การใช้ Economic Dispatch สำหรับ Incremental Cost ที่เป็นสมการเชิงเส้นที่มีความชันเป็นลบ และสมการลักษณะขั้นบันไดในประเทศไทย

USE OF ECONOMIC DISPATCH WITH LINEAR DECREASING AND STAIRCASE INCREMENTAL COST FUNCTIONS IN THAILAND

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บทคัดย่อ

ในปัจจุบันโปรแกรม Economic Dispatch ที่เป็นส่วนหนึ่งของ Automatic Generation Control (AGC) ที่อยู่ในการควบคุมของ ศูนย์ควบคุมระบบกำลังไฟฟ้าแห่งชาติ การไฟฟ้าฝ่ายผลิตแห่งประเทศไทย (กฟผ.) ได้ถูกพัฒนาขึ้นเพื่อใช้สำหรับสมการ Incremental Cost (IC) ที่มีความชันมากกว่าหรือเท่ากับศูนย์เท่านั้น ซึ่งทำให้การใช้งานเป็นไปอย่างจำกัด บทความนี้เสนอวิธีการพัฒนา Economic Dispatch เพื่อที่จะรองรับสมการเชิงเส้น IC ที่มีค่าลดลงที่เมกะวัตต์สูงขึ้น (ความชันเป็นลบ) ของโรงไฟฟ้าพลังความร้อนร่วมและสมการลักษณะขั้นบันไดของทั้งโรงไฟฟ้าพลังความร้อนและโรงไฟฟ้าพลังความร้อนร่วม โรงไฟฟ้าพลังความร้อนร่วมหนึ่งบล็อกประกอบด้วยกังหันก๊าซตั้งแต่หนึ่งหน่วยขึ้นไปและหน่วยผลิตไอน้ำ บล็อกพลังความร้อนร่วมใช้ก๊าซไอเสียอุณหภูมิสูงจากกังหันก๊าซมาผลิตไอน้ำเพื่อที่จะขับเครื่องกำเนิดไฟฟ้าพลังความร้อน สมการขั้นบันไดดังกล่าวเป็นส่วนหนึ่งของสัญญาซื้อขายไฟฟ้าระหว่าง กฟผ. และผู้ผลิตไฟฟ้าอิสระรายแรกของประเทศ (Independent Power Producer) ในการหาคำตอบ Economic Dispatch เราแบ่งโรงไฟฟ้าทั้งหมดออกเป็น 2 กลุ่ม คือ กลุ่มโรงไฟฟ้าพลังความร้อน และ กลุ่มโรงไฟฟ้าพลังความร้อนร่วม เนื่องจากตัวคูณลากรังซ์จ (LeGrangian Multiplier หรือ Lambda) ต่ำสุดของกลุ่มโรงไฟฟ้าพลังความร้อนมีค่าสูงกว่า Lambda สูงสุดของกลุ่มโรงไฟฟ้าพลังความร้อนร่วม กลุ่มโรงไฟฟ้าพลังความร้อนจะใช้วิธี Binary Search (BS) ในการหา Lambda

ที่เท่ากันทุกหน่วยผลิตเนื่องจากสมการ Lambda มีค่าเพิ่มขึ้นเมื่อเมกะวัตต์สูงขึ้น หรือ เป็นสมการลักษณะขั้นบันได ในขณะที่กลุ่มโรงไฟฟ้าพลังความร้อนร่วมใช้วิธี Merit Order Loading (MOL) โดยใช้ค่า Lambda ต่ำสุดที่เมกะวัตต์สูงสุดของแต่ละ Block พลังความร้อนร่วมเป็นดัชนีในการกำหนดลำดับการเดินเครื่อง สำหรับสมการ Lambda ที่มีค่าลดลงเมื่อเมกะวัตต์สูงขึ้นหรือสมการลักษณะขั้นบันได แนวทางที่พัฒนานี้ได้ถูกทดสอบบนโรงไฟฟ้าที่มี IC ที่เป็นสมการเชิงเส้นที่มีค่าลดลงที่เมกะวัตต์สูงขึ้นและสมการลักษณะขั้นบันได คำตอบของวิธีที่นำเสนอเหมาะสำหรับการนำไปใช้ในการควบคุมการผลิตไฟฟ้า งานวิจัยนี้ได้มูลเหตุจูงใจจากปัญหาการวางแผนการผลิต และการปฏิบัติการแบบ On-line ของ กฟผ. ในปัจจุบัน

ABSTRACT

At present, the power economic dispatch program, part of the on-line Automatic Generation Control (AGC), controlled by National Control Center, Electricity Generation Authority of Thailand (EGAT), has been developed for monotonically increasing incremental cost (IC) curves only, which results in limited flexibility. This paper presents methods to find the solution of economic dispatch with linear decreasing IC curves for existing combined-cycle (CC) blocks, and staircase IC curves for both thermal units and CC blocks. A single CC block consists of one or more gas turbine units and a steam unit. The CC block uses high temperature exhaust gas from turbines to generate steam that is used to drive a steam turbine generator. Those staircase curves are introduced as a result of the transaction agreement between the first Independent Power Producer (IPP) in Thailand and EGAT. To obtain the economic dispatch solution, we initially divide the total units into two sections: thermal section and CC section. We then treat each section separately since the lowest lambda (LaGrangian multiplier) of the thermal section is higher than the highest lambda of the CC section. The thermal section uses the binary search (BS) algorithm to determine the optimal solution based on the equal lambda principle for either monotonically increasing lambda curves or increasing staircase lambda curves. On the other hand, the CC section uses the Merit Order Loading (MOL) method with the lowest lambda at the highest operating output of each CC block as our index for either linear decreasing lambda curves of staircase lambda curves. The implementation of the developed program has been done on a test system consisting of linear decreasing IC curves for CC blocks, and staircase IC curves for both CC blocks and thermal units. The solution of the proposed method is valid and practical for on-line application. This research is motivated by the actual on-line operational and planning problems of EGAT.

1. INTRODUCTION

Economic dispatch (ED) is a problem of determining the operation schedule of generation units such that the operating cost is minimized, while satisfying the constraints such as power balance equation, upper and lower operating limits. In the Thailand's present situation, ED program, one of the on-line programming modules on a Cyber machine located at the National Control Center, Electricity Generating Authority of Thailand (EGAT), is limited in flexibility since it can handle only monotonically increasing incremental cost (IC) curves. More specifically, the existing ED program cannot accept linear decreasing IC curves and staircase IC curves. Currently, a gap between the total scheduled generation capacity and the lowest load demand in Thailand is not large, thus the combined-cycle (CC) blocks, whose IC curve is a linear decreasing function, are always scheduled at their maximum operating output to serve the base load without the need to reduce their generation during the light load. As a result, excluding the CC plants from the ED program will have no effect on the optimal scheduling [1]. In 1996, the staircase IC curves of the thermal and CC blocks were introduced in the energy transaction agreement between the first Independent Power Producer (IPP) and EGAT. In the next few years, it is expected that there will be more IPPs including the existing CC plants to be privatized by EGAT. Since it may be necessary to vary the CC output in an economical manner, there is a need to develop an ED program which can handle all types of IC curves such as monotonically increasing IC curves, linear decreasing IC curves, and staircase IC curves.

Economic dispatch with non-monotonically continuous IC functions has been investigated by using the Newton method [2]. The proposed method is not applicable to our system due to the present of staircase IC functions. In [3], they proposed the hierarchical ED for multiple piecewise quadratic cost functions of different fuel types to obtain the least production cost. However, the algorithm was developed for increasing IC functions only. In this paper, we present methods to solve the ED problem with monotonically increasing IC curves, linear decreasing IC curves, and staircase IC curves by initially dividing the total generating units into two sections: thermal section and CC section. We treat each section separately since the lowest lambda of the thermal section is higher than the highest lambda of the CC section. The thermal section includes either monotonically increasing lambda curves or increasing staircase lambda curves, while the CC section includes either linear decreasing lambda curves or staircase lambda curves. In the thermal section, the optimal dispatch rule is that all generating units are operating at the same lambda, in which we use the binary search (BS) algorithm to obtain the least production cost [4]. In the CC section, the equal lambda principle is no longer applicable because the production cost of CC blocks increases at a slower rate as the output is higher. Therefore, we propose the Merit Order Loading (MOL) method using the lowest lambda at the highest output of each CC block as our index. Comparison between the MOL using the lowest lambda at the highest output and using lambda at the lowest output indices is made on a test system consisting of staircase IC curves, and linear decreasing IC curves.

The second section of the paper illustrates types of generating cost functions used in the calculation of production cost at EGAT. The third section proposes solution methods for ED to solve monotonically increasing lambda curves, linear decreasing lambda curves, and staircase lambda curves. The fourth section renders the test results and the analysis of two case studies. Finally, the fifth section summarizes the paper.

2. TYPES OF GENERATION COST FUNCTIONS

A generation cost function (Baht/hr) is determined by the product of a heat input/output function (Mbtu/hr) and a fuel cost (Baht/Btu). In Thailand's power system, generation cost functions are generally categorized into four types:

2.1 Second Order Polynomial Cost Function for Thermal Unit

To obtain a second order polynomial cost function for a thermal unit, we fit the curve using the least square method among at least three test points, for example, 50%, 75% and 100 % of the highest output. The cost function is a quadratic type ($aP^2 + bP + c$) where the coefficient $a \geq 0$, or the IC ($2aP+b$) is a linear increasing function as illustrated in Figure 1.

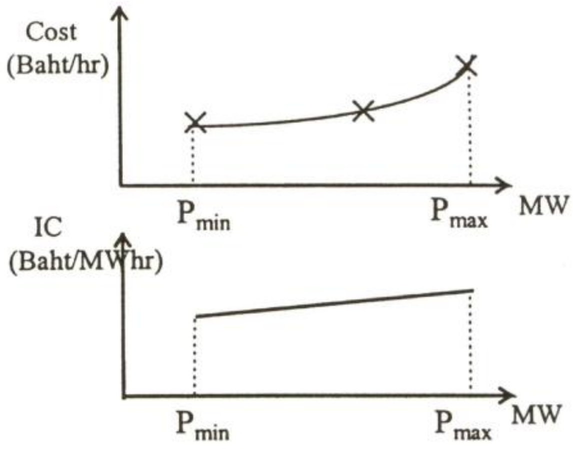

Figure 1 Quadratic Cost Curves and Their IC of a Thermal Unit

2.2 Piecewise Linear Cost Function for Thermal Unit

For convenience, we may represent a cost function for thermal unit by two straight lines connecting through three test points instead of using curve-fitting by the least square method. The piecewise linear cost curve and its increasing staircase IC curve are as follows:

$$
\begin{aligned}
Cost(P) &= a_1P+b_1, & P_{min} \leq P \leq P_{int}, \\
&= a_2P+b_2, & P_{int} \leq P \leq P_{man}, \\
IC(P) &= a_1, & P_{min} \leq P \leq P_{int}, \\
&= a_2 & P_{int} \leq P \leq P_{max}.
\end{aligned}
$$

where $a_2 > a_1$. The corresponding curves are given in Figure 2.

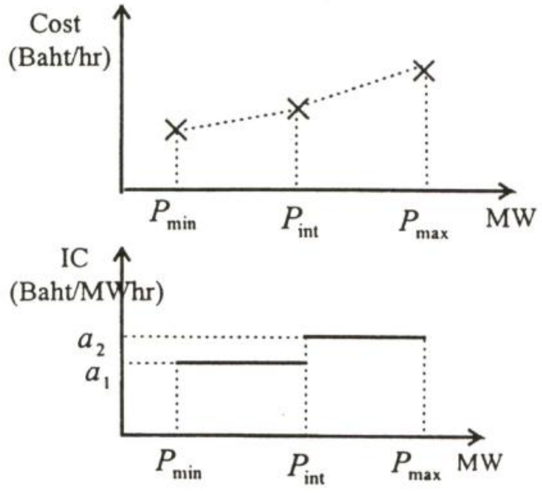

Figure 2 Piecewise Linear Cost Curves and Their IC of a Thermal Unit

2.3 Second Order Polynomial Cost Function for CC Block

A CC block may consist of one or more gas turbine units and a steam unit. In a closed-cycle operational mode, the cost function is obtained by curve-fitting among at least three test points using the least square method. Its cost function is represented by a second order polynomial function aP^2+bP+c, where $a < 0$, which results in a linear decreasing IC function $(2aP+b)$ as illustrated in Figure 3. This phenomenon is explained by the following characteristic of the CC block; the higher the output, the better the efficiency.

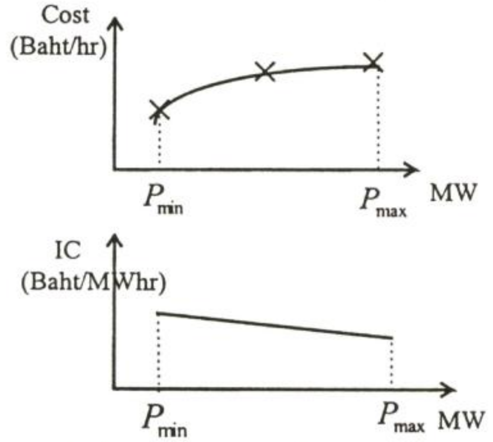

Figure 3 Quadratic Cost Curves and Their IC of a CC Block

2.4 Piecewise Linear Cost Functions for CC Block

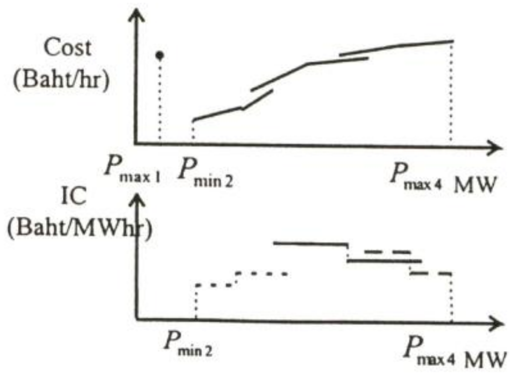

Figure 4 Piecewise Linear Cost Curves and Their IC of a CC Block

To obtain an accurate representation, we, instead of using only one quadratic equation to represent the cost function of CC block, may employ several piecewise linear functions to represent cost functions for each mode of closed-cycle operation. For instance, a CC block consisting of four turbine units and a steam unit can have four modes of closed-cycle operation. Note that one mode of operation may consist of one or two linear curves, and the output of each mode of operation may overlap among one another. The cost functions and their corresponding staircase IC curves are illustrated in Figure 4.

3. SOLUTION METHODS OF ECONOMIC DISPATCH

In Thailand's present system, the lowest lambda of the thermal plants is higher than the highest lambda of the CC plants. Thus, we initially divide the total generating units into two sections : thermal section and CC section, and treat each section separately. To obtain the economic dispatch solution for the thermal section, we use the BS algorithm based on the equal lambda principle since the lambda curves are either monotonically increasing function or increasing staircase function. On the other hand, for the CC section, we use the MOL method with the lowest lambda at the highest output of each CC block as our index since lambda curves are either linear decreasing function or staircase function.

3.1 Economic Dispatch for Monotonically Increasing IC Curves (Thermal Section)

The economic dispatch problem is to minimize the following objective function,

$$C_T^T = \sum_{i=1}^{NT} C_i(P_i^T)$$

subject to a power balance constraint,

$$TGTBD = \sum_{i=1}^{NT} P_i^T = P_D + P_L - \sum_{i=1}^{NC} P_{i,\max}^C,$$

and an operating limits constraint,

$$P_{i,\min}^T \le P_i^T \le P_{i,\max}^T,$$

where

C_T^T : Total thermal operating cost (Baht/hr),

$C_i(P_i^T)$: Operating cost of thermal unit i (Baht),

P_i^T: Real power output of thermal unit i (MW),

P_D : Total load demand (MW),

P_L : Total loss (MW),

$TGTBD$: Thermal generation to be dispatched (MW),

NT : Number of thermal units on ED,

NC : Number of CC units on ED,

$P_{i,\min}^T$, $P_{i,\max}^T$: Minimum and maximum operating outputs of thermal unit i (MW),

$P_{i,\max}^C$: Maximum operating output of CC block i (MW).

The optimal dispatch rule is:

$$IC_i^T \times l_i^T = \lambda, \ i = 1,..,NT,$$

$$\sum_{i=1}^{NT} P_i - P_D - P_L + \sum_{i=1}^{NC} P_{i,\max}^C = 0.$$

where

IC_i^T : $\frac{dC_i}{dP_i^T}$ or IC of thermal unit i (Baht/MWhr),

l_i^T : Penalty factor of thermal unit i,

λ : LaGrangian multiplier (lambda).

If I^T is a set containing the thermal units operating between operating limits, L^T is a set containing the units operating at their lower operating limits, and U^T is a set containing the units operating at their upper operating limits, the optimal dispatch rule is extended as:

$$IC_i^T \times l_i^T = \lambda, \ i \in I_i^T$$

$$IC_i^T|_{P_{i,\min}^T} \times l_i^T \ge \lambda, \ i \in L^T,$$

$$IC_i|_{P_{i,\min}^T} \times l_i^T \le \lambda, \ i \in U^T.$$

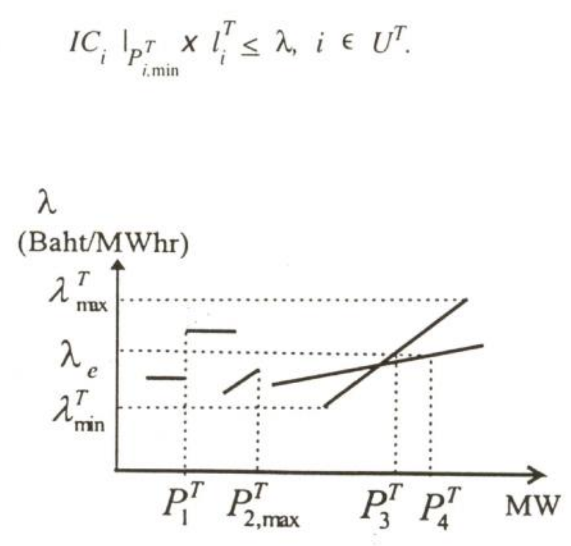

Figure 5 System Lambda of Thermal Section

Note that we shall perform the economic dispatch in the thermal section only when all CC blocks operate at their maximum operating outputs.

Figure 5 shows the IC or lambda of four steam units. The lambda function of the first unit is a staircase type with two steps. At λ_e,

$TGTBD = P_1^T + P_{2,\max}^T + P_3^T(\lambda_e) + P_4^T(\lambda_e).$

3.2 Economic Dispatch for Linear Decreasing IC Curves (CC Section)

In the CC section, we shall need to minimize the following objective function:

$$C_T^C = \sum_{i=1}^{NC} C_i(P_i^C)$$

subject to a power balance constraint,

$$CCGTBD = \sum_{i=1}^{NC} P_i^C = P_D + P_L - \sum_{i=1}^{NC} P_{i,\min}^T,$$

and an operating limits constraint,

$$P_{i,\min}^C \leq P_i^C \leq P_{i,\max}^C,$$

where

C_T^C : Total CC operating cost (Baht/hr),

$C_i(P_i^C)$: Operating cost of CC block i (Baht),

P_i^C: Real power output of CC block i (MW),

$P_{i,\min}^C$: Minimum operating output of CC block i (MW),

$CCGTBD$: CC generation to be dispatched (MW).

We shall perform the economic dispatch in the CC section only when all thermal units operate at their minimum operating outputs. Since the lambda curve of a CC block is a linear decreasing function, the equal lambda principle will no longer yield the least production cost as a result of the characteristic of the CC block; the higher the output, the lower the incremental cost. The recommendation is that we should schedule the CC blocks in such a way that they operate at their highest output (corresponding to the lowest lambda). The proposed method is the MOL method using the lowest lambda at the highest output of each CC block as our index. On the MOL list, we order the CC blocks according to the ascending order of lambda. As the system load increases, we incrementally load the first linear decreasing curve on the list until the power balance is satisfied. If the first curve reaches the operating upper limit and the power balance is still not satisfied, we shall load the next one on the list, and so on. For an example, consider the lambda curves of three CC blocks which are given in Figure 6. The ascending order of MOL list is CC blocks 1, 2 and 3 since $\lambda_{1,\min}^C < \lambda_{2,\min}^C < \lambda_{3,\min}^C$.

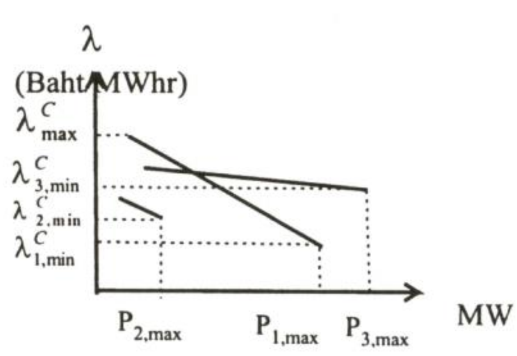

Figure 6 System Lambda of CC Section

4. TEST RESULTS AND ANALYSIS

4.1 Case Studies

We use the Rayong power plant consisting of four CC blocks (RY2_CC#1, 2, 3, 4) whose lambda curves are linear decreasing functions, and the Khanom power plant which consists of two thermal units (KN_T#1, 2), and a CC block (KN_CC#1) whose lambda curves are staircase functions as our test data (see Figure 7)

Case I : We use the lowest lambda at the *highest* operating output for each CC block (excluding those staircase lambda curves) as our index in the MOL method. In addition, if the lowest lambda at the highest output of the next CC block on the list is higher than any constant lambda segment belonging to the staircase curves, we shall incrementally load that constant lambda segment instead. Hence, the ascending order of CC blocks in Case I is: RY2_CC#2, RY2_CC#4, RY2_CC#1, KN_CC#1.2-1.3, RY2_CC#3, KN_CC#1.4-1.7.

Case II : For a comparison purpose, we use the lambda at the *lowest* operating output for each CC block as our index in the MOL method. Similarly, the ascending order of CC blocks in Case II is: KN_CC#1.2-1.3, RY2_CC#3, KN_CC#1.4-1.7, RY2_CC#2, RY2_CC#4, RY2_CC#1 when we include the constant lambda segments of staircase curves.

For the increasing staircase lambda of thermal units (KN_T#1, KN_T#2) in the thermal section for both cases, as the system load demand increases, the loading sequence starts from the lowest constant lambda segment to the highest constant lambda segment. Therefore, the loading sequence is KN_T#1.1, KN_T#2.1, KN_T#1.2, KN_T#2.2. Note that XX#y.z represents the z^{th} segment of y^{th} unit of XX plant.

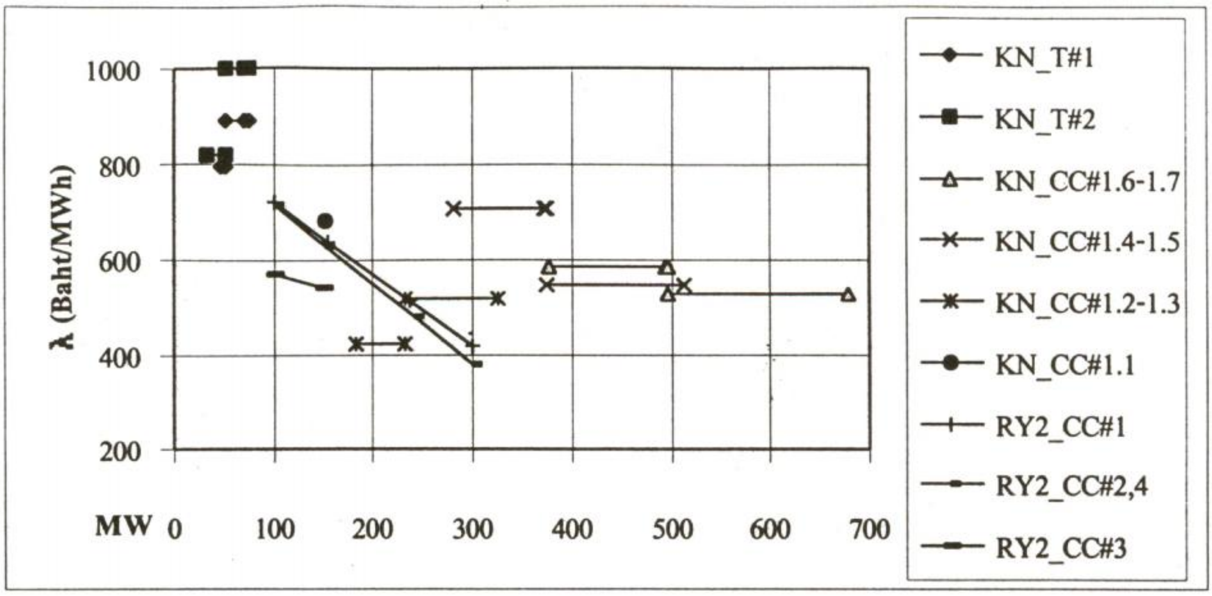

Figure 7 Lambda Curves of Rayong CC Power Plant and Khanom Thermal & CC Power Plants

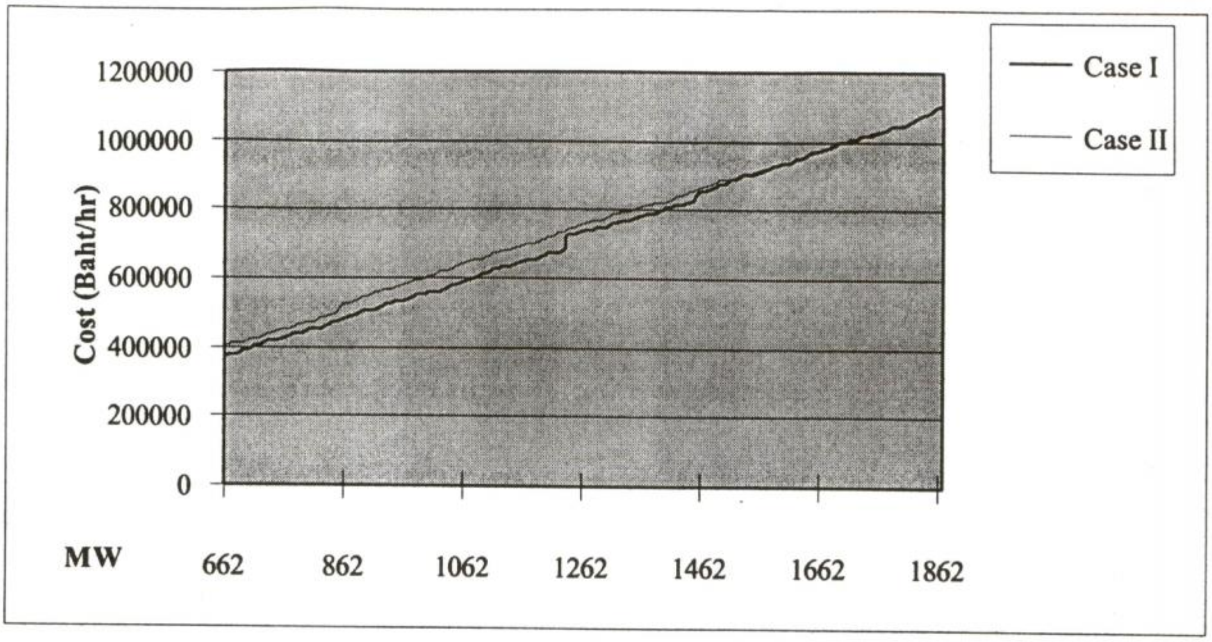

Figure 8 Production Cost of Various Load Demands

4.2 Test Results and Analysis

We test the developed ED program on a small system consisting of CC blocks based on the methods proposed for 122 different load demands. The first load demand is given as 662 MW and the next is incremented by 10 MW. Thus, the last load demand is 1872 MW. The test results indicate that Case I yields a lower production cost than Case II for most values of load demands as shown in Figure 8.

In Case II, we expect that the total production cost at any given load which is less than 800 MW would result in a lower production cost than Case I because the system lambda is lower (see the loading sequence in both cases). However, owing to the high operating cost at the minimum operating output of Khanom CC, this is not the case in our study. From our experience, the CC blocks are always committed at their maximum operating outputs in which the loading sequence of Case I would yield the lowest total production cost. Accordingly, the MOL method with the lowest lambda at the highest output for each CC block is practical for the existing on-line economic dispatch application.

5. CONCLUSIONS

In this paper, we present the methods for finding the solution of economic dispatch with monotonically increasing IC, linear decreasing IC, and staircase IC curves. Initially, we divide the total units into the thermal section and the CC section. We then treat each section separately since the lowest lambda of the thermal section is higher than the highest lambda of the CC section. In the thermal section, we use the BS algorithm to determine the optimal solution based on the equal lambda principle for all thermal units.

On the other hand, we use the MOL algorithm with the lowest lambda at the highest output of each CC block as our index for the CC section because the use of the equal lambda principle on the linear decreasing function will not yield the least production cost. Based on the experimental results, the on-line application of this method is viable.

6. ACKNOWLEDGMENTS

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