UNIT COSTS ESTIMATION IN SUGAR PLANT USING MULTIPLE REGRESSION LEAST SQUARES METHOD

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ABSTRACT

Co-generation is the concept of producing two forms of energy from one fuel. One of the forms of energy must always be heat and the other may be electricity or mechanical energy. In a co-generation plant a method for establishing unit costs of delivered steam and electrical energy is presented. This method employs the use of multiple regression least squares, based on a linear model of electrical energy generation and delivered steam as functions of generated boiler steam. The model is based on a plant design that allows steam to be extracted from between stages of the generating turbines at a reduced pressure to be used to serve heating loads. A discussion of the accuracy of the method is presented as well as an example of the use of the method using one year of Sonai sugar plant production.

KEYWORDS: *Cogeneration, multiple regression least squares methods, steam generation, steam turbines, surface fitting.*

I. INTRODUCTION

Co-generation plants are extremely beneficial and cost effective for large institutions which require both heating and electrical power. This is particularly so when heating and electrical demands are well balanced and the demand for extracted steam and electrical power complement one another closely. The symbiotic nature of the simultaneous generation of steam and electricity carries with it the inherently elusive problem of assigning unit costs to each of the two types of utilities delivered.

In one way of thinking, the steam can be viewed as a by-product of electrical generation and therefore be considered essentially a "free" utility. Equally valid, or invalid, is the view that the electricity is just "skimmed off the top" of the steam delivery process, and is therefore of negligible cost. Whenever a plant has the optional capability of discharging steam from the turbines either at service pressure or at a vacuum, however, there is a definite unit value which can be assigned to both the electrical energy generated and the service steam delivered.

A mathematical model can be developed for cost as a function of both steam and electricity delivered, and the model can be fit to data from the boiler logs by the method of least squares. This provides a systematic method by which unit costs can be accurately calculated. The accurate calculation of unit costs for utilities generated from a plant are very important whenever consumption is metered and billed to differing accounts within an organization or between organizations. Multiple regression method of least square is used for calculating unit cost of steam in process and electricity. In this paper results obtained by this method are verified by analytical method of multiple regressions.

II. SUGAR PLANT DESCRIPTION

The 16 MW capacity cogeneration project at M/s. Mula Sahakari Sakhar Karkhana Ltd (MSSKL) will integrate existing sugar mill operations with enhanced energy efficiency measures and optimum usage of bagasse. During season, generated mill bagasse will be transferred to the cogeneration plant which is to be installed in the campus of existing plant located at Sonai village in (M. S.) India. The cogeneration plant will supply the heat and power requirements of the sugar mill and evacuate excess power to the state owned grid. During off-season, the power plant will use saved and procured bagasse from nearby mills for power generation. Technical detail of plant is as follows,

Plant Capacity = 17 MW
Voltage Generated = 11 K.V.
Boiler capacity = 80 tonne per hour.
Working pressure = 67 kg/cm2
Boiler temperature = 490 C
Type of boiler = water tube
Fuel = bagasse.

Power is stepped down to 433 V for supplying to sugar mill and cogeneration auxiliaries. Where as for export to the grid, it is stepped up to 132 KV. In normal mode, the STG operates in synchronisation with the Distribution Company (M.S.E.D.C.L.) grid. In event of any undesirable disturbance in the grid, the plant will island from the grid & continue supplying home load [1].

For Case study of Sonai plant in season 2007-2008 data has been taken into an account as shown in Table 1 Sonai plant delivers steam for heating, humidification, and absorption cooling of the facilities on the campus. The plant consists of one boiler/turbine units each capable of providing 67 kg exhaust steam to the campus steam distribution system. The capacity of unit is 17 M.W. Unit is capable of exhausting steam at the 67 kg /cm2extraction pressure only. In an ideally balanced situation, the amount of steam sent to the condensers is an absolute minimum and virtually all of the exhaust steam is sent to the campus heating distribution system. This type of an operating mode is the exception rather than the rule, however, as the steam and electrical loads are determined by campus demand .There exists a tradeoffs in determining the unit cost of each utility in that sending exhaust steam to the condensers, so as to generate more electricity, means forfeiting the value of the extraction steam which could have been sent to the campus distribution system. Likewise, the dispensation of steam to the campus distribution system means forfeiting electrical energy which could have been generated, had that steam been sent through the remaining stages of the turbine and been exhausted at a vacuum. The key in assigning the proper unit costs to these two utilities lies in equating their production to the common denominator of steam generated by the boilers, which we refer to as boiler steam [2].

Table1 Plant output of Season 2007-08 (07 month)

Month	Delivered Steam(Sd) MT	Electrical Energy(E) KWH	Boiler Steam(Sb) MT
Nov.07	18924	4689267	28721
Dec07	18012	4693324	28812
Jan08	18253	4678132	28184
Feb08	17528	4598764	29602
Mar08	17382	4593925	27742
Apr08	17154	4485606	27134
May08	17103	3357982	27036
Total	$\sum S_d$ **=124356**	$\sum E$ **= 1097000**	$\sum S_b$ **=197231**

All steam generated in the plant is eventually condensed and returned to the boilers as feed water. This excludes leakage, of course, and a very small amount of steam used for such non conservative loads as humidifiers and autoclaves. Makeup water must be provided for these losses, as in any plant. Table1 shows the monthly values of steam delivered to the campus as well as the overall production of boiler steam. The value given for boiler steam includes the steam used in the production of electricity that is condensed at a vacuum, as well as the steam discharged at 67 kg/cm2 and sent to the campus distribution system. For example, during the first month of November 2007 shown in Table I,

28721 MT of boiler steam was generated and 18924 MT of that steam was extracted from the steam turbines and delivered to the campus at 67 kg/cm2 for heating purposes. The remainder was condensed at a vacuum, used exclusively in the electrical generation process. On an annual averaged basis, approximately 53% of boiler steam is extracted from the turbines at 67 kg/cm2 and sent to the campus distribution system. This leaves 47% which is used in the conventional generation of electricity only.
As can be seen from the percentages given above, the demand associated with the Sonai Plant is heavily weighted toward the electrical side of the spectrum. Occasionally, additional electrical power must be purchased from Consumer's Energy, the local utility, to meet peak electrical demand. This is particularly true when boilers may be out of service for maintenance. At no time is additional steam required to be purchased or generated to meet steam demand beyond that which is available by extraction from the electrical generation process. Steam demand is therefore handled automatically by making extraction steam available to the main distribution header at a constant pressure of 67 kg/cm2 and sending the remainder of the steam through the low pressure stages of the turbines to be used in electrical generation. Other sources of condensate are not measured, including that which condenses on the distribution lines and is periodically removed by traps placed at regular intervals along the distribution piping. The rate of heat loss, or condensate generation, therefore, is not measured or calculated for the system. This topic, however, could possibly be examined in another study, using various heat loss estimation techniques and possibly even some representative measurements taken in sample locations.

III. UNIT COST ESTIMATION IN SONAI SUGAR PLANT

3.1 Modelling the plant output

In order to establish unit costs for the electrical and steam utilities, a mathematical model must be developed which accounts for the fuel consumed in terms of the utilities delivered .We know that there is a certain cost associated with operating the plant even if no utilities are generated whatsoever. The cost of salaries for the staff to operate and maintain the plant, the cost of service contracts for specialized maintenance, and any amortization costs associated with the original construction of the plant are incurred by the Plant administration whether or not the plant is even on line. These can all be lumped into a category considered as "fixed costs." The cost of the fuel for the plant is the largest single cost associated with plant operation, and a certain amount of this cost can also be attributed to the fixed cost category. A certain amount of fuel is consumed and "lost" in terms of heat losses from piping and equipment, power for lighting the plant, etc .These costs can be lumped into the fixed cost category since they also are incurred regardless of the level of plant output. Even though the fixed costs cannot be easily converted to unit costs for electrical and steam energy delivered, it is desirable to recoup these costs by charging customers unit costs for the utilities received. These costs can be easily absorbed in a unit cost for boiler steam generated and then attributed to electrical and steam unit costs from there. The overall boiler steam unit cost can be calculated by the sum of the overall plant costs per year divided by the total number of MT of boiler steam generated [3].

$$C_{bs} = \frac{A_{main} + A_{op} + A_{fuel} + ... + A_{cont}}{S_a} \quad (1)$$

Where,

C_{bs} = Unit cost of boiler steam (Rs./Ton).

A_{main} = Annual cost of plant maintenance staff

A_{op} = Annual cost of plant operating staff.

A_{fuel} = Annual cost of fuel consumed by the plant.

A_{cont} = Annual cost of contracted supplies and services

S_a = Annual amount of boiler steam generated (ton)

With a unit cost for boiler steam obtained, the unit costs of delivered steam and delivered electrical energy can then be calculated. In order to do this, the amount of boiler steam attributable to each of the two delivered utilities must be calculated. The mathematical model for making this conversion is as follows;

$$S_b = I + X_s S_d + X_e E \quad (2)$$

Where,

S_b = boiler steam required (Ton),

I = internal steam usage (Ton),

X_s = delivered steam ratio (Ton boiler steam per Ton delivered steam).

S_d = delivered steam (Ton).

X_e = electrical steam ratio (Ton boiler steam per KWH delivered electricity).

E = delivered electricity in KWH.

The known factors in this equation are S_b, S_d, and E. These are all obtainable from the monthly boiler logs. The time intervals typically used for this equation are of one month duration, since this provides a diverse range of operating conditions to average out any errors or anomalies in the records. These type of irregularities tend to have a more imbalanced effect when measured over shorter periods. Regardless of the time period used, it is important to be consistent in using the same time period for each term in the equation. The reason for this is that the parameter, internal steam usage, varies depending on the time period used; the others do not.

3.2 Multiple regression least square method.

Multiple regression estimates the outcomes (dependent variables) which may be affected by more than one control parameter (independent variables) or there may be more than one control parameter being changed at the same time. An example is the two independent variables x and y and one dependent variable z in the linear relationship case [4, 5].

$$z = a + bx + cy$$

For a given data set (x_1, y_1, z_1),,(x_2, y_2, z_2),(x_n, y_n, z_n)

Where $n \geq 3$, the best fitting curve f(x) has the least square error, i.e.,

$$z = \sum_{i=1}^{n}[z_i - f(x_i, y_i)]^2 = \sum_{i=1}^{n}[z_i - (a + bx_i + cy_i)]^2 = \min \quad (3)$$

Please note that a, b and c are unknown coefficients while all x_i, y_i, and z_i are given. To obtain the least square error, the unknown co-efficient a, b and c must yield zero first derivatives.

$$\frac{\partial \Pi}{\partial a} = 2\sum_{i=1}^{n}[z_i - (a + bx_i + cy_i)] = 0$$
$$\frac{\partial \Pi}{\partial b} = 2\sum_{i=1}^{n}x_i[z_i - (a + bx_i + cy_i)] = 0 \quad (4)$$
$$\frac{\partial \Pi}{\partial c} = 2\sum_{i=1}^{n}y_i[z_i - (a + bx_i + cy_i)] = 0$$

Expanding the above equations (4), we have

$$\sum_{i=1}^{n} z_i = a\sum_{i=1}^{n} 1 + b\sum_{i=1}^{n} x_i + c\sum_{i=1}^{n} y_i$$
$$\sum_{i=1}^{n} x_i z_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i y_i \quad (5)$$
$$\sum_{i=1}^{n} y_i z_i = a\sum_{i=1}^{n} y_i + b\sum_{i=1}^{n} x_i y_i + c\sum_{i=1}^{n} y_i^2$$

The unknown coefficients a , b and c can hence be obtained by solving the above linear equations.

3.3 Multiple regression method used for calculation.

Use of least square multiple regression method using equation 1

Equations are as follows,

$$\sum Sb = n\,I + X_s \sum S_d + X_e \sum E \quad (6a)$$

$$\sum S_d.S_b = I \sum S_d + X_s \sum S_d^2 + X_e \sum S_d.E \quad (6b)$$

$$\sum E.S_b = I \sum E + X_s \sum S_d.E + X_e \sum E^2 \quad (6c)$$

Where, n is number of months

Table 2 Calculation Chart

$S_d.S_b$	S_d^2	$S_d.E$	$E.S_b$	E^2
543516204	358117776	$8.87*10^{10}$	$1.34*10^{11}$	$2.19*10^{13}$
518961744	324432144	$8.45*10^{10}$	$1.35*10^{11}$	$2.20*10^{13}$
514442552	333172009	$8.53*10^{10}$	$1.31*10^{11}$	$2.18*10^{13}$
518863856	307230784	$8.06*10^{10}$	$1.36*10^{11}$	$2.11*10^{13}$
482211444	302133924	$7.98*10^{10}$	$1.27*10^{11}$	$2.11*10^{13}$
465456636	294259716	$7.69*10^{10}$	$1.21*10^{11}$	$2.01*10^{13}$
462396708	292512609	$5.74*10^{10}$	$9.07*10^{11}$	$1.12*10^{13}$
∑3505849144	**∑2211858962**	**$\sum 5.71*10^{11}$**	**$\sum 9.04*10^{11}$**	**$\sum 1.47*10^{14}$**

IV. RESULT AND DISCUSSION

Employing the least squares method on the sample data given in Table 2, the resulting parameters areas follows,

$97231 = 7\ I + X_s\, 124356 + X_e\, 31097000$

$3505849144 = I\, 124356 + X_s\, 2211858962 + X_e\, 5.71*10^{11}$

$9.04*10^{11} = I\, 31097000 + X_s\, 5.71*10^{11} + X_e\, 1.47*10^{14}$

By using the values of above chart in multiple regression equations we get

I =16985.84213

X_s =0.415518312

X_e =8.572502*10^{-4}

4.1 Calculation of unit costs estimation for steam and electrical demand

By using equation 1 we can calculate unit cost of steam and unit cost of electricity separately as follows

Unit Cost of Steam = C_{bs} * X_s

Unit Cost of Electricity = C_{bs} * X_e

$A_{fuel} = 93*10^7$	$A_{main} = 36*10^5$
$A_{op} = 72*10^5$	$A_{cont} = 132*10^5$
$A_{sta} = 10*10^5$	$A_{extr} = 20*10^5$
$A_{elect} = 12*10^5$	$A_{total} = 95.82*10^5$

Where,

A_{sta} is count for stationary expenses of plant

A_{elect} is count for electricity utilised by plant

A_{extr} is cost for extra work other than above

A_{total} is total cost of plant

$C_{bs} = A_{total} / S_a$

=95.82*107/197231

=4858.262646

Unit Cost of Steam = C_{bs} * X_s = (4858.262646)*(0.428896036)

=2083.689591 Rs/Tonne

= C_{bs} * X_s = 2.083 Rs/Kg

Now,

Unit Cost of Electricity = C_{bs} * X_e

= (4858.262646)*(8.23704271*10-4*103) = 4001.77 Rs/Wh

= 4.001 Rs/Kwh

4.2. Calculation of percentage relative error

Using values of I, X_s and X_e constants in equation 2 we can find percentage error monthly between calculated boiler steam production and actual boiler steam production using following formula.

$$\% \text{ error } = \{\frac{[s_b(measured) - s_b(calculated)]}{s_b(measured)}\} * 100$$

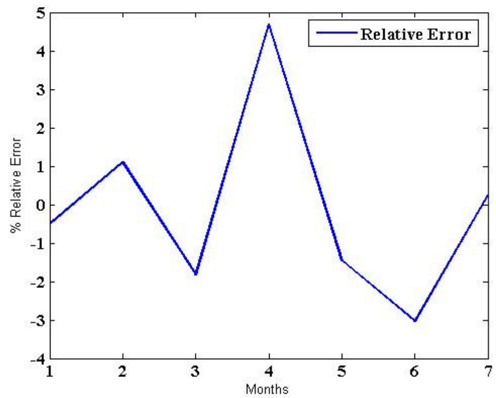

Figure1. Represents % error month wise

Figure1 shows the "residuals" from one year's (07 month) worth of data. This is the percent difference between measured boiler steam and calculated boiler steam, month by month. The errors appear to be well balanced on both sides of the axis with no characteristic signature, suggesting a good lit of the mathematical model. The standard deviation of these errors is 1.87% which is very good considering the numbers of variables which come in to power plant operation. By comparison, a trial and error procedure was used by University prior to the utilization the method of Least squares. The standard deviation of errors using this method was 4.69%. The method of least squares clearly provides more accurate solutions for the parameters which allow the mathematical model to more closely conform to the physical measurement.

V. CONCLUSION

In Cogeneration plant there is simultaneous production of heat and electricity whatever steam is produced in boiler is used for sugar process and electricity generation. That means steam generated in boiler is a linear function of steam used in sugar process and for electricity. Multiple regression method of least square is used to calculate the unit cost of steam used in sugar process and electricity. Without a systematic method for evaluating the unit costs of steam and electricity delivered from a co-generation power plant, there figures can be very difficult to obtain.

When a mathematical model is developed and fitted to a data taken from boiler logs, the unit cost of each utility can be accurately computed. The method of least squares allows the errors to be minimized between calculated and measured boiler steam delivery rates. The accuracy of this comparison gives assurance that the model is appropriate and that the unit costs have been arrived at correctly. The accurate unit cost of steam delivered and unit cost of electricity calculation becomes very simple by use of multiple regression method.

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