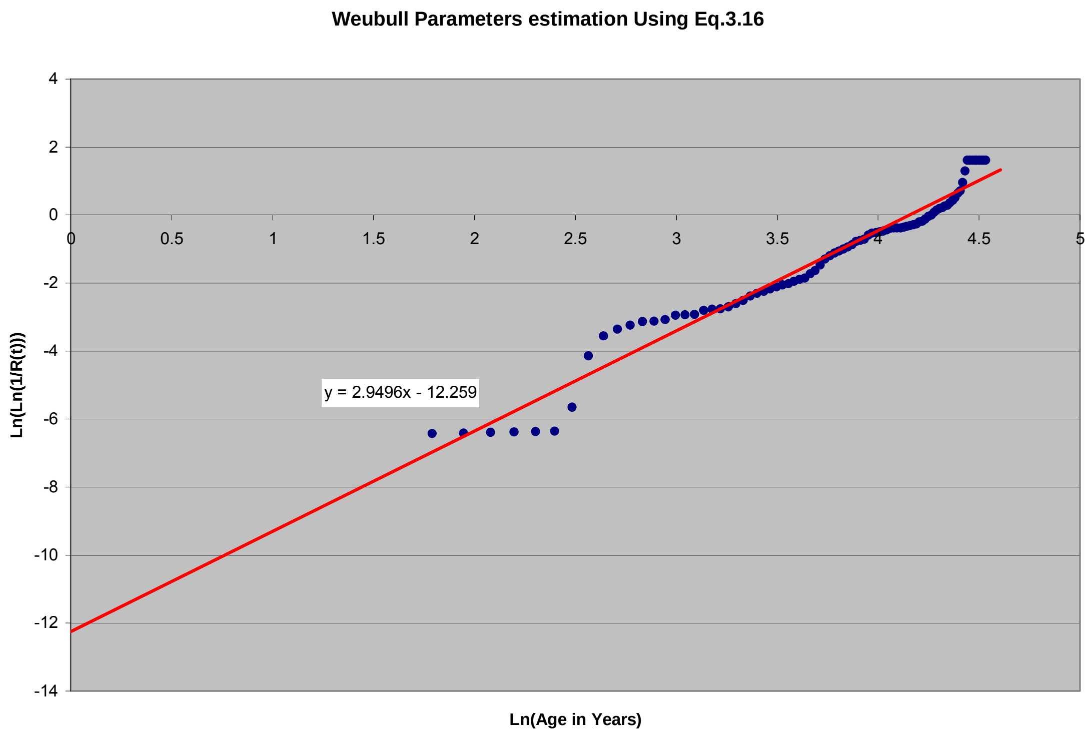

Figure 4.4 Straight Line Fitting of Baseline Data

The equation of the best fitting straight line for the best fitting shown in the Figure 4.y is equal to; y = 2.9496x - 12.259. The values of 'γ' and 'θ 'can now be easily calculated using the equation of the straight line. [12]

Now calculating the baseline Weibull reliability using Equation 4.3[Table C.1] and plotting it with respect to the age, a close approximation is an outcome, of the Equation 4.2 by Weibull reliability. The Figure 4.5 shows the plot of Weibull approximation of engineering reliability for the baseline data.

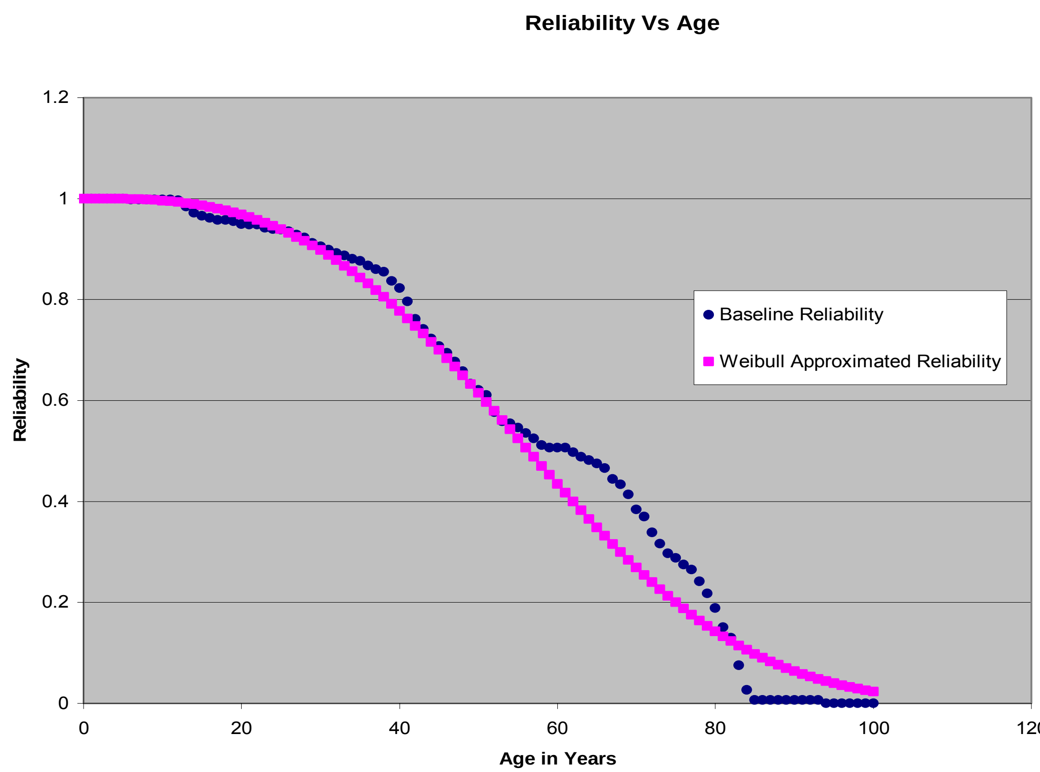

Figure 4.5 Weibull Approximations and Baseline Reliability

Besides, using straight line fitting method, simple linear regression and perform least-square fit of this sequence with n = 100 to get the Weibull parameters, since our baseline data extends up to 100 yrs, and find the Weibull parameter 'γ' and 'θ' using Equation 3.17(a) and 3.17(b).

The Equation 4.2 gives engineering reliability in terms of number of retried turbines and number of exposed turbines. As discussed above, this reliability cannot truly represent the actual condition of all the turbines as different turbines have different operational conditions. The condition indicator (CI), are the score between '0' and '100', with '0' being the worst possible condition and '100' being the excellent condition of the turbine. The condition indicators are used to represent the present condition of the turbine after series of inspections and tests are performed. The Equation 4.7 shows the reliability of the hydraulic turbine with present condition integrated.

$$R_{CI} = \frac{P_s * R}{P_s * R + P_U(1-R)} \quad (4.7)$$

Where:

R_{CI} = The reliability of equipment after taking present condition CI, into account.

R = The reliability from the survivor curve, Weibull reliability approximation.

P_s = Condition indicator given satisfactory condition.

$= \frac{CI}{50}$

P_U = Condition indicator given unsatisfactory condition.

$= \frac{50}{CI}$.

4.5.2 Case Study [10]

The Whitney hydropower plant is located on the Brazos River, about 35 miles northeast of Waco, Texas, near the town of LaGuna Park. The power house is equipped with two identical generating units, the Francis turbine rated at 20,700 hp are in vertical position with speed of 128.6 rpm and at 91.5 ft head. The Whitney units have 130.8`` diameter Francis runner and both the units has been in service since, 1953.

The runner surfaces of the units are very rough due to corrosive nature of river water at Whitney. The blade of the runner has suffered cavitation damage, and in past also it went through major repairs. One of the turbines has been repaired for holes in the bucket due to excessive corrosion. The Gibson efficiency test performed showed reduction of 4% in efficiency. Due to often repair concerns has been expressed about the contour of the turbine bucket during repair of corroded steel. With above condition being the outcome of visual inspections and tests on the turbine for present condition evaluation, a CI score [Table 3.6] was evaluated as shown in the Table 4.5.

Table 4.5 Showing CI Evaluation for Both the Turbines [10]

Parameter	Unit I	Unit II
Condition Indicator (CI)	50	50
Remark based on CI	Moderate deterioration, fair condition	Moderate deterioration, fair condition
Satisfactory condition, Ps	1	1
Unsatisfactory condition, Pu	1	1

The CI score for both the turbine has been given as per the result of inspections and tests, carried out to ascertain its present condition. The plot for the case of turbine will be same to those of baseline Weibull estimation because of the fact that the baseline data represents an average or moderate deterioration with overall fair condition, which is true with respect to present condition of the turbine as evaluated by personnel after inspections and other tests.

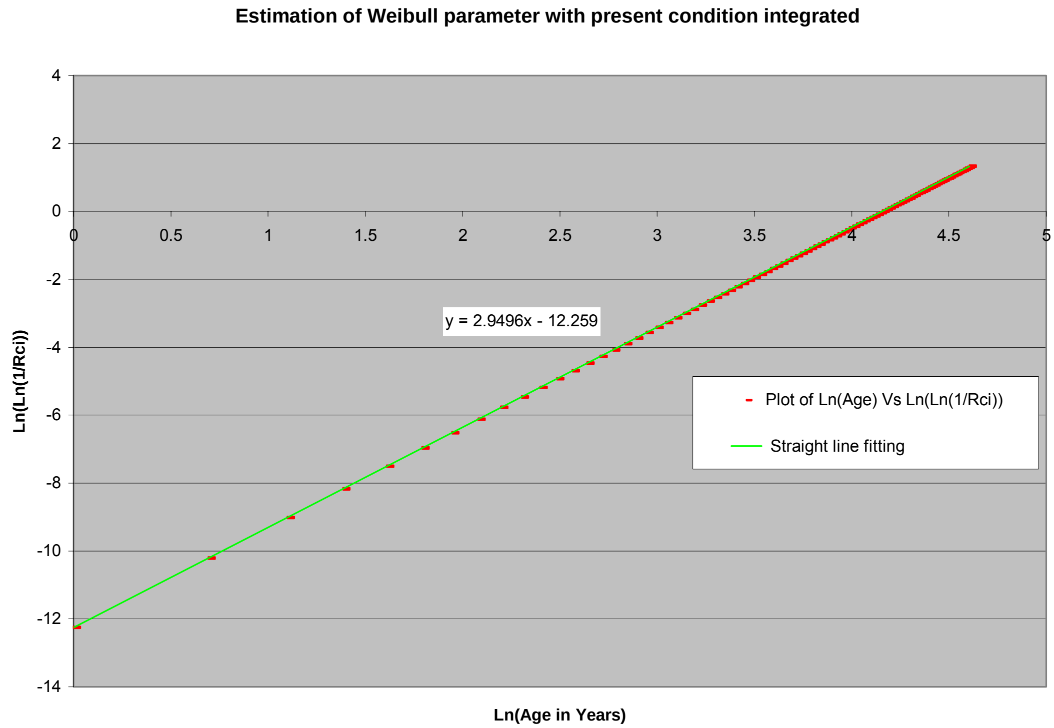

Figure 4.6 Estimation of Weibull Parameter Using Straight Line Fitting

The plot for hazard condition will also be same as the values for straight line estimation remains same. Hence, we can rightfully say that the baseline data represent an average condition of deterioration or overall fair condition of turbine. The hazard function would be same as for the Weibull reliability estimation for baseline data, as the parameters estimated using best fitting straight line remains same. The Figure 4.7 shows the plot of hazard function for turbine, both using Weibull estimation as well as after using current condition indicator comes out to be same for above mentioned reasons.

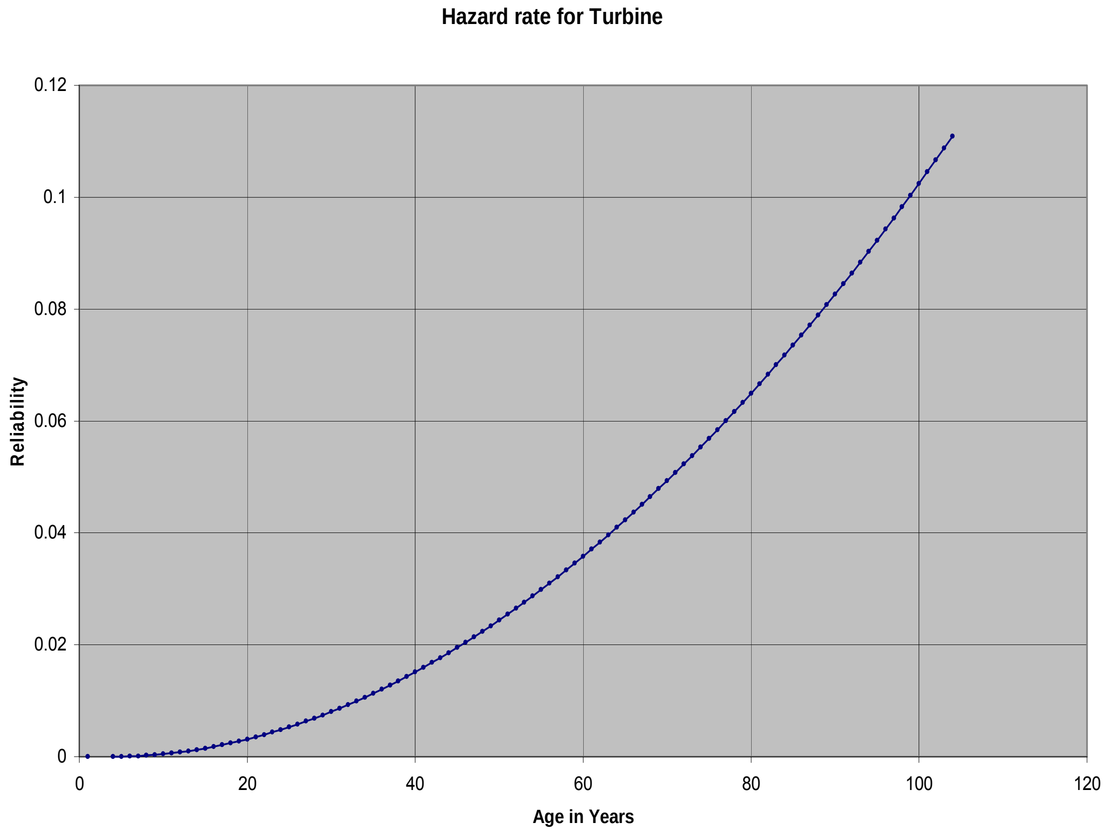

Figure 4.7 Hazard Rate for Turbine [Table C.1]

The plots for Weibull approximation of engineering reliability as well as hazard functions shows that, the statistical estimation of reliability and hazard function for the two turbines at Whitney hydropower plant were identical to the baseline data, because the base line data is expected to represent an average condition of turbine, the turbine at Whitney power plant were also evaluated as fair or average condition by the personnel after through inspections and tests. The estimate for reliability and hazard function for the turbines are shown in the Figure 4.5 and 4.7, respectively.

Based on the present condition of the turbine which was reflected by the condition indicator and present age of turbine being 53 years, the hazard rate and the failure rate of the two turbine is given in Table 4.6, which is same as the baseline failure rate and reliability of both the turbine.

Table 4.6 Parameters for Turbine I & II

Parameter	Unit I	Unit II
Hazard Rate	0.02871	0.02871
Reliability	0.61465	0.61465

CHAPTER 5

ECONOMIC ANALYSIS OF ALTERNATIVES

5.1 Cost/Benefit Analysis of Alternatives

The basic objective of the cost/benefit analysis is to provide alternatives best suited economically for rehabilitation of aging hydropower plant. The main objective for this analysis is to compile all the cost associated with all the alternatives, and to develop the relationship between the investment and the returns. The first phase of this analysis is to calculate the total cost for each alternatives, then present worth of the revenues are calculated and relationship established, if the alternatives is economically viable and best suited for both the investment/returns ratio and reliability of the unit, then project implementation phase starts. The alternatives as described in previous Sections which are available to the owner of hydropower generating facility are:

A. Option A, is a without project condition. The generator and the turbine will run as per their present condition, maintenance work will go on as scheduled and incase of outage, the defective part will be repaired.

B. Option B, is an alternative which has a project to restore the original condition of the power plant that is bring the generator and turbine, back to their original capacity. It’s basically, restoration of original efficiency of both turbine and generator. It includes the installation cost of new runner of original design though with the present technology and best available material. Once implemented this option, there will be some increase in power capacity due to more efficient technology and materials available today.

C. Option C, is an alternative with project. The option requires rewinding of the generator windings with complete new stator core and field poles, new governor system and new breakers. The turbine under this option is upgraded with high probability of runner replacement and other efficiency deteriorating components. The new efficiency which can be attained is given in Table 4.2, 4.3 and 4.4. The option leads to uprating of capacity.

D. Option D, proposes complete replacement of generator and turbine with both new turbines and generator. This options leads to uprating of capacity of the hydropower plant higher than the option C. This option is slightly expensive but if rehabilitation is not possible with existing components then this alternative is a must.

5.2 Capital Costs for Alternatives

The upgrading project cost is the sum of all the cost, required to upgrade the turbine runner, generator rewound and other worn out components of the turbine and the generator. It includes cost for rewound of windings of the generator, replacement of worn out or severely deteriorated sub-components, replacement runner design, model design, manufacturing cost, dis-assembly/re-assembly cost for turbine and generator, contingency cost, escalation factor, indirect cost like administration and supervision of project, interest on investment for the project, together with the insurance and finance charges. The total cost or the capital cost for upgrading and uprating is categorized as the following:

5.2.1 Direct Cost

The cost for procuring new material and repair and maintenance on the worn out component comes under direct cost, which can be categorized into two sub-category and they are:

1. Investment on material and equipment
    - Model design, manufacturing and testing.
    - Cost of replacement of new runner, its design and supply cost.
    - Cost of rewinding, material cost as well as insulation cost
    - Cost of any severely deteriorated component of the generator
    - High voltage test to verify the integrity of insulation
    - Testing of the new replacement runner, at any independent laboratory.
    - Performance testing after replacement.
2. Other cost
    - Cost of dis-assembly/re-assembly of the turbine generator.
    - Other cost associated with shop and site upgrading of turbine/generator components

5.2.2 Contingency Cost

While preparing estimation for any project, contingency cost are allotted to cover inaccuracies in planning estimation and also those cost which are missed out. It is usually recommended that contingency cost be 20% of the direct cost. The usual types of the cost covered under contingency cost are:

- Possible additional model testing for turbine runner.
- Extension in cavitation repair.
- Replacement of auxiliary valves, motors, piping and controls.
- Rehabilitation of more than items in the estimated direct cost.
- Overtime work or double shifts to meet the deadline.

5.2.3 Escalation Cost

The time of publishing of guidelines and the actual implementation of the project are usually different. The estimation is done in accordance with the date of the guide lines publication while the construction phase of the project is usually after few months in earliest to few years, hence for actual budgetary estimation during the construction phase is given by escalating the budget from the guidelines publishing date by escalation factor (EF), it is usually equal to expected inflation rate times any real growth of price. Using annual escalation rate, calculate escalation factor as shown below in the Equation 5.1. Using the value from [22] and extrapolating, escalation rate for 2006 is nearly equal to 2.8% as shown in Figure 5.1.

$$\text{Escalation Factor (EF)} = (1+e)^n - 1 \tag{5.1}$$

Where:

e = annual escalation rate in %

n = number of years between publication of guidelines and mid-point of Construction.

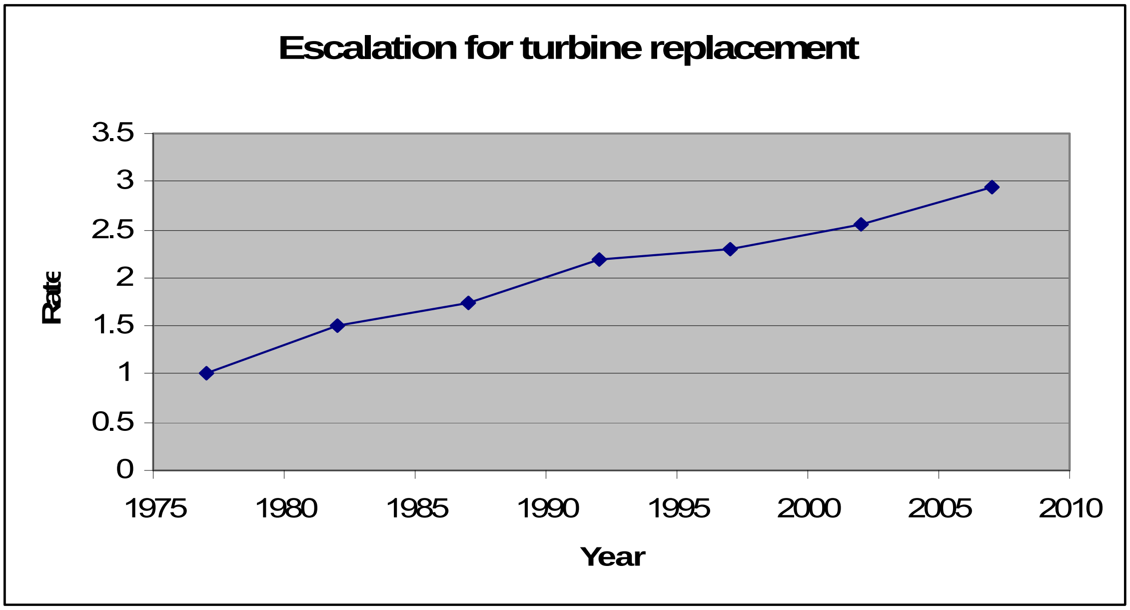

Figure 5.1 Showing Escalation Rate for Turbine Replacement [22]

5.2.4 Indirect Cost

The indirect cost usually, covers cost related to administration and supervision of the project.

5.2.5 Interest on Borrowed Capital (IBC)

Unlike any other cost associated with the upgrading capital, the interest on the borrowed capital is taken as the total project cost. The IBC depends on the interest rate on the capital, hence during any cost benefit analysis it is expected that the technical life of the upgraded units are higher than the repayment period of the loan. The Equation 5.2(a) and 5.2(b) shows the interest for borrowed capital factor (IBCF).

Compound interest during the construction = $(1+r)^n - 1$ 5.2(a)

Simple interest during the construction = $r \times n$ 5.2(b)

Where:

r = interest rate on the borrowed capital in percentage.

n = number of years from mid-point of construction to the operation.

5.2.6 Present Worth of Total Capital Cost (PWTCC) [12, 10]

The main objective of the feasibility study is to come up with the total capital cost for upgrading and uprating and the method for this is, calculation of present worth method which captures all the associated costs like insurance, depreciation, taxes, finance charges etc, usually, these charges are also categorized as the levelized annual fixed charges . The Equation 5.3 below defines the PWTCC.

Present Worth of Total Capital Cost (PWTCC) = FCF × TCC × PWAF (5.3)

Fixed Charge Factor (FCF) = LAFCR × SPWF (5.4)

Sum of the Present Worth Factors (SPWF) = $\dfrac{((1+i)^{n'}-1)}{(i \times (1+i)^{n'})}$ (5.5)

Present Worth Adjustment Factor (PWAF) = $\dfrac{1}{(1+i)^t}$ (5.6)

Where: i = Present worth of discount rate,

n' = Number of years of economic life,

TCC = Total Capital Cost,

LAFCR = Levelized Annual Fixed Charge Rate; and

t = number of years between feasibility study and commercial operation

The Table 5.1 below shows the different type of cost and charges related to the turbine upgrading capital cost, the main objective behind these calculations are to come up with the total cost of upgrading the turbine and finding its present worth as shown above in the Equation 5.3

Table 5.1 Capital Cost for Alternatives [9]

Upgrading and Uprating Project Cost Estimation			
Capital Cost	Alternatives		
	A	B	C
DIRECT COST (Cost associated with refurbishment or replacement) • Replacement runner design and supply • Model testing and prototype performance testing • Dis-Assembly/Re-Assembly of Turbine/Generator • Winding material cost, rewound and insulation cost • Circuit Breakers if needed Turbine/Generator components etc			
Sub-Total Direct cost			
Contingency factor (CF) = 20% **CONTINGENCY COST (C) = SDC * CF**			

Table 5.1 - Continued

Upgrading and Uprating Project Cost Estimation			
Capital Cost	Alternatives		
	A	B	C
ESCALATION FACTOR (EF) = $(1 + e)^n - 1$ Where e = **Escalation (E) = EF * (C + SDC)**			
Total Direct Cost (TDC) = SDC + C + E			
INDIRECT COST			
INDIRECT COST FACTOR (ICF) = **Indirect Cost (IC) = ICF * TDC**			
INTEREST ON BORROWED CAPITAL FACTOR ICBF = $(1 + r)^n - 1$ Where, r = interest rate in decimal value and n = number of years from midpoint of construction to the date of operation. *Interest on Borrowed Capital (IBC)* **IBC = IBCF * (TDC + IC)**			
Total Capital Cost (TCC) = TDC + IC + IBC			
Total Present Worth of Upgrading Cost Present Worth Adjustment Factor (PWAF) PWAF = $1/(1 + i)^t$			

Table 5.1 - Continued

Upgrading and Uprating Project Cost Estimation			
Capital Cost	Alternatives		
	A	B	C
FIXED CHARGE FACTOR (FCF) FCF = LAFCR * SPWF			
LEVELIZED ANNUAL FIXED CHARGE RATE(LAFCR)			
SUM OF PRESENT WORTH FACTORS FOR ECONOMIC LIFE OF THE UPGRADE (SPWF) (SPWF) = $\frac{((1+i)^{n'}-1)}{(i \times (1+i)^{n'})}$ Where, i = (present worth discount rate) and t = (number of years for economic life) **SPWF**			
Present Worth of Total Capital Cost (PWTCC) **PWTCC = FCF * TCC * PWAF**			
Other Cost			
Total Present Worth of Upgrade Cost (TPWC) **TPWC = PWTCC + Other Cost**			

5.3 Calculation of Present Value of Benefits

The objective of the upgrading or uprating or just refurbishing project is to, depending on the nature of the project (alternatives) increase the reliability of generating unit, either restore the original capacity or increase the capacity by upgrading and uprating which in turn will increase the revenue. Under cost/benefit analysis the project will only be justified if it is economically profitable. While calculating net operating benefits, all revenue from power sales should be considered and all the operational cost like direct operational cost as well as cost of maintenance be subtracted. Under present value of benefits, calculate the net operating benefits using step by step approach as shown below:

5.3.1 Calculations of Energy Revenue [9]

The objective behind any upgrading, uprating or capacity restoration project is to increase the energy capacity of the generation unit, for calculation of energy revenue, consider the increase in energy output from replacement or restoration of turbine runner. Based on the type of generation facility i.e. whether it’s a base load generating station or the peaking unit, determine the $/kWh value of the energy. If the unit is combination of both peaking as well as base load then, weighted average value has to be calculated. Using Equation 5.7 the present worth of energy revenue can be calculated.

$$\textit{Existing Turbine} = \frac{VG \times k \times (1-k^{n})}{(1-k)} \qquad 5.7$$

Where:

'k' is a constant, which is = $\frac{(1+e)}{(1+i)}$

VG = Value of Average annual Energy Generation @ date of feasibility study,

Which is defined in (kWh/yr X $/kWh)

n = Evaluation period in years (For not upgraded)

= Number of years Existing turbine will operate prior to upgrade.

$$\textit{Upgraded Turbine} = \frac{VG \times k \times (1-k^n)}{(1-k) \times PWAF} \qquad 5.8$$

5.3.2 Calculations of Power Revenue [9]

The benefit from power revenues are calculated using projected power uprating after the project is undertaken. "The determination of recent existing maximum available power should be based on the value of peaking power, these must be taken into account by adjusting the available power for the head available during the contractual period" [9], based on the above assumptions, calculation of the value of present worth of power revenue both for existing as well as upgraded turbine.

$$\text{Existing Turbine} = \frac{VC \times k \times (1-k^n)}{(1-k)} \qquad 5.9$$

$$\text{Upgraded Turbine} = \frac{VC \times k \times (1-k^n)}{(1-k) \times PWAF} \qquad 5.10$$

Where:

VC = Annual Value of Capacity.

n = evaluation period for Existing turbine case, and

= Plant life, financing period, payback period etc for upgraded turbine.

i = discount rate.

5.3.3 Calculations of Operation, Maintenance and Repair Cost [9]

It is a basic objective of any generating unit to reduce the cost for operation and maintenance, after carrying out one of the project alternatives it is expected to reduce the O&M cost, and increase the net operating benefits. Based on the data collected for operation and maintenance for past few years, obtain the cost for operation and maintenance from year to year basis and calculate the average cost for a year, using this information a trend can be established for the O&M cost which will be used in the Equation 5.12 below, for calculating Present Worth of O&M Costs.

$$\text{Existing Turbine} = \frac{O\,\&\,M \times k \times (1-k^{n})}{(1-k)} \qquad (5.11)$$

Where:

O&M = Averaged O&M cost for the past three years or the last years

$e_{O\&M}$ = Annual rate of increase in O&M cost.

And for

$$\text{Upgraded Turbine} = \frac{O\,\&\,M \times (1+e+e_{O\&M})^{t} \times (1-k^{n})}{(1-k)\times PWAF} \qquad (5.12)$$

Where: $e_{O\&M}$ = Annual rate of increase in O&M cost (reflecting upgrading)

‘ $$k' = \frac{(1+e+e_{O\&M})}{(1+i)}$$

Table 5.2 Calculation of Present Worth of Net Operating Benefits [9]

PRESENT WORTH NET OPERATING BENEFITS			
	ALTERNATIVES		
Present Worth Revenue benefits	A	B	C
• Energy Revenue			
• Total Benefits			
• Present Worth of Capital Cost			
• Total O&M cost			
Total Revenue benefits			
Present worth net operating benefits (PWNOB)			
PWNOB = Total Revenue benefits – O&M			
Incremental net operating benefits (INOB)			
INOB = PWNOB(alternative) – PWNOB(existing)			

5.4 Economic Analysis

The final economic analysis of the alternatives is carried out once the total present worth of the upgrade cost (TPWC) and the incremental net operating benefits (INOB) have been calculated, the best way to establish the benefit/cost advantages is using benefit/cost ratio for each alternatives as shown in the Table 5.3. The benefit/cost ratio of each alternative is compared and the one with the highest ratio is most favorable economically with greater margin for profitability. For any alternative to be profitable the benefit/cost ratio should always be greater than 1.

Table 5.3 Economic Analysis for Alternatives [9]

ECONOMIC ANALYSIS			
PARAMETER	ALTERNATIVES		
	A	B	C
PLANT MAXIMUM CAPACITY			
AVERAGE ANNUAL ENERGY GENERATION (GWh)			
INCREMENTAL NET OPERATING BENEFITS (INOB)			
TOTAL PRESENT WORTH OF UPGRADE COST (TPWC)			
NET ECONOMIC BENEFIT • NEB = INOB - TPWC			
BENEFIT/COST RATIO (BCR) • BCR = INOB/TPWC			

5.5 Case Study

The Whitney hydropower facility is located on the Brazos Rivers, Texas. The dam and the reservoir are designed for flood control, stream flow regulation and power generation. It is operated and managed by Army Corps of Engineers. The power house has two turbine-generator units commissioned in June 1953. The initial installed capacity of the power plant was 30 MW with overload capacity up to 34 MW. The present condition of Generator and Turbine has been briefly described in Chapter 3 &4. At presently the power plant is operating under derated condition with very low reliability. The Table 5.4 describes the alternatives available for aging hydropower plant in general and Whitney in particular.

Table 5.4 Options Available to the Power Plant [10]

Alternatives	**Turbines**	**Generator**	**Governor**	**Breakers**
A	Existing	Existing	Existing	Existing
B	Restore to original condition	Restore to original condition.	Restore to original condition	Restore to original condition
C	New	Rewound (21 MW)	New	New
D	New	Rewound (22.5 MW)	New	New

Cost/Benefit analysis is done because in most cases for any new, it has to be proved before the investor that investment will be recovered before the economic life of the project. Under Cost/Benefit analysis, perform economic analysis to find out the most profitable investment by using benefit to cost ratio. For any project or investment to be profitable the benefit to cost ratio should always be greater than 1.

The options in Table 5.4 will be analyzed to see whether or not, the benefit to cost ratio is higher than 1. The increase in capacity of the power plant with different options is considered. Table 5.5 shows the annual generation of different options listed with their new installed capacity.

Table 5.5 Average Annual Energy Generation for Different Options [10]

Alternatives	Operating Capacity (kW)	Dependable Capacity (kW)	Average Annual Energy Generation (kWh)
A	30,000	28,000	57,380,000
B	34,000	29,800	59,990,000
C	42,000	36,800	65,110,000
D	45,000	37,700	65,420,000

Assumptions:

- The escalation factor ‘e’ = 2.8 % [Figure 5.1]
- Contingency Factor ‘CF’ = 20 %
- The interest rate ‘i’ = 6.375 % [10]

- Economic life of the upgraded plant (options B, C & D) is assumed to be 35 years. [10]
- Inflation rate of 1.14 assumed for any calculation. [23]
- For PWAF, 't' is assumed to be 1 years in Equation 5.6
- Cost of kWh is calculated using inflation factor of 1.14.

  Unit Price = $0.027/kWh

Table 5.6 Capital Cost and Benefits of Alternatives [10]

Alternatives	TPWC*($1000)	O&M and Repair($1000)	PWNOB*($1000)	INOB*($1000)
A	2,624	16,454	14,632	NA
B	15,098	2,298	33098	18,464
C	15,279	2,298	37,661	23,028
D	21,664	2,298	37,937	23,305

*TPWC : Total Present Worth of Upgrading Cost
PWNOB : Present Worth of Net Operating Benefits
INOB : Incremental Net Operating Benefits

In Table 5.6, the TPWC for each alternative are given which includes both the capital cost as well as the interest during the construction. The Operation and Maintenance and the repair cost for alternative A, is high because any failure will warrant major repair and replacement, for other alternatives it is relatively economical. The PWNOB is calculated after reducing all the cost associated with operation and maintenance from the revenue due to energy and tax relief. The Incremental Net Operating Benefit (INOB) gives us the incremental benefit as a result of Alternatives B, C and D against Alternative A, assuming economic life to be 35 years for the refurbished, rewound and replaced components of the generation facility. Although, the Table 5.6 shows that maximum incremental benefit is obtained by C and D, but the fact that D has higher TPWC changes all hence, the implementation of the Alternatives economically viable depends up Benefit to Cost Ratio (BCR). Table 5.7 shows the annual TPWC installment payable for economic life of the component against the net annual benefits, the ratio of the two is BCR.

Table 5.7 BCR for Alternatives

Alternatives	TPWC*($1000) Annual	PWNOB*($1000) Annual	INOB*($1000) Annual	Benefit/Cost Ratio (BCR)
B	1,088	2,384	1,330	1.223
C	1,101	2,712	1,659	1.507
D	1,560	2,732	1,679	1.076

*TPWC : Total Present Worth of Upgrading Cost
PWNOB : Present Worth of Net Operating Benefits
INOB : Incremental Net Operating Benefits

5.5.1 Economic Justification of the Alternatives

The annual project cost with interest and 35 years payback period is shown in Table 5.7. The incrementing net operating benefit is defined as the increment in revenue annually due to project condition. The BCR ratio greater than one, gives the alternatives which are feasible economically. Although there is slightly less INOB for alternative D, the annual project cost is high, hence the percentage of revenue benefits are less and also the BCR is slightly higher than one. Comparison of alternatives with respect to each other revel that 'C' is best suited economically as it promises returns in maximum percentage of investment. The Figure 5.1 shows the breakeven analysis for all the alternatives. The comparison of cost of implementing project 'C' and 'D' reveals that project cost for 'D' cost nearly $6 millions more than 'C', while the revenue generated is almost similar. Hence from Figure 5.1, the alternative ‘C’ is reaches negative cost period before any other alternatives.

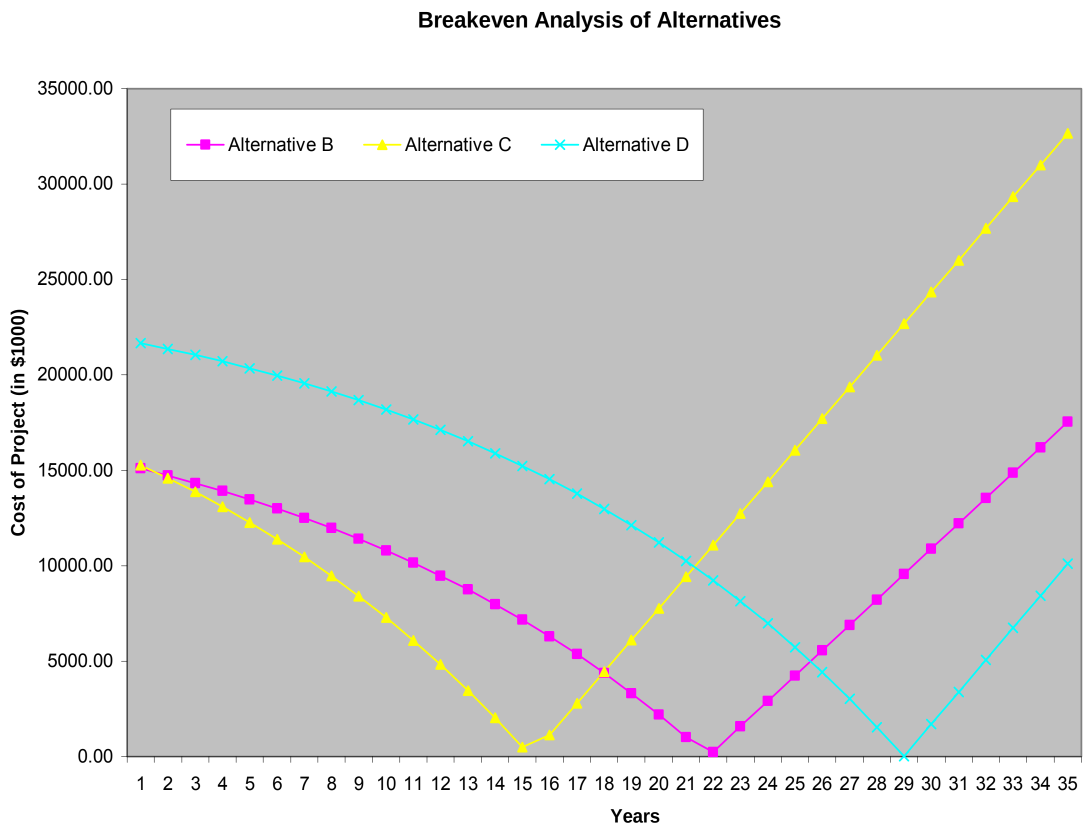

Figure 5.2 Breakeven Analysis

CHAPTER 6

REMARKS AND CONCLUSION

6.1 Remarks

The feasibility study for aging hydro power plant is done with a sole purpose of studying each alternative available to the owner and selecting the best options with highest benefit to cost ratio. The present condition evaluation of generator and turbine provides us valuable information about the performance, deterioration and condition of each component and sub-component. The evaluation is done by visual inspection and performing tests and measurement. One of the key ways to evaluate the performance of turbine and generator is the operation and maintenance history. The careful analysis of O&M records can be handy in trending the fall in performance and availability of the component or sub-component of the generator.

The visual basic based program for condition evaluation of generator provides us with the condition of generator based on weightage and scoring provided in Table 3.1, the scoring is done based on analysis of design and fabrication, operation and maintenance history, visual inspection and electrical tests performed on each sub-component of generator and the external factors influencing the upgrading and uprating project. The program for condition evaluation of the generator was tested for two different sets of reading provided in IEA guidelines [6], and results were corroborated.

The importance of feasibility study depends on timing. The best time to carry out the feasibility study of alternatives is before the generation facility is crippled by severe problems such as generator winding failures, major runner cracking, cavitation or erosion damage, bearing failures or alignment problems otherwise emergency remedies have to be undertaken which can be costly . The cost for repair as well as loss in revenues will lead to expenses and loss which would have been otherwise averted.

6.2 Conclusion

The feasibility study provides us with various alternatives for aging hydropower plant, and economic analysis gives the alternative with highest benefit to cost ratio. The advantage of upgrading and uprating of existing hydropower plants are tremendous with respect to benefits from revenue as well as availability. Once the generation facility is upgraded there is a renewed economical life of the plant ranging from 25 to 35 years and technical life even extending more. The availability of better insulation with higher temperature coefficient and better techniques used presently than 50 years ago, makes upgrading and uprating an attractive alternative. The fact that upgrading and uprating leads to increase in reliability is due to refurbished or replaced component and monitoring of all the operational parameters by modern sensors. Any deviation from normal operation is detected at the earliest and acted upon. Some of sensors used today for the early detection of faulty operation act like early warning system to alarm before hand about possible deterioration taking place so that severe condition can be avoided. Some of these sensors used are:

- Stator Frame Vibration sensor.
- Generator Windings Partial discharge measurement.
- Air Gap measurement transducer.

- RTD or Thermocouple for temperature measurement.
- Generator Guide Bearing vibration and temperature measurement.
- Thrust Bearing oil pad thickness and temperature measurements.
- Head Cover and Draft Tube vibration sensors.
- Turbine Guide Bearing vibrations and temperature measurements.
- Wicket Gate position sensors, etc.

6.3 Scope for Future Work

The program for present condition evaluation of generator can be further extended to provide estimated uprating of capacity that can be achieved based on the design and fabrication specifications and the age signifying the technology of the period. While calculating the benefit/cost ratio, the cost of new sensors and measuring devices can be included as they increase the economic life of the plant. The upgrading of protection system and calculation of overall reliability with/without project condition can be compared. Based on the condition of generator and transformer a single unit called Powerformer (Generator as well as Transformer) could be considered an option. The upgrading of hydropower facility using Powerformer can also be considered as a future work.

APPENDIX A

GUIDELINES FOR EVALUATION OF MAJOR COMPONENTS OF HYDRO-GENERATOR

A.1 Stator Windings

In multi criterion analysis we will consider the design and specification of stator windings, its failure in past together with its repair and maintenance history, visual inspections and electrical test and measurement to estimate the remaining life of the stator windings. Most of the failures in stator windings are related to insulation failures, which could be due to ineffective cooling system, thermal cycling, thermal strength of insulating material, operation under abnormal conditions etc.

A.1.1 Design and fabrications of stator winding

The design and fabrication section of multi-criterion analysis deals with the manufacturer’s specification data for each sub-component of the generator. The face plate of the generator could provide partial information but for detailed information the generator specifications provided by the manufacturer is required. Based on the manufactured specification, give weightage to each component based on its importance and its availability for upgrading; the weightage could be affected when a better technology is available in place of the existing one. The age of the components will not be the only criterion, incase the generator is running normally, for upgrading, but with age increasing the ability of the unit to perform reliably decrease hence age could be an important factor with some weightage to consider. Once data is fed, one can easily make out whether the generator is old or the new, the type of insulation in the windings and the performance of cooling system.

The input to design and fabrication of stator winding provides us with the knowledge of insulation system, type of winding, number of turn per coil, rated stator winding phase to phase voltage and fire protection system. The above parameters give us a general idea about the stator winding, and present technology that could replace them incase upgrading is decided. In our multi-criterion analysis, give no weightage incase any of the above components are being presently used with same technology.

A.1.1.1 Type of insulation: [11, 6]

Basically, stator winding insulation system is responsible for avoiding any electrical short circuits and transmission of heat to the sink from the conductor so that temperature is within the designed limits. The selection of insulating material used in the old generators were basically based on the technology at that time, availability of the material and the cost, hence materials like silk, flax, cotton, wool were used early and later asbestos, asphalt mica, mica folium, cambric began to replace the older ones etc, but in the new generators usually epoxy mica, flaked epoxy mica etc are used, which have higher thermal strength, are thinner thus, providing dense insulation with lesser voids, higher dielectric strength and lower partial discharge levels. Speaking of stator winding, there are three different types of insulation which are:

- Ground wall insulation
- Inter turns insulation
- Winding or conductor insulation

The modern insulating material which are thinner with higher thermal capacity are ideal for both upgrading and uprating since they provide higher thermal limits and thinner insulation would provide more space which could ultimately be filled by adding extra windings (uprating). The Table A.1 shows the types of insulation commonly found in the hydro generators presently running with epoxy mica being the best and the most recent one to, cambric being the oldest one with highest weightage for upgrading in the multi-criterion analysis.

Table A.1 Weightage for insulation type in multi criterion analysis [6]

S/No.	Type Of Insulation	Weightage	Evaluation
1	EPOXY MICA " b-stage"	0	
2	FLAKED EPOXY MICA	1	
3	POLYSTER MICA	2	
4	ASPHALT MICA	3	
5	MICAFOLIUM	4	
6	CAMBRIC	5	

A.1.1.2 Type of winding:

Besides, some hybrid type of windings used by some manufacturer, the two type's windings that are widely used are multi –turns and the Roebel bars. Usually, for generators rated above 50 MW, Roebel bars are used. In case of multi-turn, number of winding varies between two to twelve turns. The other type of winding called roebel bars are used mostly for large generators and these are half turns compared to multi-turns and they can be easily inserted between the slots but electrical connections have to be established between two bars at the end. The roebel bars are better technology compared to multi-turn winding and weightage for this kind of winding is zero in the analysis.

Table A.2 Weightage of stator winding types in multi criterion analysis [6]

S/No.	TYPE OF WINDING	Weightage	Evaluation
1	1 TURN (Roebel Bars)	0	
2	MULTI - TURNS	5	

A.1.1.3 Number of turns/coils:

Compared to multi turn windings, the single turn winding or the roebel bars are used more in the winding construction because they are more mechanically stiffer than the multi turns windings. Table A.3 below shows the weightage for the multi-criterion analysis based on the number of turns.

Table A.3 Weightage based on Number of turns/coils [6]

S/No.	Number of Turns/Coils	Weightage	Evaluation
1	1 TURN	1	
2	2 TURNS	2	
3	3 TURNS	3	
4	4 TURNS	4	
5	5 TURNS	5	

A.1.1.4 Rated voltage per phase of the stator winding:

The designed parameters of the windings allow them to be imposed to particular voltages. For every winding there is particular working voltage as envisaged by the designer or the manufacturer which is called the rated or nominal voltage of stator winding. Prolong Operation of generator above the rated voltage will deteriorate its insulations system thus leading to major failure or operation under derated condition. Based on the voltage rating and its feasibility for upgrading and uprating could be estimated. Lower rated stator winding voltages are usually not favored for upgrading. The Table A.4 shows the weightage of phase to phase nominal voltage on upgrading decision making.

Table A.4 Weightage for Rated stator winding Phase to Phase voltage [6]

S/No.	Rated voltage Phase to Phase of the stator winding	Weightage	Evaluation
1	2 TO 2.4 KV	0	
2	4 TO 4.4 KV	1	
3	6.6 TO 6.9 KV	2	
4	11 TO 12 KV	3	
5	13.8 KV	4	
6	GTEATER THAN 13.8 KV	5	

A.1.1.5 Stator Winding fire protection system:

Protection of stator winding is paramount concern for the generation facility both for economic reason as well as outage issues. Due to faults, high magnitude faulty currents flow through the stator winding often leading to a fire hazards, hence a reliable fire protection system is necessary for early warning. An added advantage for old generator could be addition of automatic fire protection system during upgrading, hence based on this multi-criterion analysis has weightage for upgrading based on existing fire protection system or no protection. Table A.5 below shows weightage based on type of fire protection system.

Table A.5 Weightage based on fire protection system for stator winding [6]

S/No.	Type of Fire Protection system	Weightage		Evaluation
		Epoxy	Asphalt	
1	AUTOMATIC PROTECTION	0	0	
2	MANUAL PROTECTION & AUT DETECTION	1	2	
3	MANUAL PROTECION	2	4	
4	ONLY DETECTION	3	6	

A.1.2 Maintenance and repair history

The records of maintenance, operation and repair history provide information or results of the previous tests and visual inspection regarding the condition under which generator was under service. The maintenance and operation history records, can be proper tool to analyze the performance of the component against proper operation and maintenance. These records shows us how many time in past did particular component was repaired, insulation failure, forced outage etc. Study of these records itself can tell us how healthy each component is at present, Comparison of results of electrical test and measurements for few years can give us insight on the trend of deteriorating condition of the generator component. Based on these records fill out the following sub-criterion weightage as below:

- Number and type of coil faults

- Faults in last five years
- Faults on similar Generators
- Winding age

The weightage each sub-criterion carries is shown in Section 3.9, under stator windings.

A.1.3 Visual Inspections

Visual inspections of any components can provide immense information regarding the condition of the particular component and condition under which it is being operated. Like physician, an experienced engineer can make out the health of any component by visual inspection of its sub-component. During the visual inspection the stator winding should be thoroughly checked for contamination with dust and dirt, oil leakages and other discharges, like asphalt bleeding and fine powder discharge due to looseness of wedges at end windings. Coil displacement and swelling of coil insulation should also be checked. Deteriorated asphalt insulation will exhibit swelling at bottom end windings and hardening of the insulation. Listed below are some of the topics, an expert will look into during visual inspection of stator winding.

A.1.3.1 Presence of dust and dirt

The presence of dust and dirt, on the stator bars and coils contaminates the insulation thus adversely affecting the integrity of the insulation. Based on time, the stator bars and coils have been exposed to contamination, the degradation of insulation starts and finally lead to insulation breakdown. The presence of contamination provides a path or medium for currents to flow on the surface of the insulation, which results in tracking and reduction of insulation properties. The worst condition could be penetration of insulation through cracks, and finally leading to short circuit. The Table A.6 below shows the weightage for condition of stator winding based on thickness of presence of dust.

Table A.6 Showing Weightage for Presence of Dust [6]

Presence of Dust and Dirt	Weightage	Evaluation
None	0	
Les than 1 mm	1	
1 mm to 5 mm	3	
Greater than 5 mm	5	

A.1.3.2 Radial wedging of coils

The wedges are responsible for the tightness of the stator bars in the slots. If the wedges are tight then windings stay inside the slot and there are no vibrations of the windings, loose wedges allow the stator winding in the core slots to move because of electromagnetic bar bounce forces and vibration. The movement of stator winding due to loose wedges can finally have impact on the ground wall insulation, leading to ground fault failure. The common way to detect the loose wedges is done by tapping with a suitable hammer, during the tapping the wedge should be checked along the full length, vibrations should be felt with the other hand and sound should be listened carefully. Loose wedges will vibrate noticeably and a hollow sound will be heard on tapping, while on the other hand for tight wedges solid ringing sound will be heard and there will be no vibration of the wedges. Besides the above method another test for loose wedging would be discharge of powder due to vibration of stator bars. Re-wedging is done if less than 75% of wedges are tight in the slot [7]. The Table A.7 below shows the various degree of wedge looseness in the slot and weightage given to each.

Table A.7 Showing Weightage for Loose Wedges [6]

S/No.	Radial wedging of coils	Weightage		Evaluation
		Epoxy Mica	Asphalt Mica	
1	(60 to 80)%	0	0	
2	More than 80%	1	1	
3	(50 to 60)%	2	4	
4	(25 to 50)%	3	6	
5	Less than 25%	4	8	
6	Wedges/Strip out	5	10	

A.1.3.3 Partial Discharges

The partial discharge in the stator winding could be internal partial discharge or the discharge at the slot or at the end windings. These discharges are whitish or brownish powder deposits on the stator bars or the discharges in the insulation voids or due to breakdown of the insulating gas between the stator bar ground wall insulation and iron core inside the slot [7]. The potential sites for partial discharge in the high voltage stator windings are areas witnessing highest potential differences, space between the phase stator bars and line stator bars, voids inside the insulation and surfaces between the slot portion of the winding and the grounded stator core. Partial discharge activity tends to deteriorate the insulation by abrasion and chemical reaction of the discharges, within a span of time the insulation is penetrated and faults occurs. It is impossible to detect internal partial discharge activity during the visual inspection of the windings; the evaluation is done based on the amount of discharge and its location as shown in the Table A.8 below.

Table A.8 Showing the weightage based on extent of discharge and its location [6]

S/No	Partial Discharges	Weightage	Evaluation
1	None	0	
2	On shoulders	(2 TO 6)	
3	On slots	(3 TO 9)	
4	On slots and shoulders	(5 TO 15)	

A.1.3.4 Block and Ties

Designed limitations and mechanical stresses during installation of stator winding, can result in many stator bars touching each other at the end-windings. These stator bars under normal condition will rub each other with twice the operating frequency under normal operation. Sudden change of loads and operation under abnormal condition can create a movement of stator bars at the end-windings. This kind of movement together with continuous rubbing affects the Groundwall insulation of the stator bars. To eliminate the movement block and ties are used. In older machines solid blocking was used, which became brittle after prolong operation allowing movements consequently, now days amorphous blocking is used which is made from, felt or felt-like material soaked in resins. Signs of looseness of block and ties are greasing, dry or loose ties, powder on the stator bars and missing blocks. The Table A.9 below shows the weightage for evaluation based on the condition of block and ties.

Table A.9 Showing the Weightage of Block and Ties based on Condition [6]

S/No.	Block and Ties	Weightage	Evaluation
1	Tight	0	
2	Average	2	
3	Loose	5	

A.1.3.5 Asphalt Run [11]

This asphalt run/bleeding or soft spot phenomenon is true for insulation using asphalt, which is usually seen in old generators. Asphalt insulations are normally rated class B with 130^{o}C temperature limits. Asphalt was used in large synchronous Generators to bind mica flakes for insulation purpose. At high temperature the asphalt insulation system would develop a sharp drop in its viscosity and moving/run to areas of less pressure creating voids, this lead to problems in effective heat transferring capability accelerating the thermal aging and deteriorating the insulation system leading finally to insulation breakdown. Asphalt run/bleeding/migration will be seen as a bulge of insulation in some areas while it could be felt as voids in other areas. These voids can be felt with little pressure of hand or using probes, preferably non-metallic. In severe case could lead to asphalt oozing out of the bulge (bleeding). The Table A.10 below shows the weightage of asphalt run based on its state.

Table A.10 Showing the weightage of Asphalt Run for Evaluation [6]

S/No.	Asphalt Run	Weightage	Evaluation
1	None or N/A	0	
2	Little	2	
3	Some	5	
4	More	10	

A.1.3.6 Condition of Insulation [11]

The condition of insulation depends on the composition of the insulating material. Different material react differently, usually older generators have asphalt or thermosetting insulation systems which becomes dry and brittle if there is rise in temperature, leading to cracks and fissures. Under severe condition ground fault may occur. When looking at the insulation of stator bars one should feel whether the insulation system is firm or cracking or its in crumbling state, besides what is seen during visual inspection, there are electrical test to determine the condition of insulation system and its remaining useful life. Based on the condition of insulation on the stator bars, a weighting is provided in the Table A.11 below.

Table A.11 Showing the Weightage based on insulation Condition [6]

S/No.	Condition of Insulation	Weightage	Evaluation
1	Firm	0	
2	Cracks	(5 – 20)	
3	Crumbling little	5	
4	Crumbling average	10	
5	Crumbling more or much	20	

A.1.4 Electrical Tests and Measurements

A.1.4.1 Polarization Index [7,21]

This is most widely used test to determine the soundness of winding insulation, which is determined by measuring the insulation resistance of the windings. Polarization index is defined as the ratio of insulation resistance of the windings for ten minutes to insulation resistance of windings for one minute.

$$\text{Polarization Index} = \frac{\text{Insulation Resistance after 10 Minutes}}{\text{Insulation Resistance after 1 Minute}}$$

Before any measurements are taken, the windings must be discharged against the frame, all the external connections should be removed and any charge in the windings must be completely discharged to the ground. To test the stator windings the test is done usually at the machine terminal with one phase at a time. Modern invention has led to instruments that can apply voltage up to 10 K DC and measure resistance up to 100 G Ohms (Megohmeters or Megger).

Table A.13 Sample Table Insert Title Line [6]

Winding Rated Voltage(L-L for 3 Phase and Phase to neutral for 1 Phase)	Insulation Resistance Test DC Voltage in Volts(V)
Less than 100 Volts	500 Volts DC
1000 – 2500 Volts	500 – 1000 Volts DC
2501 – 5000 Volts	1000 – 2500 Volts DC
5001 – 12000 Volts	2500 – 5000 Volts DC
Greater than 12000 Volts	5000 – 10,000 Volts DC

This test is guided by IEEE 43-2000 standard, the dc voltage to be applied depends upon the voltage ratings of the windings. Table A.13 shows the recommended voltages for the corresponding voltage rated windings. The IEEE-43 suggests that the test voltage be higher than recommended because testing at higher voltages can be useful in detecting major defects. For water cooled stator windings the PI index will be significantly reduced, to get the correct value of the index water should be drained out and windings be dried before the test is carried out. A higher polarization index means the winding insulation is strong and other tests like Hi – Pot can be carried out if necessary while a lower index is an indication of weak winding insulation, subjecting this kind of winding to high voltage during Hi – Pot test could result in major insulation break down, a machine that could otherwise have been running would be out of service. Basically polarization index is useful in analyzing the windings for:

1. Dirt and Moisture affecting the windings.
2. Its capability for higher voltage tests (Hi – Pot Tests).
3. By comparing the test result for past few years, one can track the gradual deterioration of winding insulation.
4. Could help in deciding whether the windings need to be rewound, upgraded or upgraded and uprated.
5. Based on the value of polarization index, the decision to upgrade can be boosted.

Under multi criterion analysis the value of polarization index will have weightage based on the magnitude of PI. A higher value can have less weightage for upgrading decision. The Table A.14 provides us with the approximate weightage the value of PI have for our decision making.

Table A.14 Polarization Index Test Scoring [6]

Polarization Index	Score
4 – 7	0
3 – 4	2
2 – 3	5
1 – 2	10
Less than 1	15

A.1.4.2 Hi – Pot Tests [11, 7]

The Hi–Pot tests stand for high potential or high voltage tests. Usually a high pot test is not recommended for generator whose polarization index is falling, because it could lead to insulation breakdown and to put the generator back into the service by repairing the insulation would not be an economically viable option considering both the impact of outage and cost of repairing. The Hi-Pot tests are basically of two types:

- DC High - Pot
- AC High – Pot

A winding passing this test will not fail anytime soon at least for few years, it helps us to predict the useful life of the winding insulation. This test is usually recommended for new units or newly rewound windings, as there are always risks associated with high voltage being applied across aging insulation or sometimes insulations deteriorated due to other service factors. The AC high-pot test voltage is given by (2E + 1) kV for new windings, where, E is the rated RMS phase-to-phase voltage in kV of the stator winding, for older windings it is usually 125% to 150% of E, similarly the DC voltage is 1.7 times (2E + 1) kV DC, for new windings and for maintenance and testing purpose its is 125% to 150% of (1.7E) kV DC. Usually, the DC high-pot test is used to verify whether a winding is capable of withstanding the required voltages or not according to the designed specifications without any effect on the insulation, the AC test is also used to verify same aspect but with AC test, the winding are exposed to voltages that it will have to withstand in service and done at power frequency of 60 Hz, so the AC test depicts pretty much the condition under which the winding will be in operation.

The high-pots tests be it AC or DC are very similar and in this section discussion will be about the DC high-pot test in detail. Usually high-pot test are “pass” or “fail” type of test but at times faults can be repaired for one phase and then test continued. During hi-pot test for generators, all phases are separated from one another, all windings temperature detectors, sensors etc should be grounded. Energizing each phase separately is helpful in detecting flaws more efficiently as there is electrical stress between the coils in the end winding. A suitable high voltage is applied to the winding either at switch gear or the machine terminals and based on how voltage is applied, the high-pot test is sub-divided into three categories and they are:

1. *Conventional High-Pot Test (DC)*

In conventional testing, after connecting the windings, the DC voltage is quickly raised to the test voltage quickly, and held for 1 to 5 minutes, and then the voltage lowered and grounded for safety. During the test if high current doesn’t flow nor the circuit breaker trips then the winding passes the test else there is an insulation breakdown and circuit breaker trips.

2. *Step-Stress High-Pot Test*

Here like the conventional test the connections are done and DC voltage is gradually increased to the test voltage in either equal incremental steps or in unequal steps and each voltage level is being held for one minute. After the end of each step the DC current is measured and is plotted against the applied voltage. During the testing if in the above plot, the curve takes a sharp upward turn then the current is increasing as a result of fault, the test should be stopped and winding grounded. This means that the winding has failed the high-pot test, but its insulation system might not have been completely punctured, hence this test is usually practiced for older machines which are currently in service so that after the test they can return to usual service. The increasing current could be an indication of worsening of end winding insulation but it gives no indications or warning for any flaws in the slot.

3. *DC Ramp High-Pot Test*

Unlike the above two test, here the DC voltage is increased in equal steps linearly at constant rate. The voltage and the corresponding current are plotted and curve is carefully observed for any faulty indications. Any instability in current's character should be an early warning for stopping the test so that, insulation puncture is avoided.

Before going for high-pot tests, one should carefully analyze the result of PI test; the value of PI could be a strong factor to decide whether Hi-Pot test should be carried out or not. Generally, windings with low PI will not be subjected to the high voltage tests to avoid already deteriorated insulation from completely breaking down. The Table A.15 below shows the weightage of the High-Pot test on the multi-criterion analysis of the stator windings insulation system.

Table A.15 Weightage of High-Pot Test on Multi-Criterion Analysis [6]

High-Potential (Hi-pot test)	Score
PASSED	0
PASSED (by-passed coils times 5)	# of by-pass coils times 5
FAILED	20

A.1.4.3 Resistance of Faraday Shield

A Faraday shield is defined as, a metallic housing, screen or sheath that substantially reduces the effect of electric fields or provides a means for reducing electrostatic coupling between conductors. Usually, this shield provides a path for the faulty current incase of short circuit between windings due to insulation failure thus, protecting the windings from overheating and eventually burning. The resistance of faraday shield should not be very high to block the current; it is usually desired to be as low as possible. A higher resistance value would weigh more for upgrading in the multi criterion analysis. The Table A.16, below shows the weightage of the value of resistance of faraday shield.

Table A.16 Weightage of Resistance of Faraday shield in multi-criterion Analysis [6]

Measured Value of Resistance of Faraday Shield in Ohms(Ω)	Score
2 to 5 K or N/A	0
5 to 10 K	2
10 to 20 K	4
20 to 50 K	6
Greater than 50K	10

A.1.4.4 Full Load Temperature Rise

A current passing through a wire increases the temperature of the wire, similarly when generator is loaded to full load, the rated current flows through the stator windings and as a result heat is produced based on the value of current, the insulation system of the windings have particular thermal capacity and subjecting them to higher temperature could break the insulation between the windings thus producing more heat due to higher short-circuit current. Under full load temperature rise test, either thermocouple (TC) embedded inside the stator windings or measure the resistance of winding to calculate the temperature of the windings all at full load. The maximum thermal capacity of insulating material depends on its class as standardized by NEMA MG 1. Usually, incase of older generators the Class F and Class B (old type) type of insulation is seen. Table A.17 shows the weightage of the temperature rise test on the multi-criterion analysis.

Table A.17 Full Load Temperature Rise Weightage [6]

Class F	Class B(old)	Score
< 40^{o}C	< 40^{o}C	0
40^{o}C to 60^{o}C	35^{o}C to 45^{o}C	1
60^{o}C to 80^{o}C	45^{o}C to 55^{o}C	3
80^{o}C to 90^{o}C	55^{o}C to 60^{o}C	7
> 90^{o}C	> 60^{o}C	15

A.2 Stator Core [7]

The basic function of stator core in a generator is to house the stationary stator winding and provide path for electromagnetic flux or carry electromagnetic flux. The stator core is built of thin laminations insulated from each other to reduce eddy current losses, the dimension of these sheets varies from electrical grade, 3% to 4% silicon or grain oriented, and 0.3555 mm to 0.483 mm thick steel [7]. These, thin plates are called by various names like, laminates or core plate or sheets etc. The stator core of a generator contains tens of thousands of sheets, stacked in group of 10 to 24 and tightened using key bars. The core handles magnetic flux densities in the stator teeth and core-back or yoke area. The alternating magnetic field produces changing voltages and currents, which are sources of core losses, besides losses the alternating effect leads to vibration which is one of the main reasons for core failures. Besides vibration, the inter-laminar insulation breakdown can also bring down the core. Based on design imperfection and operational condition, potential reasons for core failures could be summarized as below:

1. Application of inadequate pressure during the piling of core plates.
2. Use of resilient material excessively, which will relax later leading to imperfection in design.
3. Over heating of stator core, which will eventually lead to thermal aging of the generator.
4. Excessive eddy current flow and consequently leading to breakdown of inter-laminar insulation due to over heating by eddy currents.

A.2.1 Design and fabrications of stator winding

The design and fabrication data of stator core as provided by the manufacturer basically, tells us about the sub-components of stator core, their design technology, type of insulation etc. Incase of stator core, analyze few design parameters of stator core and its sub-component and compare these to the technology at present, and based on better technology available give weightage for upgrading. This basically helps us to find whether wrongly designed component was in place or not and also to look for technology used presently. The following are design and fabrication specifications of different sub-component, for our analysis:

- *Lamination quality of stator core*

  Here look at the age of the lamination used in the stator core, based on its age evaluate, lamination quality using given weightage as given in Appendix D.

- *Stacking Method*

  Based on the technology used then, stacking method of core plates or laminates is evaluated.

- *Radial keys*
- *Height*
- *Output Coefficient*
- *Stator Core Flanges*

Above mentioned are few components that will be studied under design and fabrication of stator core.

A.2.2 Maintenance and repair history

The maintenance and repair records besides showing number of starts and stops is useful in analyzing the trend of deterioration of stator core, it consist of all the past test records for visual inspection, scheduled maintenance, scheduled outage, forced outages, faults, age of stator core, condition of laminations, repair work performed, electrical test and measurements etc. A study of these records for any component can help us to trace the extent of deterioration and take preclusive measures. A study of these may provide important information regarding condition of stator core. In our upgrading and uprating analysis basically, use records related with the in service condition of the stator core that could be useful in predicting its useful life. These data are helpful in a way that it can help us look at both economic factor as well as reliability factor, which are most important for any utility, looking at these data one can easily predict whether Upgrading and Uprating could be a better choice or just operation and repair incase of fault. The following are the basics sub-criterion that will be discussed. The weightage for these sub-criterions are solely based on, its importance for optimal operation of stator core and its condition then.

- Faults in Slots
- Damage to Stator Core by Foreign Object

The stator core damage by foreign objects can be massive based on energy picked up by the rotating foreign object or striking with rotor. This could affect insulation or the damage core resulting in local hotspots and degradation of stator core insulations.

- Displacement of laminations at Joints
- Sliding of Laminations
- Core Age

Besides, the above sub-criterion there is much important information provided by operation and maintenance records for analyzing whether:

1. The need for maintenance is growing or not for any component or sub-component.

2. If particular type of fault or problem is recurring or not.
3. There is unavailability, of spare parts.
4. There were previous failures on same equipment or similar design or,
5. Operation, outside normal perimeter.

A.2.3 Visual Inspections

The visual inspection of stator core gives us the first hand information regarding the operating condition of stator core sub-components. Besides dust and dirt, during visual inspection of stator core, look at the short between laminations; damage resulting from the coil failures, broken teeth, core waviness, looseness. During visual inspection a close examination should be made of at bore surfaces to look for evidence of damage due to foreign object, loose laminations or inter-laminar shorts. The weightage for visual inspection is based on visible condition of stator core and besides that evaluation could be done perfectly by experienced personnel.

A.2.3.1 Dust and Dirt

The evaluation for presence of dust and dirt for stator core depends on how much dust as accumulated on the duct passage. Based on amount of dust evaluation is carried out, the inspection can be carried out with the aid of light source. The Table A.18 shows the corresponding weightage of dust and dirt based on amount of blockage to cooling ducts.

Table A.18 Showing Weightage for Dust and Dirt [6]

S/No.	Dust and Dirt	Weightage	Evaluations
1	Ducts blocked < than 3%	0	
2	Ducts blocked 3% to 10%	1	
3	Ducts blocked 10% to 30%	3	
4	Ducts blocked 30% to 50%	6	
5	Ducts blocked > than 50%	10	

A.2.3.2 Core Waviness

The distortion on the designed specification of the stator core is called core waviness. The core waviness is measured in millimeters, based on degree of waviness there are different weightage. If the waviness increases then its evaluations for upgrading has greater weightage. Figure 3.1 shows a core with certain degree of waviness below. Usually, core waviness is found at the core splits.

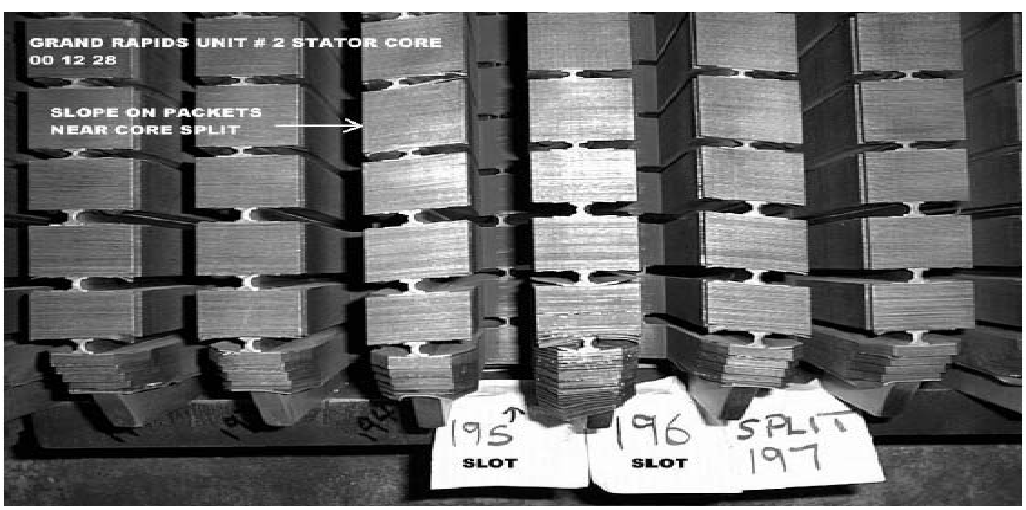

Figure A.1 Showing Core Waviness [16]

It is neither economical nor advisable to repair the core waviness if the generator has operated satisfactorily for decades and core waviness is not severe. On the other hand if the waviness is severe and extensive in nature, then the core should be replaced. Table A.19 shows the weightage, stator core waviness carries on our analysis based on its magnitude:

Table A.19 Showing Weightage for Core Waviness [6]

S/No.	Core Waviness	Weightage	Evaluation
1	None	0	
2	< than 3 mm	1	
3	3 to 5 mm	3	
4	5 to 8 mm	5	
5	> than 8 mm	10	

A.2.3.3 Sliding of Laminations

The laminations in stator core are stacked together, but sometimes due to operational conditions the laminations gets loosen, as a result the laminations slide over each other, moving from designed location. The sliding of lamination is usually inward towards the bore of the stator core; worst condition could lead to deterioration of ground wall insulation resulting into multiple ground faults. The sliding can be detected by removing the rotor. Based on extent of sliding of laminations, Table A.20 shows the weightage based on amount of sliding for evaluation.

Table A.20 Showing weightage for sliding of stator core laminations [6]

S/No.	Sliding of Laminations	Weightage	Evaluation
1	None	0	
2	Little	1	
3	Average	3	
4	Much	5	

A.2.3.4 Lamination Vibration

Stator core are subjected to continuous thermal expansion and contraction, dues to years of operation the component of cores becomes loose due to abrasion, fatigue and results in reduction of core’s stacking pressure. As a result the tightness of core is affected and core laminations starts vibrating, these loose core when vibrating rub with each other at twice the operating frequency resulting, which results in wearing and tearing of laminations and deposits of iron powder (red powder). The extent of loose laminations can be seen looking at amount of red powder. Besides loose laminations, the loose wedges also results in deposits of iron powder, hence it is important to locate the source to evaluate the lamination vibration condition for multi-criterion analysis. Table A.21 [6] shows the weightage for lamination vibration based on extent of red powder deposits.

Table A.21 Showing Weightage for extent of lamination vibration in stator core

S/No.	Lamination Vibrations(Red Powder)	Weightage	Evaluation
1	None	0	
2	Little	1	
3	Average	3	
4	Much	5	

A.2.3.5 Mechanical Damage

During visual inspection, the stator core should be thoroughly checked for any mechanical damages to its sub-component. The damage could be caused due to presence of foreign objects, due to loosening of laminations, due to contacts or due to prolong operation resulting in wear and tear. Based on the extent of damage to the stator core, Table A.22 shows corresponding weightage for the evaluation, higher the extent of damage higher will be its weightage for upgrading and uprating.

Table A.22 Showing Weightage based on extent of damage [6]

S/No.	Mechanical Damage	Weightage	Evaluation
1	None	0	
2	Little	(# X 2)	
3	Average	(# X 6)	
4	Much	(# X 10)	

A.2.4 Electrical Tests and Measurements

The OEM of electrical generators sets certain test to assess the condition of in service generators for the purpose of analyzing the condition of certain component of the generator. In case of stator winding, there are few electrical tests which are useful in evaluating the condition of winding. These tests are useful in evaluating the useful life left for winding, its reliability of operation and study of these results for past few years could be analyzed to determine the trend of deterioration. The electrical test is usually performed offline, and proper care should be taken while performing these tests both for safety as well as proper results. Besides test to verify the perfection of core (ELCID), perform Core loop test or ring test to evaluate the integrity of the core. The measurements of the stator core dimensions, bolt tightness, stator frame specifications gives us clear picture of condition of stator core mechanical integrity.

Besides testing, the measurement of tolerances for circularity, verticality and air gap could give us important information about change in designed specification, which could eventually lead to operation under derated condition. The starting of any core problem starts with vibration of frame, which could be due to various reasons like, uneven placement of windings on the slot, loose lamination or sliding of laminations. Below are discussed each of these tests both electrical and mechanical on the stator core, to check the condition of stator core for analysis in our evaluation

A.2.4.1 Magnetization (Ring) Test [21]

The magnetization test or ring test or rated flux or stator core loop test is performed to evaluate the integrity of the core lamination insulation. Besides, visual inspections which could vary based on how experience personnel is, the electrical test for core integrity gives us the result based on the condition of the core. The damage to the stator core could be caused by foreign objects, loosening of stator windings, vibrations beyond the allowed level, deterioration of insulation which could be both due to overheating or aging.

The basic principle of performing this test is simple, around nearly rated flux or in some cases it could be 80% of the rated flux is induced in the stator core yoke, this produces circulating currents and excessive heating takes place in areas where stator core has been damaged leading to hotspots, which are viewed using infrared thermal imaging.[21,6] The voltage is induced in stator core yoke by wrapping an excitation winding around stator core and frame. Once the flux is induced in the stator core, it is kept for around thirty minutes to one hour; care should be taken to maintain the temperature of the core near the operating temperature. After this compare the temperature rise profile in core under investigation with any other “Good” condition core. Usually, any spot showing temperature equal to or greater than 5^{o}C above the average core temperature is considered hot spots. Based on these results the decision to repair or upgrading could be taken. The Table A.23 shows weightage for multi-criterion analysis, based on the temperature and number of hot spots.

Table A.23 Showing Weightage for Ring Test [6]

S/No.	Magnetization(Ring) Test	Weightage	Evaluation
1	No hot spots	0	
2	Hot spots < $5^{o}C$	(# X 2)	
3	Hot spots $5^{o}C$ to $10^{o}C$	(# X 4)	
4	Hot spots > $10^{o}C$	(# X 6)	

A.2.4.2 Bolt Tightness Test [7]

Checking bolt tightness is one of the most important aspects of OEM guidelines for stator core. Few years of operation and thermal cycling makes the stator loose, besides these the stator core could be loosened by relaxing of pre-tensioned through bolts. This could lead to inter-laminar fretting of insulation coating on the laminations affecting inter-lamination insulation; worst condition can lead to shorting of two laminations and excessive heating in the affected area. Usually, this test is done in absence of rotor; the bolts are axially inserted through a hole in the core iron, bolts are located symmetrically around the circumference of the core. The Table A.24 shows the weightage for bolt tightness test based on tightness of the bolt for multi-criterion evaluation.

Table A.24 Showing weightage for Bolt tightness evaluation [6]

S/No.	Bolt tightness	Weightage	Evaluation
1	Rated value	0	
2	80 to 100 %	3	
3	60 to 80 %	5	
4	40 to 60 %	7	
5	Less than 40 %	9	

A.2.4.3 Tolerances Measurements [7]

Several years of operation, thermal cycling and number of start ups distorts the original designed specification of stator core and air gap, which affects the output directly. These imperfections can be found out by simply measuring the circularity, perpendicularity and concentricity of the stator core. After, measuring compare these measurements with the original design, while comparing it should be kept in mind that these measurements are to be compared to the standard that was then, usually, 40 to 50 years ago. Today due to technological advancement, there are exact designed specifications and standards, usually probes are used to measure these quantities and these can be done with generator in service.

These measurements are done with the rotor in place, the capacitor type air gap probes are installed at top of the core bore, with each probe at 90^o spacing [iea]. These will give required information about the circularity and eccentricity of the core and rotor. Based on the measurements of stator core circularity, verticality and air gap and comparing it to the standard of its period, find the distortion in above measurements, based on the magnitude of these measurements, evaluate the stator core for the analysis. From these reading one can decide whether the stator should be repositioned, and/or the rotor rim shrunk and rounded, all to match the air gap dimensions to the designed parameters. Table A.25, A.26 and A27 shows the weightage for circularity, verticality and air gap based on the tolerances obtained by measurements for evaluation.

The Table A.25 shows the tolerances for circularity, and its respective weightage.

Table A.25 Showing the Weightage for circularity of Stator Core [6]

S/No	Circularity	Weightage	Evaluation
1	Less than 8 %(compared to nominal air gap)	0	
2	8 to 16 %	1	
3	16 to 24 %	3	
4	24 to 32 %	5	
5	32 to 40 %	8	
6	Greater than 40 %	10	

The Table A.26 shows the tolerances for verticality and its respective weightage.

Table A.26 Showing tolerances for verticality of Stator Core [6]

S/No	Verticality	Weightage	Evaluation
1	Less than 6 %	0	
2	6 to 12 %	3	
3	12 to 18 %	5	
4	18 to 24 %	7	
5	24 to 30 %	9	
6	Greater than 30 %	10	

The Table A.27 shows the tolerances for Air Gap and its respective weightage.

Table A.27 Showing weightage based on Tolerances for Air Gap [6]

S/No	Air Gap	Weightage	Evaluation
1	Less than 7 %	0	
2	7 to 14 %	2	
3	14 to 21 %	4	
4	21 to 28 %	6	
5	28 to 35 %	8	
6	Greater than 35 %	10	

A.2.4.4 ELCID Test

The electromagnetic core imperfection detector (ELCID) test is used to detect and analyze the damages to the stator core laminations. This test was developed around 25 years ago and was mostly used to analyze the motors and steam turbine generators []. But recent advancement made it possible to find the defects in hydro generator as well with rotor in place. The basic advantage of this test over ring test is that its requires only 3 to 4 % of the rated flux, compared to compared to more then 80% of rated flux for ring test. It is based on the basic principle that eddy currents will flow through failed or significantly aged core insulation. In this test use special coil called “Chat tock coil”, which magnify the voltage level corresponding to the magnitude of eddy current flowing on the laminations. This measured voltage is fed to the signal processor that gives output in mA, representing the axial component of the measured voltage.

A signal processor showing relatively higher readings indicate fault. Usually, reading above 100 mA, indicate significant core lamination shorting. It is tuff to find the degree or severity of damage using ELCID test, and one has to depend on ring test to locate the temperature rise at damaged portion, besides that this test is used to check the repair of core, studies is still going on, on how to correlate the temperature with the faulty currents. The Table A.28 [6] shows the weightage for ELCID test based on the magnitude of the signal in the signal processor.

Table A.28 Showing the Weightage based on Magnitude of eddy currents for ELCID

S/No.	ELCID Test Result	Weightage	Evaluation
1	Less than 50 mA	0	
2	50 to 100 mA	3	
3	#1 times 100 to 200 mA	5	
4	#2 times or more 100 to 200 mA	9	
5	Greater than 200 mA	15	

A.2.4.5 Frame Vibration Test

The basic purpose of stator frame is to provide support for the stator core. It essentially includes the outer frame to which circumferential ribs and the key bars are attached, on the outside there is a welded structure attached to secure the generator to the foundation. The measuring of frame vibration for the purpose of diagnosis purpose essentially tells us about the condition of coupling of the stator frame with respect to core. Higher magnitude of vibration can be reduced by tightening the coupling between the stator core and frame. Frame vibrations level increasing over the time are indications of slender, flexible frame which will require stiffening or replacement for an upgrading. The vibration is measured using accelerometer and displacement sensors which are placed at various locations for measuring vibration. Based on the level of vibration of the frame, Table A.29 shows the weightage based on amount of vibration for the multi-criterion analysis.

Table A.29 showing the weightage for level of frame vibration [6]

S/No.	Frame Vibration	Weightage	Evaluation
1	Less than 0.025 mm	0	
2	0.025 to 0.075 mm	2	
3	0.075 to 0.125 mm	4	
4	0.125 to 0.250 mm	7	
5	Greater than 0.250 mm	10	

A.3 Rotor

The rotor is the dynamic component of generator, it rotates at very high speed, rotor should be highly stressed out and hence should have good amount of strength to carry copper windings and operate under mechanical and thermal loading. A rotor generally consist of spider attached to the shaft, a rim constructed of solid steel or laminated rings and field poles attached to the rim. Rotor is the most susceptible to operating incident such as motoring or negative sequence currents etc. It is also subjected to very high centrifugal forces during normal operation. The rotor winding has slots around its circumference placed symmetrically; in these slots are placed rotor windings between the poles. The rotor is made of essentially one piece steel forging, now days two piece rotor are no more common. The material used in rotor forging is usually, high permeable magnetic steel to carry the flux produced by the rotor winding.

Under operation, very high stresses occur; if these stresses are not properly compensated then performance of rotor is slowly derated leading to major failure finally.

The rotor is coupled to prime mover which in turn rotates the rotor. In hydro generation facility the prime mover is the turbine, which is coupled to the generator, the turbine in turn is rotated by the energy of falling water. Basically while monitoring the rotor, check the condition of rotor winding insulation, pole impedance, rotor vibration and whether coupling with the turbine is tight enough or not. The rotating rotor is the reason for alternating voltage, in three phase generator the poles and the per phase winding are placed at 120^o apart from each other.

A.3.1 Design and fabrications of Rotor

The design and fabrication, parameters of rotor gives us first hand information regarding upgrading of rotor. It gives us knowledge about the type of sub-component present in the rotor, based on this information look for the availability of better technology and scope of upgrading and uprating. Under design and fabrication, basically look at few sub-component and its designed specification, operational capacity and availability of more useful technology that could help in upgrading as well as uprating, after looking at these aspect give weightage for each of these as shown in Table 3.1, under rotor's designed and fabrication sub title. Basically, we will be looking at following sub components of rotors, designed and specification as provided by the manufacturer:

1. Type of Ground Insulation

2. Type of Insulation between Turns

3. Field Leads

4. Pole Connections

5. Pole Collars

6. Static Exciters Type

A.3.2 Maintenance and repair history of Rotor

The maintenance and repair records, similarly as mentioned above for stator winding and stator core, here for rotor also, shows repair and maintenance work done on the rotor, regular OEM as well as repair based on the type of fault. It shows the importance of maintenance for optimal operation, similarly, a study of these records for past few years shows the trend of rotor deterioration over years of operation. A well maintained operation and maintenance records shows the following records pertaining to rotor:

- Maintenance needs increasing with time or faults re-occurring.
- Spare parts becoming unavailable.
- Operating outside of the desired voltage (rated voltage).
- Sustained overloading.
- Number of time the unit has been subjected to over speed or runaway.
- Previous failures on this equipment related to rotor.

Besides above, specifically to our upgrading and uprating study, we will look for age of winding insulation and other faults that have affected the performance of rotor over the period. Based on re-occurrence of these faults and age of windings, provide weightage for evaluation. The following will be basically, evaluated for our multi-criterion based upgrading and uprating study:

1. Age of Insulation
2. Number of Ground Faults
3. Number of Short Circuited Poles
4. Inter Pole Connection Breaks
5. Rotating Exciters

A.3.3 Visual Inspections of Rotor

A through inspection of rotor is required for necessary assessment of rotor winding condition, dirtiness, cracks and physical damage to insulation should be looked at carefully. Insulation collars and core insulation may be broken because of stresses from starts and stops. Besides these during visual inspection, several types of rotor problems can be detected, like overheating loose and vibrating components, damage and contamination. Basically, under this criterion, consider the following condition, and based on severity of each condition weightage is given which will be guidelines for evaluation.

A.3.3.1 Presence of dirt

The presence of dirt on the rotor provides immense information regarding the operational condition of the rotor. The presence of these dirt usually, have internal source and mostly it is rubbing between two components. The presence of excessive copper dust in the winding slot radial vents should be enough to alert the personnel about existing of shorted turns and/or ground faults, which can be easily seen just by looking at vent holes in the winding slot wedges. It is usually, advisable for dirt coated rotor to inspect twice, once without cleaning dirt and once after cleaning the dust, in later case many cracks and fissures may be visible. Besides other problems associated with heavy dust, it also creates a block for cooling gas or air, thus causing rising temperature beyond designed specifications, which leads to de-rating of unit. Based one the presence of dust and dirt, Table A.30 provides weightage for the evaluation.

Table A.30 Showing Weightage Based on Level of Dirt. [6]

S/No.	Presence of dirt	Weightage	Evaluation
1	None	0	
2	Less then 1 mm	1	
3	1 to 5 mm	3	
4	Greater than 5 mm	5	

A.3.3.2 Insulation Condition

There are basically three types of rotor insulation, the first consist of taped winding turns, all the turns including the end winding section is taped, the second type involves use of strip turn insulation in the slots and taped ends and the third one involves the use of strip turn insulation and in this case the insulation strips are normally made of Nomex or glass laminate. The rotor insulation is thoroughly checked during visual inspection, general reasons for failure of rotor winding are moisture contamination, oil vapors emanating from the bearing, or dust from the operating environment, these results in turn to turn or ground short circuits. Besides above the centrifugal force imposed on the rotor winding insulation and bracing components during normal operation of generator affect the insulation. Based on the present visible condition of the insulation in the rotor, weightage is given in Table A.31, below for multi-criterion evaluation of rotor's condition.

Table A.31 Showing Weightage for Insulation Condition [6]

S/No.	Insulation Condition	Weightage	Evaluation
1	Firm	0	
2	Separated turns	3 - 6	
3	Broken Collars	4 - 8	
4	Crumbling	6 - 10	

A.3.3.3 Condition of Rim

The rotor rim is designed for maximum turbine over speed of twice the rated speed. The rotor rim tightness should be checked thoroughly, if there is any looseness then weightage will be based on the degree of looseness, once checked the rim should be tightened and bolts changed. The shrink fit should be checked for any key movements and reset, if necessary. Besides the above it is important to check the braking surface of the rotor also, Table A.32 shows the weightage for the evaluation based on the tightness of the keys and its present condition.

Table A.32 Showing the Weightage for Condition of Rim [6]

S/No.	Insulation Condition	Weightage	Evaluation
1	Keys tight	0	
2	Loose keys	3 - 5	
3	Keys vibration(red powder visible)	6 - 10	
4	Floating rim	10	

A.3.3.4 Condition of Spider

Each field pole of the rotor is bolted to the spider and in some cases it is also dovetailed to the spider. The spider is keyed to the generator shaft. The rotor spider should be inspected for any cracks on the surface, as it is stressed to the centrifugal forces so during abnormal operation, the nature of force is hard to predict, may damage the spider. Based on the condition of the spider, Table A.33 shows the weightage.

Table A.33 showing the weightage based on condition of spider [6]

S/No.	Spider condition	Weightage	Evaluation
1	No cracks	0	
2	Cracked welds	# X 4	
3	Cracked plates	# X 10	
4	Insufficient stiffness	5 to 25	

A.3.3.5 Brake Track Condition

The brake track should be thoroughly checked, the inspection personnel should look for damaged or over used condition of brake track and also see whether plates are aligned or not, each of above symptoms has weightage as shown in Table A.34. The weightage for evaluation depends on the finding of the inspection personnel.

Table A.34 showing the weightage for brake track [6]

S/No.	Brake Track	Weightage	Evaluation
1	Good condition	0	
2	Used or damaged	1 to 5	
3	Plates not aligned	5	

A.3.3.6 Amortisseur Winding

The Amortisseur winding or the damper winding comes into action, when ever the generator is operating under abnormal conditions. During unbalanced load conditions, alternating currents are established in the body of the rotor, which results in vibrations of rotor. The damper winding dampens torsional oscillations and provides a path for induced currents to flow. Besides dampening the vibration of the rotor during abnormal condition, it also helps divert the negative sequence currents and motoring currents from flowing in the rotor forging, thus saving from overheating. Based on the condition of the damper winding, give weightage as show in Table A.35. For upgrading evaluation, vibrating and damaged damper windings have more weightage for upgrading the generator.

Table A.35 showing weightage for Amortisseur winding [6]

S/No.	Amortisseur winding	Weightage	Evaluation
1	Good/ N/A	0	
2	Vibration	1 to 3	
3	Damaged welds	1 to 3+	
4	Bars/Slots	1 to 3+	
5	Damages	10	

A.3.3.7 Shaft condition

The most frequent problem associated with the shaft is its alignment. It is often connected to poor coupling flanges, which results in forces beyond designed specification leading to cracking of shaft and in worst case bending of shaft. During the visual inspection of shaft, the alignment should be checked and matched with IEEE-1095 standard. The shaft and flanges should be thoroughly checked for cracks and rusting. The shaft should also be measured for perpendicularity and bent. Based on above inspection, give our evaluation for the shaft condition in Table A.36.

Table A.36 Showing the weightage based on shaft condition [6]

S/No.	Shaft	Weightage	Evaluation
1	Good	0	
2	Cracked (repairable)	1 to 7	
3	To replace	10	

A.3.4 Electrical Tests and Measurements of Rotor [7]

While the information given by the visual inspection depends on how experienced the inspection team or the personnel were, and the history of operation and maintenance record shows the trend of deterioration of the machine on the other hand electrical test and measurement shows actual condition and are usually foolproof if performed with set standard. One of the advantages of electrical test is that, a good result for any component can be treated as expected life of that particular component.

Possible electrical test for rotor are impedance measurement for interturn short circuits, Megger and high voltage tests. Besides, above electrical test, take few measurements of the rotor dimensions and condition of mechanical components important to rotor like guide bearing. The below are few test and measurements that are done to verify the condition of rotor and based on the outcome of the test, weightage is given for each test result.

A.3.4.1 Megger at 500 V dc

Megger is an instrument used to measure very high resistance, unlike conventional ohmmeter which uses current for measuring the megger uses voltage for measuring the resistance. Megger test is done basically to check the soundness of the insulation. During testing a voltage of 500 V dc is applied across the winding and the frame, megger is an instrument used to measure the resistance of insulation between the conductor and the frame. The good insulation condition has higher value of resistance, if resistance value is decreasing lesser than the threshold value, it should be an alarming situation. Based on the measurement shown by the megger, weightage is given for our evaluation.

Table A.37 showing the weightage based on megger test result [6]

S/No.	Megger at 500 V dc	Weightage	evaluation
1	Greater than 100 Meg	0	
2	50 to 100 Meg	2	
3	5 to 50 Meg	5	
4	2 to 5 Meg	8	
5	Less than 2 Meg	10	

A.3.4.2 Pole Impedance

The pole impedance of the rotor pole is affected by inter-turn short circuit of the field windings. The winding is energized at 120 V, 60 Hz and the voltage drop is measured across the pole. Based on the voltage drop magnitude weightage is given for the evaluation, poles with appreciably lower voltage drop may have shorted turns. The voltage drop across the immediately adjacent poles may be low as well due to the influence of the defective pole on the magnetic circuits of the adjacent poles. This test can detect appreciable amount of shorting in the coils either between turns or to the ground. The Table A.38 below shows the weightage for the evaluation based on the variation of impedance of pole compared to nominal value

Table A.38 showing weightage based on pole impedance variation [6]

S/No.	Pole Impedance	Weightage	evaluation
1	Variation of < 10 %	0	
2	Variation of 10 to 20 %	5	
3	Variation of > 20 %	10	

A.3.4.3 Tolerances

Due to several years of operation of machine, it is subjected to wear and tear which results in distortion of original designed specifications, it is always important to measure these dimensions and compare with the original. The air gap measurement and rotor stator core clearance measurement provides us important information regarding the operation condition of the machine. Besides direct measurement, the air gap can be measured by measuring the roundness of rotor and stator with respect to each other, and the core verticality.

Based on measurement of circularity and concentricity of the rotor, compare with the original designed specification and calculate the tolerances for each, based on the level of distortion presently, weightage is given which will be used in evaluation for multi criterion analysis of generator for upgrading. The Table A 39 and A.40, shows these weightage.

Table A.39 Showing weightage based on circularity level [6]

S/No.	Circularity	Weightage	Evaluation
1	Less than 6 %	0	
2	6 to 12 %	3	
3	12 to 18 %	6	
4	18 to 24 %	10	
5	24 to 30 %	15	
6	Greater than 30 %	20	

Table A.40 showing weightage based on distortion in concentricity

S/No.	Concentricity	Weightage	Evaluation
1	Less than 1.2 %	0	
2	1.2 to 2.4 %	3	
3	2.4 to 3.6 %	6	
4	3.6 to 4.8 %	10	
5	4.8 to 6.0 %	15	
6	Greater than 6%	20	

A.3.4.4 Guide Bearing Vibrations

Guide bearing are used to restrain the radial movement of the shaft, they are lubricated in oil and any vibration or deterioration on these can be an indication for trouble. A displacement sensor is used to measure the vibration of the guide bearing. In our analysis for upgrading decision making, give weightage based on the magnitude of the vibration measured in microns. Table A.41 [6] shows the weightage for guide bearing vibration based on the magnitude of vibration. Besides displacement sensors, spectral analysis is also done to verify the condition of guide bearing.

Table A.41 showing the weightage for guide bearing based on vibration level

S/No.	Concentricity	Weightage	Evaluation
1	Less than 25 microns	0	
2	25 to 100 microns	2	
3	100 to 300 microns	4	
4	300 to 500 microns	7	
5	Greater than 500 microns	10	

A.3.4.5 Collector full load temperature rise

The collector wear and tear basically depends on the operation environment, some of the condition that affect the collector are insulation condition at the bottom of collector, level of humidity, contamination, brush pressure, ambient temperature and cooling of collector and brushes. Here monitor the full load temperature rise in the collector and based on the temperature attained, weightage is given for evaluation in Table A.42 below.

Table A.42 showing weightage based on temperature rise at full load [6]

S/No.	Collector Temp Rise	Weightage	Evaluation
1	Full load temp rise Less than 75^{o}C	0	
2	75^{o}C to 85^{o}C	1	
3	Greater than 85^{o}C	2	

A.4 Mechanical Components

Besides the stator and rotor, the integrity of mechanical components mentioned below is important for optimal performance of the generator. The mechanical components like stator frame, bearings, brake etc, are essential for reliable operation of generator as envisaged by designers, any malfunction can be risky for the safety of personnel as well as, lead to complete outage of the unit with loss of revenue and extra cost of repair and replacement. One of most important mechanical component of the generator are the bearings, which should be in good condition for mechanical integrity of the generator. The bearing insulation should be checked as bearing current has adverse effect on the lubrication oil by altering its chemical properties. Below are few types of mechanical components that will be examined for condition analysis of the hydro generator for upgrading and Uprating decision.

A.4.1 Stator Frame

The stator frame is one of the most robust designs of the generator which will normally not undergo any ageing. The operation of generator outside the designed parameter leads to extra stress on the frame which may crack at times or lead to deformation in shape (ovality). The welds attaching the core keybars to the frame should be inspected for cracks with dye-penetrant, if any cracks or separation is found, re-welding should be done. Inspections should be basically made for cracks on stator frame, damage to sole plates, concrete degradation due to alkali aggregate reactions (AAR) and insufficient rigidity. Based on the condition, score should be provided in the Table A.43.

Table A.43 Showing Stator Frame condition Evaluation [6]

S/No.	Stator Frame Condition	Weightage	Evaluation
1	No cracks	0	
2	Cracked welds	1 to 6	
3	Cracked plates	3 to 15	
4	Deficient plates	5 to 15	
5	Concrete movement	5 to 25	
6	Insufficient rigidity	5 to 25	

A.4.2 Thrust bearing

The basic function of the thrust bearing is to support the mass of the generator, turbine as well as the hydraulic thrust imposed by the turbine runner. The thrust bearing is located either above the rotor in suspended unit or below the rotor in umbrella unit. Thrust bearing are constructed from oil lubricated, segmented, babbit-lined shoes. The possible problems with the bearing pads may be caused by bearing currents, deformation in shape of stator and rotor, stress due to bad alignment of the shaft, lubrication and cooling failure. Insulation test for bearing is done if there are no visible sign of deterioration, Babbitt is checked for any cracks and oil level checked, based on these, provide the weightage for the upgrading analysis in Table A.44.

Table A.44Showing condition of Thrust bearing and its Weightage

S/No.	Thrust bearing condition	Weightage	Evaluation
1	Insulation to replace	1	
2	Babbit damaged	1	
3	Babbit to be replaced	3	
4	Oil injection required	5	
5	Deficient design	1 to 8	

A.4.3 Coolers

Since, the problem with any component of generator, be it stator, rotor, stator winding or mechanical components, heat is the main reason for its early aging and deterioration resulting in failure. An efficient cooling system that can take away heat and allow operation of generator at designed temperature, results in the best performance. In our evaluation the cooling system is thoroughly examined and based on its condition, give the Weightage as shown in Section 3.3

A.4.4 Brakes and Jacks

Through inspection of brake jacks should be undertaken. Operation and maintenance log book should be looked at, incase brake jacks have a history of problems, and then it should be replaced. During inspection the personnel should look for heavy burnt sections and area of repair. Personnel should check for type of brake installed and look for installation of new brake linings free from asbestos. Based the condition of brake jacks, evaluation is done in the Table A.45.

Table A.45 showing evaluation of brakes and jacks based on its condition [6]

S/No.	Brakes and Jacks Condition	Weightage	Evaluation
1	Good condition	0	
2	Minor repair	1	
3	Major repair	2	
4	Replacement required	4	

APPENDIX B

RELIABILITY EVALUATION OF GENERATOR

Table B.1 Generator Baseline Data

										Pu = 2.941				Pu = 4.167	
										Ps = 0.34	gamma = 1.8335			Ps = 0.24	gamma = 1.6207
								gamma = 2.5126		CI = 17	theta = 28.9378			CI = 12	theta = 23.45
								theta =48.7183		UNIT 1				Unit 2	
Age	No. of Exp	No. of retir	Nr (net)	Ne= (Nexp	Reliability	ln(age)	ln(ln(1/R(t)	Weibull R(	Hazard fn	Rci	ln(ln(1/R(t)	Hazard fn	Rci	ln(ln(1/R(t)	Hazard fn h
0	1142	0	0	1142	1			1	0	1		0	1		0
1	1142	0	0	1142	1			0.999943	0.000144	0.999503	-7.60669	0.003834	0.999003	-6.91026	0.00975241
2	1124	0	0	1124	1	0.693147		0.999672	0.000412	0.99717	-5.86613	0.006833	0.994336	-5.17086	0.01499552
3	1109	1	1	1110	0.999099	1.098612	-7.01166	0.999092	0.000761	0.992199	-4.84956	0.00958	0.984464	-4.1568	0.01928685
4	1095	0	1	1096	0.999088	1.386294	-6.99897	0.99813	0.001176	0.984052	-4.13038	0.012176	0.968497	-3.4417	0.02305742
5	1084	1	2	1086	0.998158	1.609438	-6.29619	0.996726	0.001648	0.972373	-3.575	0.014665	0.946052	-2.89213	0.02648273
6	1070	3	5	1075	0.995349	1.791759	-5.36831	0.994829	0.002171	0.956971	-3.12398	0.017072	0.917225	-2.44873	0.02965587
7	1059	5	10	1069	0.990645	1.94591	-4.6672	0.992393	0.002741	0.93781	-2.74563	0.019412	0.882537	-2.0798	0.03263356
8	1031	6	16	1047	0.984718	2.079442	-4.17341	0.989376	0.003355	0.915004	-2.42107	0.021697	0.842857	-1.76634	0.03545358
9	1005	0	16	1021	0.984329	2.197225	-4.14806	0.985743	0.004009	0.8888	-2.13806	0.023936	0.799289	-1.49596	0.03814261
10	983	1	17	1000	0.983	2.302585	-4.06598	0.981463	0.004701	0.859559	-1.88825	0.026133	0.753049	-1.2601	0.04072041
11	957	4	21	978	0.978528	2.397895	-3.83015	0.976506	0.00543	0.827728	-1.66564	0.028293	0.705354	-1.05253	0.04320207
12	928	4	25	953	0.973767	2.484907	-3.62748	0.970849	0.006194	0.793814	-1.46574	0.030422	0.657322	-0.8685	0.04559948
13	908	4	29	937	0.96905	2.564949	-3.45971	0.964472	0.006992	0.758347	-1.28513	0.03252	0.609915	-0.70434	0.0479222
14	896	12	41	937	0.956243	2.639057	-3.10682	0.957358	0.007821	0.721861	-1.12109	0.034592	0.563905	-0.5571	0.05017805
15	864	3	44	908	0.951542	2.70805	-3.00232	0.949494	0.008681	0.684861	-0.97143	0.03664	0.519869	-0.42437	0.05237354
16	830	4	48	878	0.94533	2.772589	-2.87847	0.94087	0.009572	0.647812	-0.83436	0.038665	0.478202	-0.30419	0.05451417
17	802	6	54	856	0.936916	2.833213	-2.73088	0.931481	0.010491	0.611125	-0.70835	0.040669	0.439142	-0.19488	0.05660461
18	783	5	59	842	0.929929	2.890372	-2.62214	0.921326	0.011438	0.575145	-0.59216	0.042653	0.4028	-0.09506	0.05864889
19	750	8	67	817	0.917993	2.944439	-2.45847	0.910406	0.012413	0.540158	-0.48468	0.04462	0.369187	-0.00355	0.06065051
20	725	10	77	802	0.90399	2.995732	-2.29326	0.898727	0.013414	0.506383	-0.38498	0.046569	0.338239	0.08066	0.06261256
21	690	13	90	780	0.884615	3.044522	-2.09881	0.886298	0.014442	0.473986	-0.29226	0.048501	0.309847	0.158437	0.06453772
22	663	9	99	762	0.870079	3.091042	-1.97205	0.873133	0.015494	0.443078	-0.20578	0.050419	0.283866	0.230519	0.06642841
23	639	9	108	747	0.855422	3.135494	-1.85687	0.859247	0.016572	0.413728	-0.12494	0.052322	0.260136	0.297547	0.06828677
24	610	6	114	724	0.842541	3.178054	-1.76415	0.844661	0.017674	0.385966	-0.04918	0.054211	0.238488	0.360074	0.07011473
25	588	10	124	712	0.825843	3.218876	-1.65365	0.829398	0.0188	0.359794	0.02198	0.056088	0.218754	0.418584	0.07191401
26	561	12	136	697	0.804878	3.258097	-1.52756	0.813486	0.019949	0.335189	0.088982	0.057951	0.200769	0.473497	0.07368619
27	535	11	147	682	0.784457	3.295837	-1.41567	0.796953	0.021121	0.31211	0.152204	0.059803	0.184379	0.525179	0.07543269
28	515	10	157	672	0.766369	3.332205	-1.32392	0.779833	0.022315	0.290504	0.211991	0.061644	0.169437	0.573955	0.07715483
29	490	11	168	658	0.744681	3.367296	-1.22146	0.762161	0.023532	0.270307	0.268649	0.063474	0.155809	0.620106	0.07885379
30	467	12	180	647	0.721793	3.401197	-1.12081	0.743976	0.02477	0.251451	0.322452	0.065293	0.14337	0.663886	0.08053066
31	440	16	196	636	0.691824	3.433987	-0.99852	0.725319	0.026029	0.233863	0.373645	0.067102	0.132009	0.705514	0.08218647
32	415	8	204	619	0.670436	3.465736	-0.91672	0.706232	0.02731	0.217469	0.422452	0.068901	0.121622	0.745189	0.08382213
33	398	5	209	607	0.655684	3.496508	-0.86257	0.68676	0.028611	0.202198	0.469071	0.070691	0.112117	0.783085	0.08543852
34	390	6	215	605	0.644628	3.526361	-0.82307	0.66695	0.029933	0.187977	0.513682	0.072472	0.10341	0.819361	0.08703643
35	366	7	222	588	0.622449	3.555348	-0.74635	0.646849	0.031274	0.174738	0.556448	0.074245	0.095428	0.854155	0.08861661
36	329	5	227	556	0.591727	3.583519	-0.64491	0.626507	0.032636	0.162415	0.597517	0.076008	0.0881	0.887594	0.09017976
37	299	3	230	529	0.565217	3.610918	-0.56116	0.605973	0.034017	0.150945	0.637023	0.077764	0.081368	0.919792	0.09172652
38	282	3	233	515	0.547573	3.637586	-0.50707	0.585297	0.035417	0.140268	0.675086	0.079512	0.075177	0.95085	0.09325751
39	259	8	241	500	0.518	3.663562	-0.41888	0.564531	0.036836	0.130329	0.711819	0.081252	0.069478	0.980861	0.09477328
40	224	9	250	474	0.472574	3.688879	-0.28827	0.543724	0.038274	0.121076	0.747323	0.082985	0.064226	1.009908	0.09627439
41	182	7	257	439	0.414579	3.713572	-0.12727	0.522927	0.039731	0.11246	0.781688	0.084711	0.059382	1.038069	0.09776132
42	168	7	264	432	0.388889	3.73767	-0.05714	0.502188	0.041205	0.104436	0.815001	0.08643	0.054911	1.065413	0.09923456
43	148	0	264	412	0.359223	3.7612	0.023532	0.481557	0.042698	0.096963	0.847337	0.088141	0.050781	1.092002	0.10069456
44	125	2	266	391	0.319693	3.78419	0.131374	0.46108	0.044209	0.090001	0.878769	0.089847	0.046962	1.117895	0.10214173
45	120	1	267	387	0.310078	3.806662	0.157801	0.440804	0.045738	0.083514	0.909362	0.091545	0.04343	1.143144	0.10357648
46	113	0	267	380	0.297368	3.828641	0.192918	0.420771	0.047284	0.07747	0.939175	0.093238	0.040159	1.167799	0.10499918
47	108	2	269	377	0.286472	3.850148	0.223235	0.401026	0.048848	0.071836	0.968264	0.094924	0.03713	1.191903	0.1064102
48	101	3	272	373	0.270777	3.871201	0.26732	0.381606	0.050428	0.066585	0.996679	0.096605	0.034322	1.215498	0.10780988
49	98	4	276	374	0.262032	3.89182	0.292138	0.36255	0.052026	0.061691	1.024469	0.098279	0.031718	1.238623	0.10919854
50	92	1	277	369	0.249322	3.912023	0.32859	0.343893	0.05364	0.057129	1.051676	0.099948	0.029304	1.261311	0.11057649

Table B.1 - continued

										Pu = 2.941			Pu = 4.167		
										Ps = 0.34	gamma = 1.8335		Ps = 0.24	gamma = 1.6207	
								gamma = 2.5126		CI = 17	theta = 28.9378		CI = 12	theta = 23.45	
								theta =48.7183		UNIT 1			Unit 2		
Age	No. of Exp	No. of retir	Nr (net)	Ne= (Nexp	Reliability	ln(age)	ln(ln(1/R(t)	Weibull R(	Hazard fn	Rci	ln(ln(1/R(t)	Hazard fn	Rci	ln(ln(1/R(t)	Hazard fn h
51	90	4	281	371	0.242588	3.931826	0.348113	0.325668	0.055271	0.052876	1.078341	0.101612	0.027063	1.283595	0.11194403
52	83	5	286	369	0.224932	3.951244	0.400088	0.307903	0.056919	0.048913	1.104501	0.10327	0.024983	1.305506	0.11330143
53	75	0	286	361	0.207756	3.970292	0.45196	0.290625	0.058582	0.045218	1.130192	0.104922	0.023052	1.327071	0.11464897
54	73	1	287	360	0.202778	3.988984	0.467278	0.273859	0.060262	0.041776	1.155444	0.10657	0.02126	1.348315	0.1159869
55	71	1	288	359	0.197772	4.007333	0.482823	0.257625	0.061958	0.038569	1.180288	0.108212	0.019596	1.369263	0.11731546
56	69	1	289	358	0.192737	4.025352	0.498607	0.24194	0.06367	0.035582	1.204751	0.10985	0.01805	1.389937	0.11863489
57	67	1	290	357	0.187675	4.043051	0.514644	0.22682	0.065398	0.0328	1.22886	0.111482	0.016615	1.410358	0.11994541
58	65	0	290	355	0.183099	4.060443	0.529292	0.212277	0.067141	0.030211	1.252637	0.11311	0.015284	1.430544	0.12124724
59	63	0	290	353	0.17847	4.077537	0.54426	0.198318	0.0689	0.027802	1.276107	0.114733	0.014048	1.450513	0.12254059
60	63	0	290	353	0.17847	4.094345	0.54426	0.18495	0.070674	0.025561	1.299288	0.116352	0.012901	1.470282	0.12382565
61	62	0	290	352	0.176136	4.110874	0.55187	0.172176	0.072463	0.023479	1.322201	0.117966	0.011837	1.489867	0.1251026
62	57	0	290	347	0.164265	4.127134	0.591266	0.159997	0.074268	0.021544	1.344863	0.119576	0.010851	1.509281	0.12637165
63	53	0	290	343	0.154519	4.143135	0.624568	0.14841	0.076087	0.019748	1.36729	0.121181	0.009938	1.528538	0.12763295
64	52	1	291	343	0.151603	4.158883	0.634716	0.137411	0.077921	0.018082	1.389499	0.122782	0.009092	1.54765	0.12888668
65	46	0	291	337	0.136499	4.174387	0.688859	0.126993	0.07977	0.016538	1.411503	0.124379	0.008309	1.566629	0.130133
66	46	1	292	338	0.136095	4.189655	0.690346	0.117147	0.081634	0.015107	1.433316	0.125972	0.007584	1.585484	0.13137207
67	44	0	292	336	0.130952	4.204693	0.709474	0.107863	0.083512	0.013784	1.45495	0.127561	0.006915	1.604227	0.13260404
68	40	0	292	332	0.120482	4.219508	0.749648	0.099127	0.085405	0.01256	1.476416	0.129146	0.006298	1.622866	0.13382905
69	40	0	292	332	0.120482	4.234107	0.749648	0.090926	0.087311	0.01143	1.497725	0.130727	0.005728	1.641409	0.13504725
70	35	0	292	327	0.107034	4.248495	0.804068	0.083244	0.089233	0.010388	1.518887	0.132304	0.005203	1.659864	0.13625877
71	31	0	292	323	0.095975	4.26268	0.851716	0.076064	0.091168	0.009427	1.53991	0.133878	0.004719	1.678238	0.13746375
72	30	0	292	322	0.093168	4.276666	0.864304	0.069368	0.093117	0.008543	1.560802	0.135447	0.004275	1.696538	0.1386623
73	26	0	292	318	0.081761	4.290459	0.917871	0.063139	0.09508	0.00773	1.581571	0.137014	0.003867	1.714768	0.13985456
74	25	0	292	317	0.078864	4.304065	0.932174	0.057355	0.097057	0.006985	1.602224	0.138576	0.003492	1.732935	0.14104063
75	25	0	292	317	0.078864	4.317488	0.932174	0.051999	0.099048	0.006301	1.622766	0.140135	0.003149	1.751043	0.14222065
76	23	0	292	315	0.073016	4.330733	0.962059	0.047048	0.101052	0.005675	1.643205	0.141691	0.002835	1.769096	0.14339471
77	23	0	292	315	0.073016	4.343805	0.962059	0.042483	0.10307	0.005103	1.663543	0.143243	0.002549	1.787099	0.14456292
78	23	1	293	316	0.072785	4.356709	0.963269	0.038284	0.105102	0.004581	1.683788	0.144792	0.002287	1.805054	0.14572539
79	22	0	293	315	0.069841	4.369448	0.978901	0.034429	0.107147	0.004105	1.703941	0.146338	0.002049	1.822965	0.14688223
80	22	0	293	315	0.069841	4.382027	0.978901	0.030899	0.109205	0.003672	1.724007	0.14788	0.001833	1.840834	0.14803352
81	21	0	293	314	0.066879	4.394449	0.995054	0.027674	0.111276	0.003279	1.74399	0.149419	0.001637	1.858664	0.14917937
82	21	0	293	314	0.066879	4.406719	0.995054	0.024734	0.113361	0.002923	1.763891	0.150955	0.001459	1.876455	0.15031987
83	14	0	293	307	0.045603	4.418841	1.127456	0.02206	0.115458	0.002601	1.783714	0.152488	0.001298	1.894211	0.1514551
84	11	0	293	304	0.036184	4.430817	1.199703	0.019634	0.117569	0.00231	1.803461	0.154018	0.001152	1.911932	0.15258515
85	11	0	293	304	0.036184	4.442651	1.199703	0.017437	0.119693	0.002047	1.823133	0.155544	0.001021	1.929619	0.15371011
86	9	0	293	302	0.029801	4.454347	1.256528	0.015454	0.121829	0.001811	1.842732	0.157068	0.000903	1.947272	0.15483007
87	9	0	293	302	0.029801	4.465908	1.256528	0.013667	0.123978	0.001599	1.86226	0.158589	0.000797	1.964893	0.1559451
88	9	0	293	302	0.029801	4.477337	1.256528	0.01206	0.12614	0.001409	1.881717	0.160107	0.000703	1.982482	0.15705527
89	6	0	293	299	0.020067	4.488636	1.363201	0.010619	0.128314	0.001239	1.901104	0.161622	0.000618	2.000038	0.15816067
90	4	0	293	297	0.013468	4.49981	1.460343	0.00933	0.130501	0.001088	1.920422	0.163134	0.000542	2.017563	0.15926137
91	4	0	293	297	0.013468	4.51086	1.460343	0.00818	0.132701	0.000952	1.939671	0.164644	0.000475	2.035054	0.16035744
92	4	0	293	297	0.013468	4.521789	1.460343	0.007155	0.134913	0.000832	1.958851	0.16615	0.000415	2.052513	0.16144895
93	4	0	293	297	0.013468	4.532599	1.460343	0.006245	0.137137	0.000726	1.977964	0.167654	0.000362	2.069938	0.16253597
94	4	0	293	297	0.013468	4.543295	1.460343	0.005439	0.139374	0.000632	1.997008	0.169155	0.000315	2.087329	0.16361856
95	0	0	293	293	0	4.553877		0.004726	0.141623	0.000549	2.015984	0.170654	0.000273	2.104686	0.1646968
96	0	0	293	293	0	4.564348		0.004097	0.143884	0.000475	2.034892	0.17215	0.000237	2.122007	0.16577074
97	0	0	293	293	0	4.574711		0.003544	0.146157	0.000411	2.053731	0.173643	0.000205	2.139291	0.16684044
98	0	0	293	293	0	4.584967		0.003059	0.148442	0.000355	2.0725	0.175134	0.000177	2.156538	0.16790597
99	0	0	293	293	0	4.59512		0.002634	0.150739	0.000305	2.091201	0.176622	0.000152	2.173747	0.16896739
100	0	0	293	293	0	4.60517		0.002263	0.153048	0.000262	2.109831	0.178108	0.000131	2.190916	0.17002474

APPENDIX C

RELIABILITY EVALUATION OF TURBINE

Table C.1 Turbine Baseline Data

							BASE LINE			UNIT I AND II		
							theta = 63.826			theta = 63.	Pu = 1	
					R = (1-Nr/Ne)		Gamma = 2.9496			gamma = 2	Ps = 1	
Age	Number of	Net No. of	Nr	Ne = Nr +	Baseline re	Ln(Age)	Ln(Ln(1/R)	eliability R(	Hazard Fn	Rci	Ln(Ln(1/R(	weibull Reliability
0	657	0	0	657	1	0		1	0	1		1
1	657	0	0	657	1	0		0.999995	1.4E-05	0.999995	-12.259	0.999995258
2	648	0	0	648	1	0.693147		0.999963	5.4E-05	0.999963	-10.2145	0.999963366
3	638	0	0	638	1	1.098612		0.999879	0.000119	0.999879	-9.01854	0.999878865
4	630	0	0	630	1	1.386294		0.999717	0.000209	0.999717	-8.17	0.999717021
5	625	0	0	625	1	1.609438		0.999454	0.000322	0.999454	-7.51181	0.99945356
6	620	1	1	621	0.99839	1.791759	-6.43053	0.999065	0.00046	0.999065	-6.97404	0.999064571
7	611	0	1	612	0.998366	1.94591	-6.41591	0.998526	0.000621	0.998526	-6.51935	0.998526467
8	601	0	1	602	0.998339	2.079442	-6.39943	0.997816	0.000806	0.997816	-6.12549	0.99781597
9	593	0	1	594	0.998316	2.197225	-6.38604	0.99691	0.001014	0.99691	-5.77808	0.996910125
10	584	0	1	585	0.998291	2.302585	-6.37076	0.995786	0.001245	0.995786	-5.46731	0.995786312
11	579	0	1	580	0.998276	2.397895	-6.36217	0.994422	0.0015	0.994422	-5.18618	0.994422278
12	574	1	2	576	0.996528	2.484907	-5.66122	0.992796	0.001777	0.992796	-4.92953	0.992796178
13	566	7	9	575	0.984348	2.564949	-4.14927	0.990887	0.002077	0.990887	-4.69344	0.990886613
14	553	7	16	569	0.97188	2.639057	-3.55706	0.988673	0.0024	0.988673	-4.47485	0.988672688
15	540	3	19	559	0.966011	2.70805	-3.36447	0.986134	0.002746	0.986134	-4.27135	0.986134061
16	529	2	21	550	0.961818	2.772589	-3.24599	0.983251	0.003114	0.983251	-4.08098	0.983251009
17	521	2	23	544	0.957721	2.833213	-3.14193	0.980004	0.003504	0.980004	-3.90217	0.980004487
18	515	0	23	538	0.957249	2.890372	-3.1306	0.976376	0.003918	0.976376	-3.73357	0.976376202
19	509	1	24	533	0.954972	2.944439	-3.07752	0.972349	0.004353	0.972349	-3.57409	0.97234868
20	505	3	27	532	0.949248	2.995732	-2.95488	0.967905	0.004811	0.967905	-3.4228	0.967905341
21	499	0	27	526	0.948669	3.044522	-2.94323	0.963031	0.005291	0.963031	-3.27889	0.963030571
22	493	0	27	520	0.948077	3.091042	-2.93145	0.95771	0.005793	0.95771	-3.14167	0.957709805
23	485	3	30	515	0.941748	3.135494	-2.81311	0.95193	0.006318	0.95193	-3.01056	0.951929598
24	479	1	31	510	0.939216	3.178054	-2.76923	0.945678	0.006864	0.945678	-2.88502	0.945677706
25	473	0	31	504	0.938492	3.218876	-2.75702	0.938943	0.007433	0.938943	-2.76462	0.938943161
26	464	1	32	496	0.935484	3.258097	-2.70768	0.931716	0.008024	0.931716	-2.64893	0.931716345
27	456	3	35	491	0.928717	3.295837	-2.60435	0.923989	0.008636	0.923989	-2.53761	0.923989068
28	452	3	38	490	0.922449	3.332205	-2.51673	0.915755	0.009271	0.915755	-2.43034	0.915754632
29	445	5	43	488	0.911885	3.367296	-2.38335	0.907008	0.009927	0.907008	-2.32684	0.907007903
30	430	2	45	475	0.905263	3.401197	-2.3073	0.897745	0.010606	0.897745	-2.22684	0.897745372
31	419	2	47	466	0.899142	3.433987	-2.24135	0.887965	0.011306	0.887965	-2.13012	0.887965215
32	406	2	49	455	0.892308	3.465736	-2.17205	0.877667	0.012028	0.877667	-2.03648	0.877667342
33	393	1	50	443	0.887133	3.496508	-2.12226	0.866853	0.012771	0.866853	-1.94571	0.866853445
34	390	3	53	443	0.880361	3.526361	-2.06024	0.855527	0.013537	0.855527	-1.85766	0.855527038
35	384	1	54	438	0.876712	3.555348	-2.02817	0.843693	0.014324	0.843693	-1.77216	0.843693486
36	373	3	57	430	0.867442	3.583519	-1.95047	0.83136	0.015132	0.83136	-1.68906	0.831360032
37	356	1	58	414	0.859903	3.610918	-1.8909	0.818536	0.015963	0.818536	-1.60825	0.818535804
38	342	0	58	400	0.855	3.637586	-1.85372	0.805232	0.016815	0.805232	-1.52959	0.805231827
39	318	4	62	380	0.836842	3.663562	-1.7253	0.791461	0.017688	0.791461	-1.45297	0.791461015
40	293	1	63	356	0.823034	3.688879	-1.636	0.777238	0.018583	0.777238	-1.37829	0.777238151
41	265	5	68	333	0.795796	3.713572	-1.4766	0.76258	0.0195	0.76258	-1.30546	0.762579866
42	246	9	77	323	0.76161	3.73767	-1.30077	0.747505	0.020438	0.747505	-1.23438	0.747504601
43	227	2	79	306	0.74183	3.7612	-1.20853	0.732033	0.021397	0.732033	-1.16498	0.732032554
44	211	2	81	292	0.722603	3.78419	-1.12425	0.716186	0.022378	0.716186	-1.09717	0.716185624
45	196	0	81	277	0.707581	3.806662	-1.0616	0.699987	0.02338	0.699987	-1.03088	0.699987337
46	184	0	81	265	0.69434	3.828641	-1.00842	0.683463	0.024404	0.683463	-0.96605	0.683462767
47	176	3	84	260	0.676923	3.850148	-0.9411	0.666638	0.025449	0.666638	-0.90262	0.666638439
48	171	5	89	260	0.657692	3.871201	-0.86984	0.649542	0.026515	0.649542	-0.84052	0.649542226
49	162	5	94	256	0.632813	3.89182	-0.7818	0.632203	0.027602	0.632203	-0.7797	0.632203237
50	154	0	94	248	0.620968	3.912023	-0.74134	0.614652	0.028711	0.614652	-0.72011	0.614651693

Table C.1 - continued

							BASE LINE			UNIT I AND II		
							theta = 63.826			theta = 63.	Pu = 1	
					R = (1-Nr/Ne)		Gamma = 2.9496			gamma = 2	Ps = 1	
Age	Number of	Net No. of	Nr	Ne = Nr +	Baseline re	Ln(Age)	Ln(Ln(1/R)	eliability R(	Hazard Fn	Rci	Ln(Ln(1/R(	weibull Reliability
51	152	3	97	249	0.610442	3.931826	-0.70609	0.596919	0.029842	0.596919	-0.6617	0.596918792
52	139	5	102	241	0.576763	3.951244	-0.59725	0.579037	0.030993	0.579037	-0.60442	0.579036569
53	129	0	102	231	0.558442	3.970292	-0.54025	0.561038	0.032166	0.561038	-0.54824	0.561037753
54	127	0	102	229	0.554585	3.988984	-0.52842	0.542956	0.033359	0.542956	-0.4931	0.542955607
55	125	2	104	229	0.545852	4.007333	-0.50185	0.524824	0.034574	0.524824	-0.43898	0.52482377
56	120	0	104	224	0.535714	4.025352	-0.47136	0.506676	0.03581	0.506676	-0.38583	0.506676096
57	117	2	106	223	0.524664	4.043051	-0.43851	0.488546	0.037068	0.488546	-0.33363	0.488546487
58	113	2	108	221	0.511312	4.060443	-0.39932	0.470469	0.038346	0.470469	-0.28233	0.470468722
59	111	0	108	219	0.506849	4.077537	-0.38634	0.452476	0.039646	0.452476	-0.23191	0.452476293
60	111	0	108	219	0.506849	4.094345	-0.38634	0.434602	0.040966	0.434602	-0.18233	0.434602235
61	111	0	108	219	0.506849	4.110874	-0.38634	0.416879	0.042308	0.416879	-0.13358	0.416878964
62	111	4	112	223	0.497758	4.127134	-0.36005	0.399338	0.043671	0.399338	-0.08562	0.399338111
63	107	0	112	219	0.488584	4.143135	-0.33374	0.38201	0.045054	0.38201	-0.03842	0.38201037
64	106	2	114	220	0.481818	4.158883	-0.31445	0.364925	0.046459	0.364925	0.00803	0.364925347
65	103	0	114	217	0.474654	4.174387	-0.29415	0.348111	0.047885	0.348111	0.053761	0.348111419
66	102	3	117	219	0.465753	4.189655	-0.26906	0.331596	0.049332	0.331596	0.098794	0.331595595
67	96	3	120	216	0.444444	4.204693	-0.20957	0.315403	0.050799	0.315403	0.14315	0.315403401
68	92	0	120	212	0.433962	4.219508	-0.18057	0.299559	0.052288	0.299559	0.186849	0.299558761
69	86	2	122	208	0.413462	4.234107	-0.12421	0.284084	0.053798	0.284084	0.229909	0.284083898
70	76	0	122	198	0.383838	4.248495	-0.04339	0.268999	0.055328	0.268999	0.27235	0.268999244
71	74	4	126	200	0.37	4.26268	-0.00576	0.254323	0.056879	0.254323	0.314189	0.25432337
72	65	1	127	192	0.338542	4.276666	0.079835	0.240073	0.058452	0.240073	0.355443	0.240072918
73	60	3	130	190	0.315789	4.290459	0.142089	0.226263	0.060045	0.226263	0.396128	0.226262561
74	55	0	130	185	0.297297	4.304065	0.193115	0.212905	0.061659	0.212905	0.436259	0.212904963
75	53	1	131	184	0.288043	4.317488	0.218849	0.200011	0.063294	0.200011	0.475852	0.200010768
76	50	1	132	182	0.274725	4.330733	0.256179	0.187589	0.06495	0.187589	0.51492	0.187588592
77	49	4	136	185	0.264865	4.343805	0.284077	0.175645	0.066626	0.175645	0.553477	0.175645036
78	44	2	138	182	0.241758	4.356709	0.350528	0.164185	0.068323	0.164185	0.591537	0.16418471
79	40	6	144	184	0.217391	4.369448	0.422687	0.15321	0.070042	0.15321	0.629112	0.153210271
80	34	2	146	180	0.188889	4.382027	0.510783	0.142722	0.07178	0.142722	0.666214	0.142722474
81	26	1	147	173	0.150289	4.394449	0.639322	0.13272	0.07354	0.13272	0.702856	0.132720235
82	22	0	147	169	0.130178	4.406719	0.712389	0.123201	0.075321	0.123201	0.739048	0.123200706
83	12	0	147	159	0.075472	4.418841	0.949338	0.114159	0.077122	0.114159	0.774801	0.114159359
84	4	0	147	151	0.02649	4.430817	1.289504	0.10559	0.078944	0.10559	0.810126	0.105590078
85	1	0	147	148	0.006757	4.442651	1.60888	0.097485	0.080786	0.097485	0.845033	0.097485264
86	1	0	147	148	0.006757	4.454347	1.60888	0.089836	0.08265	0.089836	0.879531	0.089835937
87	1	0	147	148	0.006757	4.465908	1.60888	0.082632	0.084534	0.082632	0.913631	0.082631858
88	1	0	147	148	0.006757	4.477337	1.60888	0.075862	0.086438	0.075862	0.947341	0.075861643
89	1	0	147	148	0.006757	4.488636	1.60888	0.069513	0.088363	0.069513	0.98067	0.069512882
90	1	0	147	148	0.006757	4.49981	1.60888	0.063572	0.090309	0.063572	1.013627	0.063572267
91	1	0	147	148	0.006757	4.51086	1.60888	0.058026	0.092276	0.058026	1.04622	0.058025714
92	1	0	147	148	0.006757	4.521789	1.60888	0.052858	0.094263	0.052858	1.078456	0.052858485
93	1	0	147	148	0.006757	4.532599	1.60888	0.048055	0.096271	0.048055	1.110344	0.048055312
94	0	0	147	147	0	4.543295		0.043601	0.0983	0.043601	1.141891	0.043600514
95	0	0	147	147	0	4.553877		0.039478	0.100349	0.039478	1.173104	0.039478113
96	0	0	147	147	0	4.564348		0.035672	0.102418	0.035672	1.20399	0.035671945
97	0	0	147	147	0	4.574711		0.032166	0.104509	0.032166	1.234556	0.032165765
98	0	0	147	147	0	4.584967		0.028943	0.106619	0.028943	1.264809	0.028943346
99	0	0	147	147	0	4.59512		0.025989	0.108751	0.025989	1.294754	0.025988573
100	0	0	147	147	0	4.60517		0.023286	0.110903	0.023286	1.324399	0.023285524

APPENDIX D

ECONOMIC ANALYSIS

Table D.1 Economic Analysis

	Feasibility Study Alternatives ($1000)			
CAPITAL COST	**A**	**B**	**C**	**D**
DIRECT COST				
Sub-total Direct Capital (SDC)	1565.00	9006.0000	9114.0000	12923.00
Contingency Factor (CF) = 20%				
Total contingency cost (C) = CF X SDC	313.000	1801.2000	1822.8000	2584.600
Escalation Factor (EF) = (1+e)^n - 1	0.1802	0.1802	0.1802	0.1802
e = 2.9% from figure 4.1 and n = 6 for example.				
Escalation (E) = EF X (C + SDC)	338.431	1947.5478	1970.9028	2794.599
Total Direct Cost (TDC) = SDC + C + E	2216.43	12754.747	12907.7028	18302.19
Indirect Cost				
Indirect Cost Factor (ICF)	0.0700	0.0700	0.0700	0.0700
Indirect Cost (IC) = ICF X TDC	155.150	892.8323	903.5392	1281.153
Interest on the Borrowed Capital Factor (IBCF) = (1+r)^n-1	0.0638	0.0638	0.0638	0.0638
n=1yr				
Interest on the Borrowed Capital (IBC) = IBCF X (TDC + IC)	141.297	813.1152	822.8661	1166.765
r = 6.375%				

Table D.1 - continued

Total Capital Cost (TCC) = TDC + IC + IBC	2512.8790	14460.695	14634.1081	20750.1184
Total Present Worth of Upgrading Cost				
Present Worth Adjustment Factor (PWAF) = (1/(1 + i)^t)	0.9401	0.9401	0.9401	0.9401
t = 1 yrs				
Levelized Annual Fixed Charge Rate (LAFCR) = 11.5 %				
Fixed Charge Factor (FCF) = LAFCR X SPWF	1.1106	1.1106	1.1106	1.1106
SPWF for Economic Life of Upgrade = Equation 4.5	13.8827	13.8827	13.8827	13.8827
PWTCC = FCF X TCC X PWAF	2623.5892	15097.792	15278.8450	21664.3092
Total Present Worth of Upgrade Cost (TPWC) = PWTCC + Other Cost	2623.5892	15097.792	15278.8450	21664.3092
AVERAGE ANNUAL PRESENT WORTH OF UPGRADE COST	188.9827	1087.5259	1100.5675	1560.5259
PRESENT WORTH NET OPERATING BENEFITS				
	ALTERNATIVES ($1000)			
PRESENT WORTH REVENUE BENEFITS	**A**	**B**	**C**	**D**
ENERGY REVENUE				

Table D.1 - continued

k=(1+e)/(1+i)=	0.9664	0.9664	0.9664	0.9664
n=upgrade to evaluation period = 35 years				
Total Annual Energy Generation(kWh)	57380000	59990000	65110000	65420000
Energy price per unit ($/kWh)= $0.027 or $27/MWh	*0.0270*	*0.0270*	*0.0270*	*0.0270*
Equation 5.8 (VG) =	1549260.0	1619730.0	1757970.00	1766340.00
TOTAL BENEFITS($1000)	31087.603	34573.642	37524.4174	37703.0776
Tax Credit Section 45, IRS @ $0.009/kWh*	NA	822.1500	2434.9500	2532.6000
* Incremental capacity between Aug 2005 and Jan 2008 for 10 Yrs				
Total Annual Benefits including Tax Rebate				
TOTAL PRESNT WORTH BENEFITS ANNUAL	31087.603	35395.792	39959.3674	40235.6776
ANNUAL OPERATION AND MAINTENANCE	820.0286	104.0551	104.0551	104.0551
e = 2.8 %, Escalation Factor = 0.1802				
TOTAL OPERATION AND MAINTENANCE (Equation 5.11 & 5.122)	16454.775	2298.3108	2298.3108	2298.3108
PRESENT WORTH NET OPERATING BENEFITS(PWNOB)				
Present worth net operating benefits = total revenue benefits - O&M costs	14632.828	33097.481	37661.0566	37937.3669
AVERAGE ANNUAL PRESENT WORTH OF NET OPERATING BENEFITS (PWNOB)	1054.0335	2384.0814	2712.8054	2732.7087
INCREMENTAL NET OPERATING				

Table D.1 - continued

BENEFITS (INOB)				
INOB = PWNOB (ALTERNATIVE) - PWNOB(EXISTING)	NA	18464.653	23028.2286	23304.5389
Annual INOB		1330.0479	1658.7719	1678.6751
ECONOMIC ANALYSIS				
	ALTERNATIVES ($1000)			
PARAMETER	**A**	**B**	**C**	**D**
PLANT MAXIMUM CAPACITY	30 MW	34 MW	42 MW	45 MW
AVERAGE ANNUAL ENERGY GENERATION (GWh)	57.38	59.99	65.11	65.42
INCREMENTAL NET OPERATING BENEFITS (INOB)	NA	18464.653	23028.2286	23304.5389
TOTAL PRESENT WORTH OF UPGRADE COST (TPWC)	NA	15097.792	15278.8450	21664.3092
ANNUAL PRESENT WORTH OF UPGRADE COST (TPWC) @ 35 Yrs		1087.5259	1100.5675	1560.5259
Federal Discount Rate = 6.375 % annual ((A/P, i %,n))				
NET ECONOMIC BENEFIT (ANNUAL)				
(NEB = PWNOB - TPWC)	NA	17999.689	22382.2116	16273.0577
BENEFIT/COST RATIO (BCR)				
(BCR = (INOB/TPWC)		1.2230	1.5072	1.0757

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BIOGRAPHICAL INFORMATION

Sandip R. Sharma was born in Pokhara, Nepal in 1980. He completed his Bachelor of Technology from National Institute of Technology (Previously Regional Engineering College REC), Rourkela, India in July 2003. He is currently pursuing Masters in Electrical Engineering from The University of Texas at Arlington. His Current research interests are in the areas of power system protective relaying, power system reliability and hydropower generation. He has been a Graduate Teaching Assistant for various courses during his MS in UTA.