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Thermodynamic Model of the Loss Factor Applied to Steam Turbines

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Abstract

Erosion, roughness, steam path damage, etc., are factors that reduce power capacity in a steam turbine. Any power loss occurring locally in intermediate stages of a steam turbine results in more available energy in the downstream stages, this effect is well known as the *Loss Factor* (Salisbury, 1974; Stodola, 1927; Husain, 1984). Currently, the Loss Factor is been calculated by graphical methods (Cotton, 1996). In this work a new thermodynamic expression for the Loss Factor (LF) is introduced, in order to improve applications to evaluate malfunctions in the first and intermediate stages of steam turbines. The new thermodynamic expression for the Loss Factor, is based on Second Law Analysis; and concepts like the internal parameter θ, and the dissipation temperature T_d; (Royo, 1992). An Example of a steam turbine in a conventional power plant of 158 MW is analyzed by comparing a classical graphical method (ASME/ANSI PTC-6, 1970; and Cotton, 1993), and the proposed expression of the Loss Factor (LF). Special emphasis is made on the thermoeconomical deviations that could arise by an imprecise application of the Loss Factor Method, during an energy audit of the steam turbine internal parts.

Keywords: Loss factor, steam turbine malfunctions

1. Introduction

Any power loss occurring at the first or intermediate stages in a turbine section results in more available energy for all downstream stages, It is because the non-parallelism in isobars (known as the *Reheat Effect*) increases the energy available of the downstream stages where a part of this power lost can be recovered. It is convenient to multiply local power loss (first or intermediate stages) by a *Loss Factor* (LF) that accounts for the increased power by the following stages (Salisbury, 1974; Stodola, 1927; Cotton, 1993). There are two important application of the *Loss Factor* applied to steam turbines:

a) *Energy audits* (turbine out of service during an overhaul).

b) *On-line monitoring* and *acceptance test* (turbine operating).

In an overhaul, a *steam turbine energy audit* is a good way for determining internal energy losses in stage components like nozzle, bucket, seals, leaks, end-packings, etc. (affected by solid particles, erosion, roughness, damage in the steam path, etc.), giving a good reference to develop an optimum maintenance and rehabilitation program.

When the turbine starts operating, the managers in the power plants are very interested

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in implementing *on-line monitoring systems*, in order to account for heat transfer rates, power generated, and fuel-impact cost due to malfunctions in the components of the plant (Zaleta et. al., 1999). The hardware of these on-line monitoring systems is based on modern field instrumentation (pressures transmitters, temperature, and mass flow meters, etc.), data acquisition processes, and very fast computers.

Software codes for steam turbine energy-audit and on-line monitoring systems include thermodynamic models (one of them is the *Loss Factor* method) and algorithms, for processing data and translate it in thermoeconomic information to managers.

In this paper a new thermodynamical model of the *Loss Factor* is introduced, in order to implement it into the algorithms for steam turbine energy audit, and for on-line monitoring systems.

According to *Figure 1*, the apparent loss of power capacity ($\Delta h_{intermediate}$) occurring locally in an intermediate stage, represents only a lower global effect ($\Delta h_{end\ point}$). It is, as referred above, due to the non-parallelism in isobars increases the energy available of the downstream stages

The Loss Factor, defined in Eq. (1), is typically represented in a Mollier Chart, as shows *Figure 1*.

$$LF = \frac{\Delta h_{end-point}}{\Delta h_{intermediate}} \qquad (1)$$

Currently LF is calculated by published graphical methods (ASME/ANSI PTC-6, 1970; and Cotton, 1993). *Figures 2* and *3* show the graphics typically available in the literature to

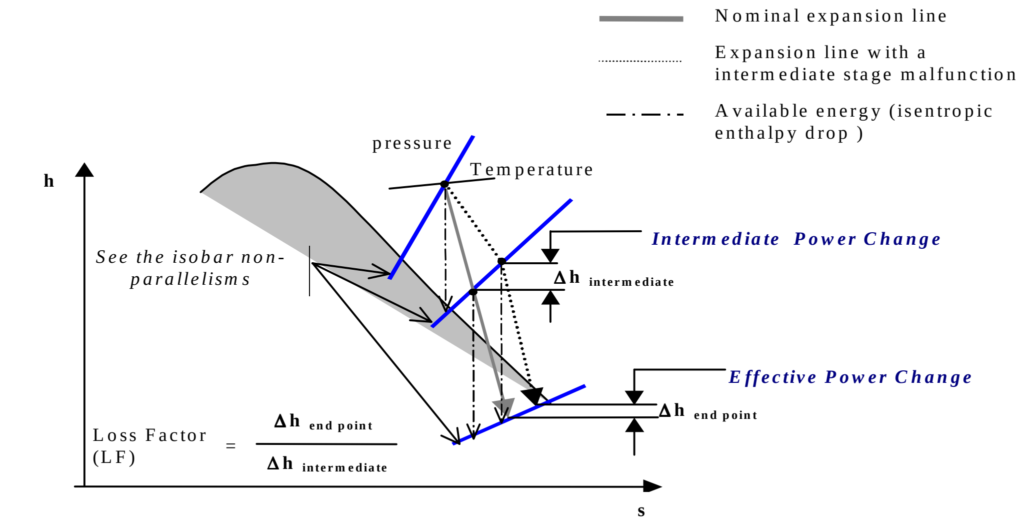
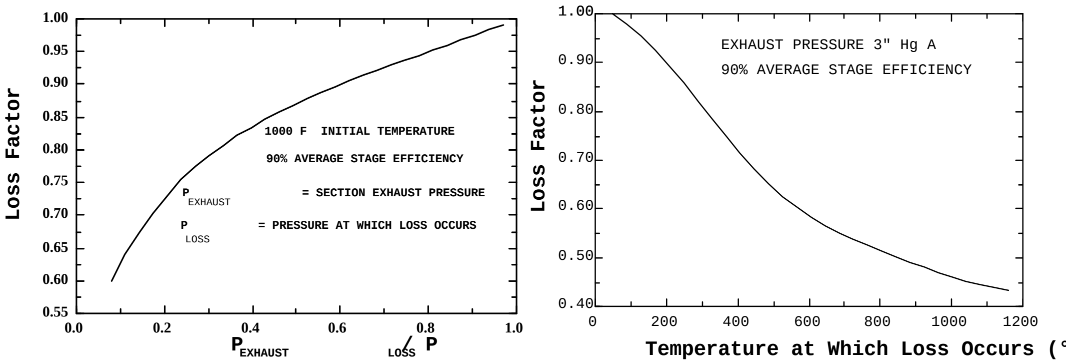


Figure 1. Scheme of the Loss Factor (LF) Effect When a Malfunction Occurs in a First or Intermediate Stage of the Steam Turbine.



(a) (b)

Figure 2. Published Graphical Methods to Determine Loss Factor for (a) HP and IP Sections, and (b) for LP sections (Cotton, 1993)

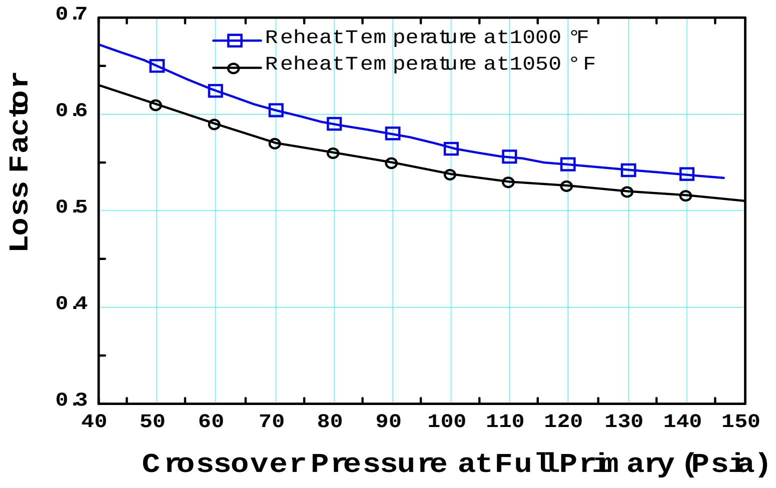


Figure 3. Published Graphical Methods to Determine Loss Factor vs Crossover Pressure for Reheat-ST Sections (ASME/ANSI PTC-6).

determine LF. These methods require to know specific data like pressure ratio, temperature at which loss occurs, or crossover[1] pressures.

2. The Proposed Thermodynamic Model

The graphical models to determine the Loss Factor, shown in *Figure 2* and *3*, could be characterized numerically and introduced into the algorithm programs. However under certain conditions it will be unpractical and imprecise.

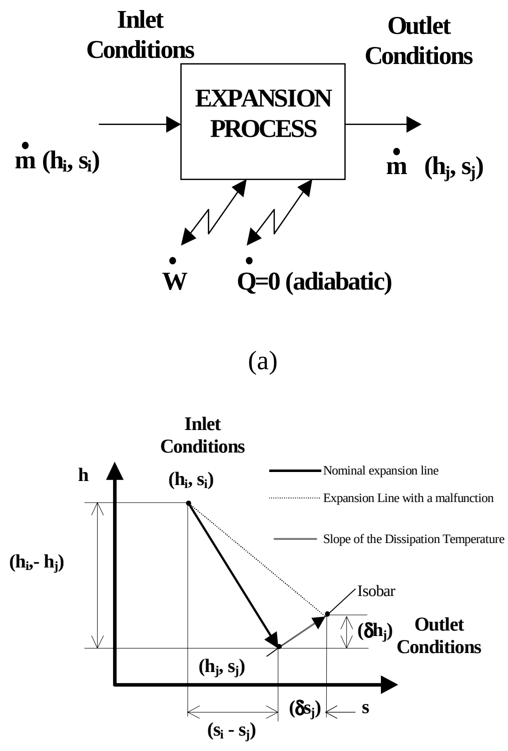
In order to improve the LF model and make it more suitable for a wide range of steam turbine evaluations, in this work the thermodynamic behavior of the Loss Factor (LF) is analyzed and a new model is proposed.

The model (shown in *Figure 4*) assumes an adiabatic expansion process, and it uses definitions of *the Internal Parameter θ,* and the concepts of the *Dissipation Temperature* T_d , in accordance with previous works of Royo (1992), and other existing arrangements made by Ishida (1996), and Bejan (1994). For this model the *Internal Parameter* θ^2 , in K units Eq.(2), is defined as the slope between inlet *(i)* and outlet *(j)* conditions of the expansion process:

$$\theta_{ij} = \frac{h_i - h_j}{s_i - s_j} \qquad (2)$$

and the *Dissipation Temperature* T_d, Eq.(3), in K units, is defined as the slope generated for the changes in thermodynamic properties of the expansion line end-point *(j)*, when a malfunction occurs.

$$T_{d,j} = \frac{dh_j}{ds_i} \qquad (3)$$



(b)

Figure 4. Schematic Definition of the Parameters Considered for an Adiabatic Expansion Process (a) Control Volume, (b) Expansion Line.

[1] Duct that feed steam to the LP section

[2] [2] Kinetic and Potential terms can be include in enthalpy as $h = h_{static} + v^2/2 + gz$

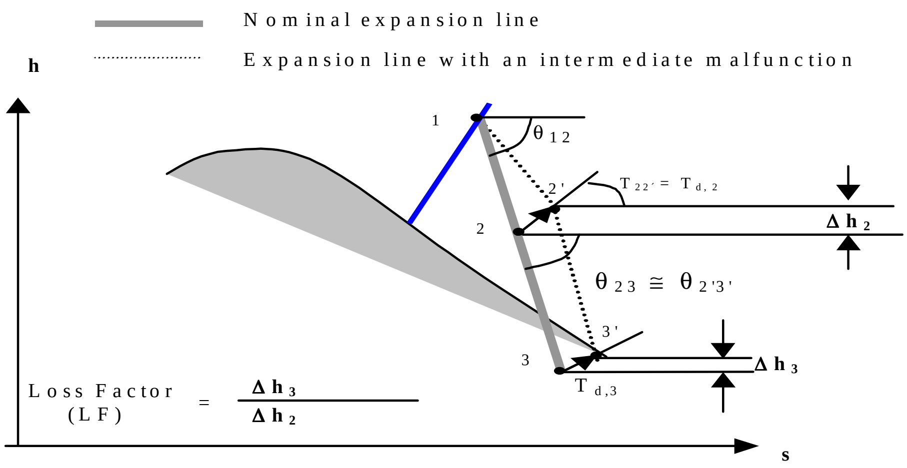
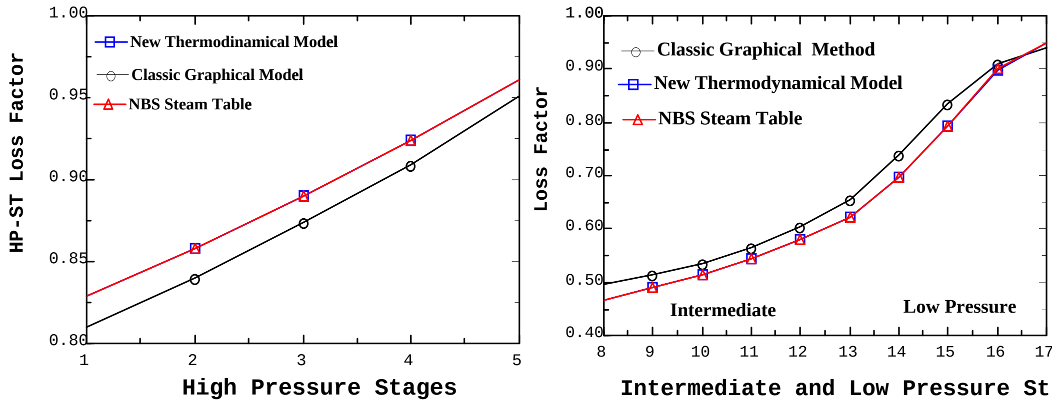


Figure 5. Scheme of the Loss Factor (LF) Model using the Internal Parameter θ, and the Dissipation Temperature T_d.



(a) (b)

Figure 6. Comparison of the Loss Factor Model between the Proposed Thermodynamic Model of LF, the classical Graphical Model and Reference Values from NBS Steam Tables, for (a) High Pressure Section, and (b) for Intermediate and Low Pressure Section.

Given that pressures at intermediate stage($p_2 \approx p_{2'}$), depend strongly on the mass flow rate, when a malfunction occurs with a constant mass flow rate ($\dot m$), then pressure remain approximately constants (see Cooke, 1984 for a wide explanation of Stodola´s Ellipse). According to a previous definition the slope of T_d on isobaric conditions is equal to the instant temperature T_j,

$$T_d = \left.\frac{\partial h_j}{\partial s_i}\right|_{\dot m, p_j} = T_j \qquad (4)$$

The ratio *δh/δs* depends on the kind of process. In this case the partial derivatives at *p=const* should be applied according to the Stodola´s Ellipse.

Figure 5 could represent a schematic expansion line of a steam turbine when a malfunction appears in an intermediate pressure section (IP) and it discharges to a Low Pressure Section (LP). According to Spencer et. al. (1974) the slope of the expansion line in the Low Pressure Sections (LP) remains approximately constant ($\theta_{23} \cong \theta_{2'3'}$) even if Intermediate Pressure (IP) develops a malfunction. Where thermodynamic conditions at point 2' represent the expansion line end-point at which loss occurs (upstream), and point 3' represents the expansion line end-point of the downstream stages after. Under an adequate handling of the previous definition, Eqs.(1)-(4), applied to the model sketched in *Figure 5*, they can be expressed:

$$LF = \left(\frac{dh_3}{dh_2}\right)$$

$$\theta_{23} = \frac{h_2 - h_3}{s_2 - s_3} = \frac{dh_2 - dh_3}{ds_2 - ds_3} = \text{constant}.$$

$$T_{d,loss} = T_{d2} = \left(\frac{dh_2}{ds_2}\right) = T_2\Big|_{p_2=cons}$$

$$T_{d,end} = T_{d3} = \left(\frac{dh_3}{ds_3}\right) = T_3\Big|_{p_3=const}$$

by multiplying and dividing θ_{23} by dh_2,

$$\theta_{23} = \frac{(dh_2 - dh_3)\left(\frac{1}{dh_2}\right)}{(ds_2 - ds_3)\left(\frac{1}{dh_2}\right)} = \frac{1 - LF}{\frac{1}{T_{d2}} - \frac{ds_3}{dh_2}}$$

by multiplying and dividing by dh_3,

$$\theta_{23} = \frac{1 - LF}{\frac{1}{T_{d2}} - \left(\frac{ds_3}{dh_2}\right)\left(\frac{dh_3}{dh_3}\right)} = \frac{1 - LF}{\frac{1}{T_{d2}} - \left(\frac{1}{T_{d3}}\right)(LF)}$$

the expression of the Loss Factor (LF) can be re-defined as follows:

$$LF = \frac{\partial h_3}{\partial h_2}\bigg|_{\dot{m},p_j} = \left(\frac{1 - \frac{\theta_{23}}{T_2}}{1 - \frac{\theta_{23}}{T_3}}\right) \quad (5)$$

for non-differential cases of LF, it can be expressed as:

$$\overline{LF} = \left(\frac{1 - \frac{\theta_{23}}{\overline{T}_2}}{1 - \frac{\theta_{23}}{\overline{T}_3}}\right) \quad (6)$$

where θ_{23} is evaluated at nominal steam turbine conditions, $\overline{T}_2$ and $\overline{T}_3$ are represented by the average mean logarithmic temperature expressed as $\overline{T}_2 = \frac{(T_{2'} - T_2)}{\ln(T_{2'}/T_2)}$ and $\overline{T}_3 = \frac{(T_{3'} - T_3)}{\ln(T_{3'}/T_3)}$, respectively (Bejan, 1994).

TABLE I. STEAM PROPERTIES FOR EACH STAGE IN A 158 MW STEAM TURBINE

		Inlet Condition		Outlet Condition		Nominal Parameters	
Section	**STAGE**	**Pressure bars**	**Temperature °C**	**Pressure bars**	**Temperature °C**	**Mass Flow kg/sec**	**Power KW**
HP-ST	1	124.10	538	99.29	507	128.9	6695
	2	99.29	507	81.72	476	128.9	7045
	3	81.72	476	65.37	444	128.9	7494
	4	65.37	444	52.3	413	128.9	7195
	5	52.30	413	41.84	382	128.9	7195
	6	41.84	382	33.47	353	128.9	6895
IP-ST	7	30.13	538	23.54	502	120.9	8819
	8	23.54	502	18.18	465	120.9	8995
	9	18.18	465	13.88	426	120.9	9558
	10	13.88	426	10.51	388	116	8904
	11	10.51	388	7.673	346	116	9444
	12	7.673	346	5.366	304	110.2	9231
	13	5.366	304	3.600	258	110.2	9744
LP-ST	14 T	3.600	258	1.977	195	50.8	6144
	15 T	1.977	195	0.999	132	49.53	5991
	16 T	0.999	132	0.467	80	45.63	5466
	17 T	0.467	80	0.194	59	45.63	5572
	18 T	0.194	59	0.076	41	45.63	5307
	14 G	3.600	258	1.977	193	50.8	6381
	15 G	1.977	193	0.999	134	49.53	5530
	16 G	0.999	134	0.467	80	45.63	5731
	17 G	0.467	80	0.194	59	45.63	5519
	18 G	0.194	59	0.076	41	45.63	5307
	Mechanical Power Loss						–2240
	Generator Power Loss						–2990
	Total (kW):						158,932

TABLE II. INTERNAL PARAMETER θ AND DISSIPATION TEMPERATURES T_D IN STEAM TURBINE STAGES TO OBTAIN LF VALUE AND CALCULATION ERROR.

Section	Stage	θ [K]	$T_{d,loss}$ [K]	$T_{d,end}$ [K]	LF (Proposed model)	Proposed Model Error*%	LF (Graphical model)	Graphical Model Error*%
HP-ST	1	–3988	779.7	625.6	0.8292	0.0130	0.8097	2.358
	2	–3833	749.3	625.6	0.8580	0.0105	0.8404	2.066
	3	–3917	716.8	625.6	0.8903	0.0084	0.874	1.829
	4	–4215	685.7	625.6	0.9237	0.0054	0.9089	1.606
	5	–4113	655	625.6	0.9610	0.0025	0.9508	1.073
	6	0	625.6	625.6	1	0	1	0
IP-ST	7	–4001	774.9	313.64	0.4480	–0.0086	0.4833	–7.869
	8	–4004	738.1	313.64	0.4667	–0.0140	0.4959	–6.257
	9	–3882	698.9	313.64	0.4901	–0.0208	0.5131	–4.739
	10	–3770	660.5	313.64	0.5152	–0.0264	0.5352	–3.912
	11	–3669	619.3	313.64	0.5453	–0.0348	0.5657	–3.779
	12	–3670	576.6	313.64	0.5799	–0.0443	0.6053	–4.440
	13	–3629	531.1	313.64	0.6231	–0.0529	0.6563	–5.385
LP-ST	14	–3570	468.1	313.64	0.6966	–0.0709	0.6966	–6.265
	15	–3590	404.5	313.64	0.7934	–0.0937	0.7934	–5.180
	16	–3323	352.65	313.64	0.8989	0.0753	0.8989	–1.281
	17	–2847	332.49	313.64	0.9489	0.0406	0.9489	0.994
	18	0	313.64	313.64	1	0	1	0

*respect to value obtained by using NBS Steam Tables

3. Study Case

To show the main features and easiness of the application of the proposed method, a 158 MW conventional steam turbine is analyzed. This turbine has three sections *High Pressure* (HP), *Intermediate Pressure* (IP), and *Low Pressure* (LP); sections respectively, with the following characteristics:

- High Pressure Section (HP) with 6 Impulse Stages.
- Intermediate Pressure Section (IP) with 4 Impulse Stages, 3 Reaction Stages.
- Low Pressure Section (LP) with 5 Reaction Stages in double compound .

By using manufacturer information, it was possible to determine pressure ratios, efficiencies, and nominal operating conditions (at pitch nozzle-bucket conditions) for each stage in the turbine sections, (TABLE I). From these data it was possible to evaluate threes different way for obtaining LF:

i) by *graphical method* (*Figures 2* and *3*),
ii) by *new thermodynamical model* of LF (eq. 5), and
iii) by evaluating directly LF[3] from eq.(1), when a efficiency change is *simulated*, *using NBS steam tables* (It is considered as the expected value at real conditions).

Information provided in TABLE II, allows to demonstrate that the proposed thermo-dynamical model for LF, Eq. (5), is more accurate and practical than the graphical methods. *Figures 6* also shows the discrepancy of each method.

4. Conclusions

Procedures on energy auditing for all internal parts of the 158 MW turbine, as given by Cotton (1996), were followed. Final results on this energy audit are shown in *Figure 7*, where recovered power due to maintenance activities (aprox. 6.2 MW recovered) at the different turbine stages is shown. This figure also shows a discrepancy index, in percentage about 1.4 - 4 % when a graphical method of LF is compared with respect a simulated value. Such differences, represents almost 0.18 MW of uncertain audited power in this steam turbine due to LF used method. Nevertheless Proposed Method is as much about 0.02- 0.1 % of error with respect to calculated value of the steam tables. It is shown that the method proposed will provide a more accurate and practical way to determine the Loss Factor. This method, coupled with a good recording of field parameters, will provide a more reliable way to determine the impact of power loss in turbines.

[3] This value of LF is a reference to compare the discrepancy of the methods (Figs. 2, and 3; and eq. (5).

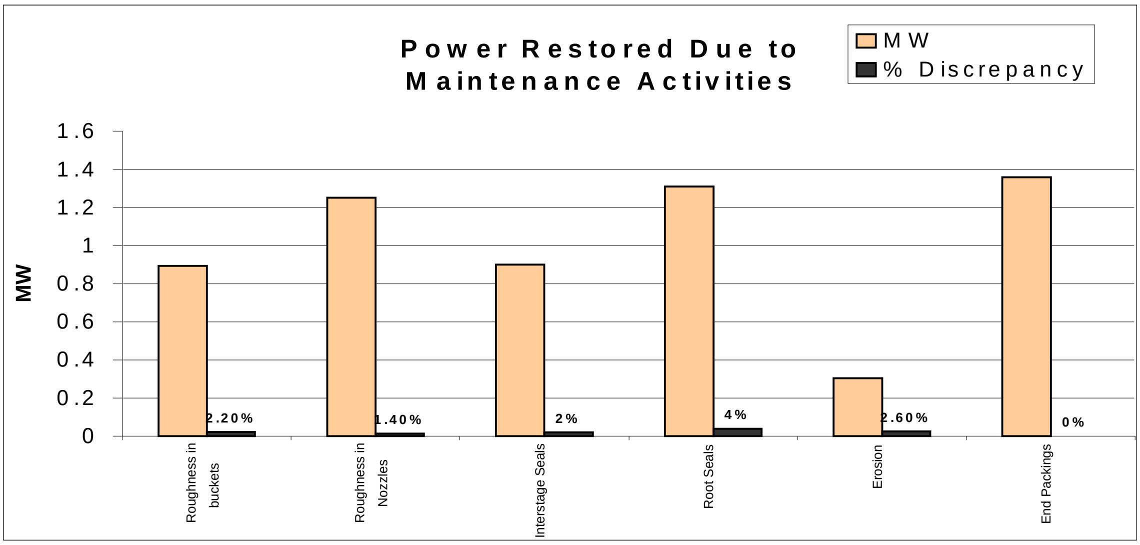


Figure 7. Results of a Typical Steam Turbine Audit, and Comparison in Percentage % of Discrepancy Occurred when Graphical Methods of LF are Used with respect a Simulated Value of LF.

Nomenclature

$\Delta h_{end\ point}$	Enthalpy Changes at Expansion Line End Point Conditions
$\Delta h_{intermediate}$	Enthalpy Changes at Intermediate Expansion Line Conditions
G	Generator Side
H	Enthalpy
HP	High Pressure Section
IP	Intermediate Pressure Section
LF	Loss Factor
LP	Low Pressure Section
P	Pressure
$P_{exhaust}$	Pressure at Steam Turbine Exhaust Condition
P_{loss}	Pressure at which Loss Occurs
Q	Heat Flow
S	Entropy
ST	Steam Turbine
θ	Internal Parameter
T	Temperature
T	Referred to Turbine Side
T_d	Dissipation Temperature
W	Shaft Work

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