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Heat rate curve approximation for power plants without data measuring devices

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Abstract
In this work, a numerical method, based on the one-dimensional finite difference technique, is proposed for the approximation of the heat rate curve, which can be applied for power plants in which no data acquisition is available. Unlike other methods in which three or more data points are required for the approximation of the heat rate curve, the proposed method can be applied when the heat rate curve data is available only at the maximum and minimum operating capacities of the power plant. The method is applied on a given power system, in which we calculate the electricity cost using the CAPSE (computer aided power economics) algorithm. Comparisons are made when the least squares method is used. The results indicate that the proposed method give accurate results.

Keywords: Power systems; Power economics; Heat rate curve; Electricity unit cost.

1. Introduction

Power plant performance is described by the input-output curve derived from tests of the individual equipment [1]. Figure 1 shows the general trend of such curve, which follows the approximate form defined by the polynomial:

$$\bar{I}_i = \sum_{j=1}^{n} c_j L_i^{j-1} \tag{1}$$

where $\bar{I}_i$ is the approximation of the input energy in kJ at various load values i, $i = 1, 2, 3, ..., m$, c_j, $j = 1, 2, 3, ..., n$ are unknown coefficients of the $n-1$ polynomial and L_i is the electrical energy output in kWh at various load values i, $i = 1, 2, 3, ..., m$.

At zero load (L=0) the positive intercept for I measures the amount of energy required to keep the apparatus functioning. This energy dissipates as frictional and heat losses. Any additional input over the no-load input produces a certain output, the magnitude depending upon the machine. All additional input does not appear as output, owing to partial dissipation as losses [2]. From the basic input-output curve the more familiar heat rate curve may be derived [5].
The heat rate, *HR*, curve in kJ/kWh, is derived by taking at each load the corresponding input, that is,

$$HR = \frac{I}{L} \tag{2}$$

The above can be expressed also mathematically. By using equation (1) then

$$\overline{HR}_i = \frac{I_i}{L_i} = \sum_{j=1}^{n} c_j L_i^{j-2} \tag{3}$$

where $\overline{HR}_i$ is the heat rate approximation given by an $n-2$ polynomial.

The objective of this paper is to develop a numerical approximation to the heat rate curve when data is available only at the maximum and minimum operating capacities of a given power plant. The method is based on the one-dimensional finite difference technique. Using the Computer Aided Power Economics (CAPSE) algorithm, the method is applied for the calculation of the electricity cost for a given power system.
In section 2, both the least-squares method and the finite difference method for heat rate curve approximation are presented and compared. In section 3, the main features of the CAPSE algorithm are illustrated and the results obtained are discussed. The conclusions are summarized in section 4.

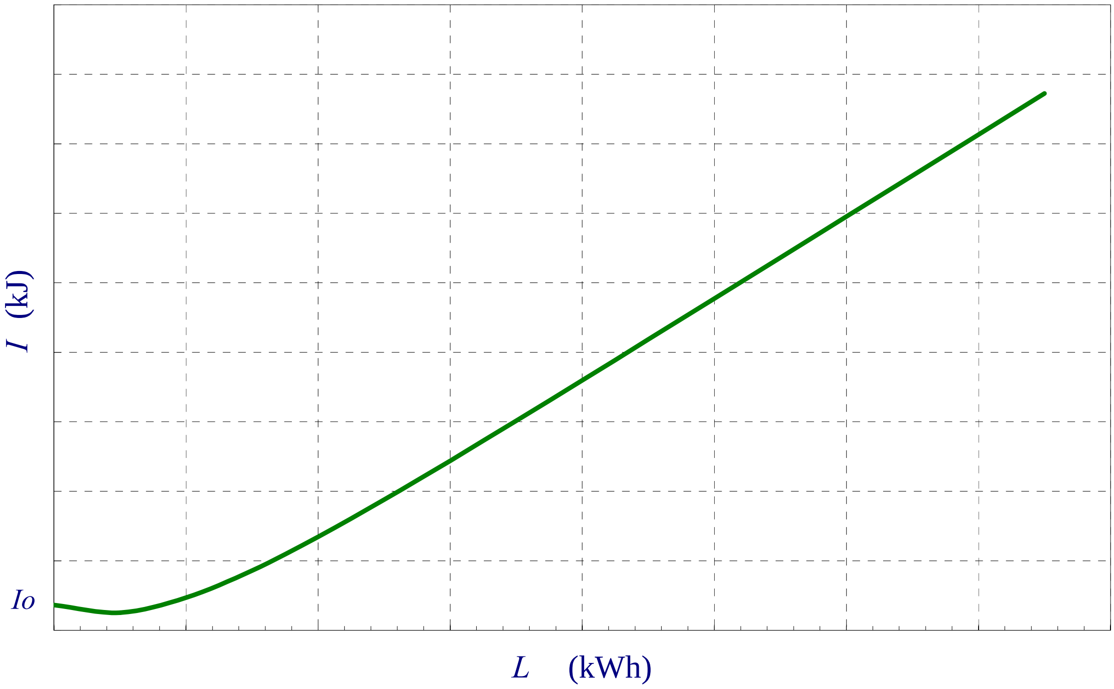

Figure 1. Input – output curve

2. Heat rate curve approximation

The most common method for heat rate curve approximation is the least squares fitting method. Suppose that we are fitting *m* data points or measurements (based on measurements or on the design parameters of the equipment) to a model, which has *n* adjustable parameters. The model predicts a functional relationship between the measured independent and dependent variables:

$$\mathbf{HR} = f(\mathbf{L};\mathbf{c}) \tag{4}$$

We assume that the solution **HR** is approximated by a model, which is a linear combination of any *n* unknown coefficients $\mathbf{c} = [c_1, c_2, ..., c_n]^T$. We also choose *m* to represent the number of load values on which the approximation will be based on and, therefore, $\mathbf{L} = [L_1, L_2, ..., L_m]^T$. We seek the following approximation of the solution for a load value L_i:

$$\overline{HR}_i(\mathbf{c}) = \sum_{j=1}^{n} c_j L_i^{j-2} \quad (5)$$

Since $\overline{HR}$ satisfies (4), the unknown coefficients are determined by least squares approximation. To achieve this we minimize the functional [6],

$$F(\mathbf{c}) = \sum_{i=1}^{m} \left(\overline{HR}_i - HR_i\right)^2 \quad (6)$$

where $\overline{HR}_i$, in kJ/kWh, is the heat rate approximation for the load value C_i, in kWe.

Least-squares method requires three or more data points in order to approximate the heat rate curve. However, sometimes power plants have no data measuring devices available and the heat rate data points are known only at minimum and maximum operating capacities. If this is the case, the one-dimensional finite difference method can then be applied. We assume that the heat rate at minimum operating capacity is given by $HR_{\min}$ and at maximum operating capacity by $HR_{\max}$. Then using finite differences, the approximated heat rate curve can be obtained by,

$$\overline{HR}_i = \overline{HR}_{i-1} - \frac{\overline{HR}_{i-1} - HR_{\max}}{S} \quad (7)$$

where $\overline{HR}_i$ is the heat rate approximation at heat rate curve point *i* and *S* is the step of the approximation which can take values based on the required accuracy.

Both of the above approximations were applied for the approximation of the heat rate curve shown in Figure 2, which represents the performance of a 120MWe steam turbine [3]. We observe that least squares fitting method gives very accurate results, however, in order to use such method at least three values of the heat rate curve must be known a priori. The finite differences method give accurate results with a maximum absolute error of 0,33%. A second example is shown in Figure 3, in which, data from a 30MWe steam turbine have been used. As before, we observe that the least squares fitting method gives very accurate results. The finite differences method give results with a maximum absolute error of 4,55%.

3. Simulation of a given power system

In order to calculate the end effect on the electricity cost, when the finite difference method is used for the heat rate curve approximation, a given power system is simulated using the CAPSE algorithm. This is a user-friendly software tool which takes into account the daily loading of each generator, the fuel consumption and cost, and operation and maintenance (O&M) requirements of each generator and calculates the electricity cost of each generator and the total cost of the power system.

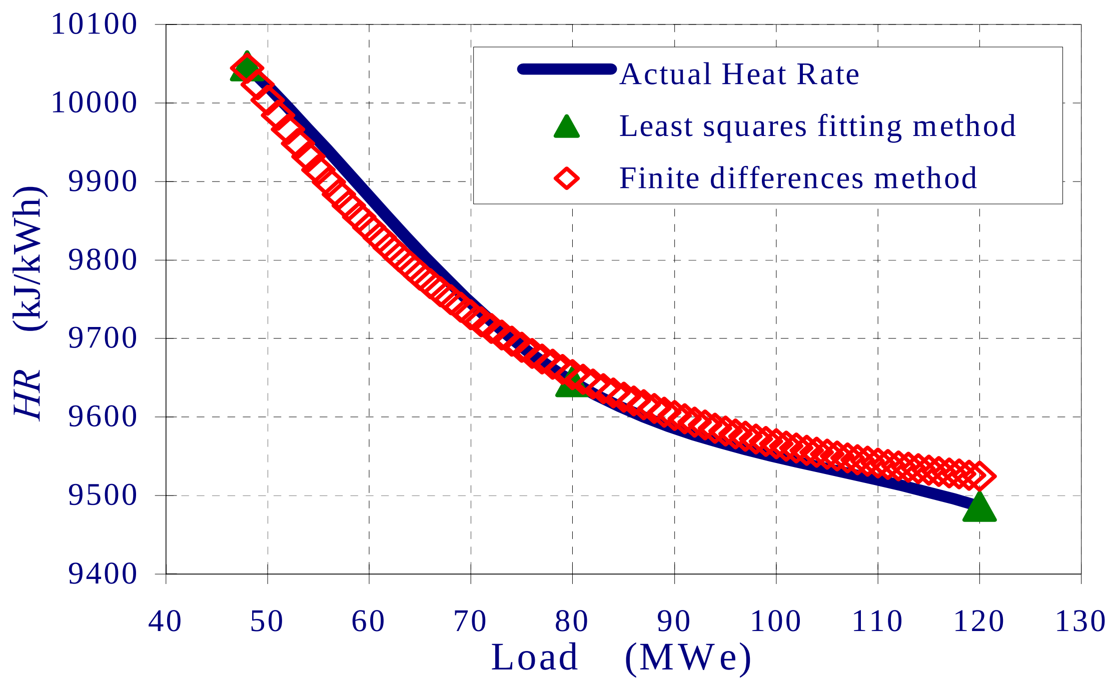

Figure 2. Example one; heat rate curve approximation

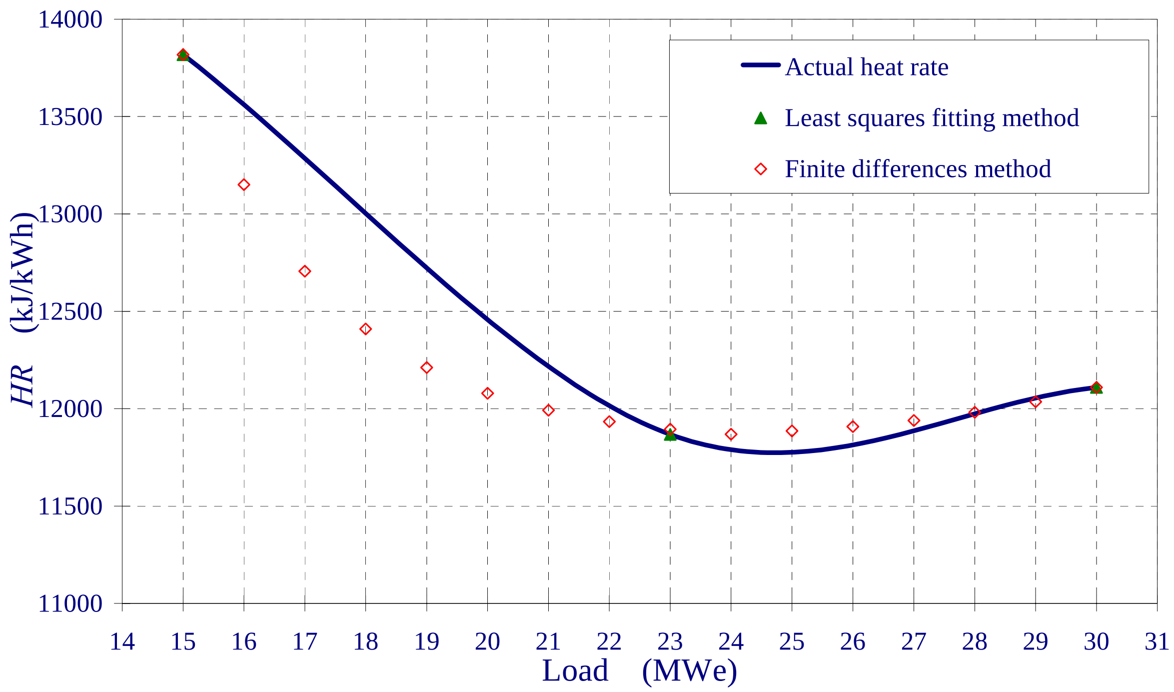

Figure 3. Example two; heat rate curve approximation

The generated electrical energy E_{ij} in kWh, by each generator i at a given loading at a point j, is given by:

$$E_{ij} = PL_{ij} \times T_{ij} \tag{8}$$

where PL_{ij} is the loading at point j of generator i in kWe during the time period T_{ij} (i.e., for every 15 minute, T_{ij} = 0,25). The daily production of electricity is given by;

$$E = \sum_{j=1}^{m}\sum_{i=1}^{n} E_{ij} = \sum_{j=1}^{m}\sum_{i=1}^{n} PL_{ij} \times T_{ij} \tag{9}$$

where m is the total number of time periods (i.e., for every 15 minutes, m=96) and n is the number of generators.

The cost of fuel CF_{ij} in US$ is calculated by:

$$CF_{ij} = \frac{F_i \times HR_{ij} \times E_{ij}}{CV_i} \tag{10}$$

where F_i is the fuel specific cost in US$/kg and CV_i is the fuel calorific value in kJ/kg. The heat rate HR_{ij}, which is measured in kJ/kWh can be approximated using either the least-squares or the finite difference.

The daily fuel cost can then be determined by

$$CF = \sum_{j=1}^{m}\sum_{i=1}^{n} CF_{ij} = \sum_{j=1}^{m}\sum_{i=1}^{n} \frac{F_i \times HR_{ij} \times E_{ij}}{CV_i} \tag{11}$$

The specific O&M cost is composed of two components, namely, the fixed O&M cost and the variable O&M cost. The fixed O&M costs include staff costs, insurance charges, rates and fixed maintenance. The variable O&M costs include spare parts, chemicals, oils, consumables, town water and sewage. The O&M cost in US$ is given by

$$COM_{ij} = COMF_{ij} + COMV_{ij} \tag{12}$$

where $COMF_{ij}$ is the fixed O&M cost in US$ and $COMV_{ij}$ is the variable O&M cost in US$. The fixed O&M cost can be obtained by the relation

$$COMF_{ij} = 1{,}37 \times 10^{-3} \times OMF_i \times E_{ij} \times \frac{PC_i}{PL_{ij}} \tag{13}$$

where PC_i is the installed capacity of the generator i in kWe and OMF_i is the fixed O&M cost in US$/kW-month. The variable O&M cost is given by

$$COMV_{ij} = OMV_i \times E_{ij} \tag{14}$$

where OMV_i is the specific variable O&M cost in US$/kWh. The daily specific O&M cost can be obtained by

$$COM = \sum_{j=1}^{m}\sum_{i=1}^{n} COM_{ij} = \sum_{j=1}^{m}\sum_{i=1}^{n} \left(COMF_{ij} + COMV_{ij}\right) \tag{15}$$

The electricity production cost in US$ is given by:

$$CM = CF + COM \tag{16}$$

The CAPSE algorithm implementing the above mathematical formulation takes into account the available capacity of each generator, the daily loading (every 15 minutes) of each generator, the fuel cost of each generator, the calorific value of each fuel, the approximated heat rate curve of each generator and the O&M cost of each generator. The electricity production cost can then be determined for each generator and for the power system.

Estimates have been prepared for a small power system with available capacity of 487MWe. The power system technical and economic parameters used [4] in this example are shown in Table 1. The one day 15 minutes-loading schedule used, for each generating unit, is presented in Figure 4. The heat rate curves have been approximated using either the least squares or the finite difference methods. The results obtained are shown in Table 2. Comparing the results obtained when the least squares method is used for the approximation of the heat rate curve with that obtained when the proposed finite difference method is used we observe that are in good agreement with an overall maximum error of 0,8%.

Table 1. Power system technical and economic parameters

Power plant	Fuel	Available capacity	Fuel		Heat rate		O&M	
			Cost	*C.V.*	Minimum	Maximum	Fixed	Variable
		MWe	US$/tonne	kJ/kg	kJ/kWh		US$/kWe-month	US$/MWh
Steam turbine 1	Heavy fuel oil	60	100	42200	11400	10990	1,53	0,83
Steam turbine 2	Heavy fuel oil	60	100	41800	11260	10832	1,50	0,53
Steam turbine 3	Heavy fuel oil	60	135	42100	11303	10980	1,54	0,64
Steam turbine 4	Heavy fuel oil	60	135	42400	11300	10904	1,51	0,55
Steam turbine 5	Heavy fuel oil	60	135	42000	11302	10906	1,51	0,56
Steam turbine 6	Heavy fuel oil	30	80	42000	12000	11806	3,03	2,54
Steam turbine 7	Heavy fuel oil	30	120	42600	12057	11816	3,03	2,56
Steam turbine 8	Heavy fuel oil	30	120	42600	12007	11898	3,09	2,51
Steam turbine 9	Heavy fuel oil	30	80	42900	12200	11871	3,08	2,58
Steam turbine 10	Heavy fuel oil	30	80	42600	11777	11537	3,07	2,54
Gas turbine 1	Gasoil	37	230	45000	16290	11842	0,18	0,77

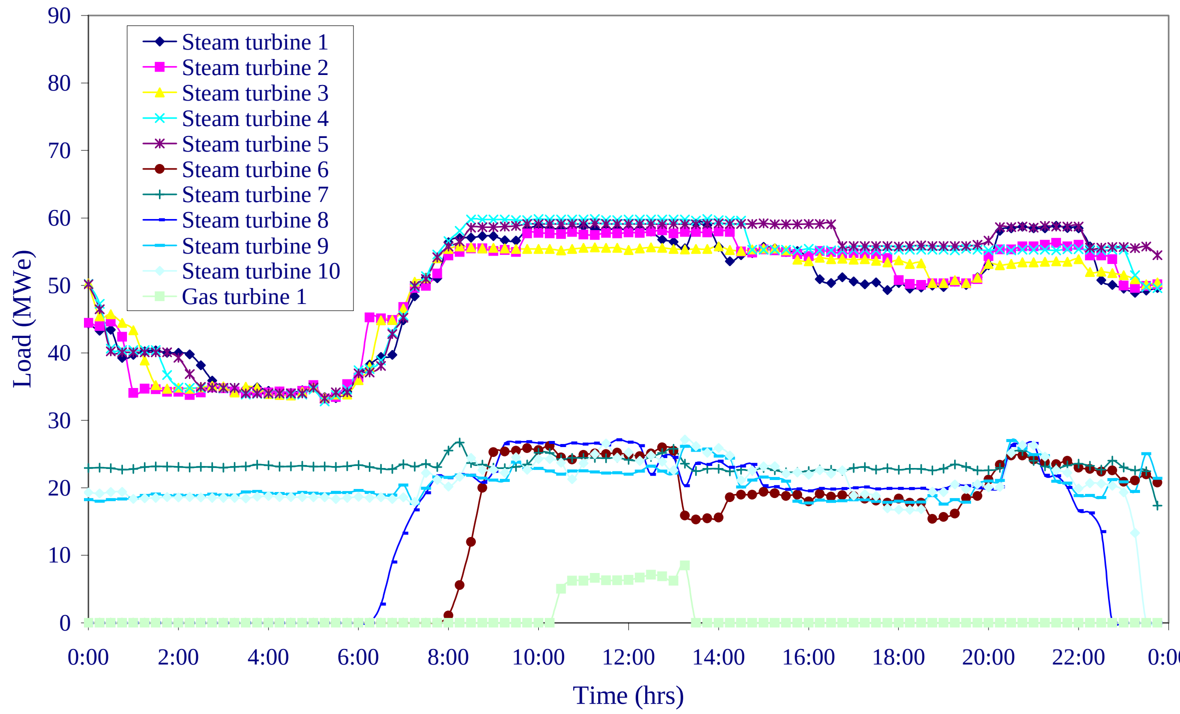

Figure 4. One day, 15 minutes-loading schedule of each generating unit

Table 2. Power system economics

Power plant	Generation	Least squares method		Finite difference method		Absolute error
		Total cost	Specific cost	Total cost	Specific cost	
	MWh	US$	USc/kWh	US$	USc/kWh	%
Steam turbine 1	1189	36114	3.0373	36118	3.0377	0.01
Steam turbine 2	1187	35568	2.9965	35572	2.9968	0.01
Steam turbine 3	1177	46466	3.9478	46475	3.9486	0.02
Steam turbine 4	1220	47549	3.8975	47593	3.9011	0.09
Steam turbine 5	1237	48625	3.9309	48658	3.9335	0.07
Steam turbine 6	329	10340	3.1429	10459	3.1790	1.15
Steam turbine 7	559	23400	4.1860	23512	4.2061	0.48
Steam turbine 8	350	12698	3.6280	12711	3.6317	0.10
Steam turbine 9	492	15509	3.1522	15453	3.1409	0.36
Steam turbine 10	494	12180	2.4656	12093	2.4480	0.71
Gas turbine 1	20	1769	8.8450	1798	8.9900	1.64
Power system	8254	290218	3.5161	290442	3.5188	0.08

4. Conclusion

In this work, a numerical method, based on the one-dimensional finite difference technique, was proposed for the approximation of the heat rate curve. This method can be applied for power plants in which no data acquisition is available. Unlike other methods in which three or more data points are required for the approximation of the heat rate curve, the proposed method can be applied when the heat rate curve data is available only at the maximum and minimum operating capacities of the power plant. The method was applied on a given power system, in which the electricity cost using the CAPSE algorithm was calculated. The results indicate that the proposed method give accurate results.

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