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Estructura y Nivel de Tarifas y Costos Marginales

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1. INTRODUCCION

Entre los enfoques utilizados para la fijación de precios de la energía eléctrica se destaca el de la fijación de tarifas con base en los costos marginales.

El análisis marginal bastante conocido de la teoría económica y de los economistas fue aplicado al sector eléctrico como base de fijación de tarifas por Electricité de France, a quien se debe la primera aplicación práctica y organización teórica de sus principios.

El presente trabajo tiene por objetivo analizar, de forma organizada, el razonamiento marginal para la fijación de tarifas de energía eléctrica, aclarando algunos principios, explicando algunas definiciones y discutiendo algunos resultados.

2. ESTRUCTURA Y NIVEL DE TARIFAS

Cuando el concesionario de energía eléctrica solicita tarifas compatibles con su equilibrio económico y financiero, está visualizando el ingreso total de las tarifas no el precio de cada categoría de consumidores. Es el nivel de las tarifas que está en juego y no sus estructuras.

Cuando una categoría particular de consumidores pide tarifas más bajas, es su gasto el que está visualizando y no los gastos de otras categorías. Es la estructura de las tarifas que está en juego y no sus niveles.

El nivel tarifario tiene relación con el ingreso total. La cantidad global a recaudar es elemento de negociación en casi todos los países teniendo en cuenta el carácter monopolista del sistema eléctrico. Es a través de esta negociación que el poder concedente impide que el concesionario monopolista explote al consumidor y también impide que el consumidor, al pagar poco, ponga en peligro el equilibrio económico y financiero del concesionario.

La estructura tarifaria no debe ser objeto de negociación; debe ser justa, pues proyecta la relatividad de precios entre categorías de consumidores. La estructura se aproximará a lo ideal cuando pueda dar a cada categoría de consumidores la convicción de estar pagando un precio justo por los servicios que recibe y la sensación de no estar siendo perjudicado por el precio que las otras categorías pagan.

La energía eléctrica es un servicio que a lo largo de la cadena, producción, transporte, distribución se valoriza sumando sus costos. El nivel de tensión de entrega representa una figura comercial de la energía abastecida. Así, kilovatios-hora entregados en distintos niveles de tensión son productos comerciales diferentes, con usos y costos diferentes. Por eso se debe buscar una estructura justa de las tarifas basada en los costos del suministro.

Se puede repetir los argumentos de Electricité de France:

> "El costo marginal, como referencia tarifaria para los nuevos consumos y no el costo medio de las plantas ya en servicio, es lo que indica correctamente a cada usuario las consecuencias económicas de sus actos de consumidor, proponiendo un precio tal que toda decisión marginal tomada le costará aquello que costará al productor-distribuidor, es decir, a la colectividad. El indicará al consumidor de una sola vez qué economía realizará la colectividad si disminuyera su consumo, si rompiera el límite o lo anulara completamente.
> El mismo costo marginal se justifica como referencia para los antiguos consumidores, visto el hecho que todo el consumo puede ser considerado como suplemento,

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pues la decisión de renunciar puede ser tomada a cada instante; se observa que la disminución del abastecimiento a un consumidor permite atender el crecimiento del consumo de otro, cuya demanda exigiría la construcción de una nueva fuente productora.

La estructura tarifaria determinada a partir de los costos marginales será una estructura justa, estable y racional pues será "neutral", "equitativa" y "eficaz". **Neutral** porque conducirá a facturar cada prestación de servicio a su costo real para la colectividad; **equitativa** porque hará pagar a cada consumidor según el costo que provoca, eliminando por principio, toda subvención oculta, toda discriminación y todo juego de influencias; **eficaz** porque la tarifa resultante orienta de forma óptima la expansión del consumo, para las horas y los lugares donde el suplemento de abastecimiento es globalmente el menos oneroso para la nación."(1)

3. FIJACION DE TARIFAS CON BASE EN LOS COSTOS MARGINALES

La fijación de tarifas con base en los costos marginales tiene como objetivo principal hacer que cada consumidor pague el costo efectivo que el sistema (colectividad) incurre para su atención.

En términos de costo para el sistema se puede decir que no existen dos abastecimientos iguales de energía eléctrica. Cabe, por eso, a la teoría y práctica tarifaria definir cuales de los suministros pueden ser agregados y tratados de forma semejante.

La aplicación del principio de neutralidad tarifaria, implícito en el principal objetivo de fijación de tarifas al costo marginal implica:

a) que se distingan, cuidadosamente, los períodos del año donde los costos marginales son diferentes;
b) que se identifiquen los parámetros que caracterizan la curva de carga de los consumidores y que explican mejor la formación de los costos.

Las consideraciones anteriores demuestran que la tarifa con base en los costos marginales se origina de un balance entre sistemas de oferta y demanda y deberá tomar en cuenta las características de ambos lados. Este balance no es muy simple de realizar, pues en cuanto a empresa de electricidad se coloca en la posición de vendedora de productos (potencia por período P_i y consumo por período C_i) el comprador (consumidor) se coloca en la posición de quien está adquiriendo un "servicio" que la electricidad proporciona a través de equipos. Es evidente, por eso, que para que haya un perfecto balance entre el consumidor y productor ambos deben visualizar la energía eléctrica con la misma óptica.

Para los costos de producción de una unidad de energía son extremadamente relevantes los parámetros P_i y C_i que el usuario consumirá. El hecho de ser dos productos ligados, es decir que uno no puede existir sin el otro, vuelve el problema de cierta forma más complejo, pero no descarta la necesidad del consumidor de saber exactamente como su forma de utilizar la energía afecta a los costos de producción. Las tarifas resultantes permitirán que el consumidor visualice en la factura, los costos que él causa al sistema, pudiendo contribuir para la racionalización del consumo, con una consecuente reducción de costos para la colectividad.

Además de las preocupaciones mencionadas es necesario que la propuesta tarifaria final presente una estructura suficientemente simple, para que se asegure una evaluación del beneficio colectivo relacionada al costo de su implantación.

Estas consideraciones vuelven el problema de fijación de tarifas con base en los costos marginales en un problema de determinación de la estructura de costos marginales pero sin la construcción de un proceso completo de fijación de tarifas.

4. ESTRUCTURA HORARIO-ESTACIONAL DE COSTOS MARGINALES

4.1 Sistema Puramente Térmico

Supóngase que las curvas de carga de los diversos tipos de consumidores, tanto por clase de consumo como por nivel de tensión, son conocidas y posibles de proyectar. Con estas curvas es posible construir una única curva equivalente que se supone localizada junto al sistema de producción. La incorporación de los costos de transporte y distribución se puede hacer posteriormente, sabiendo que en una operación óptima la energía fluye de puntos donde es más barata a puntos donde es más cara.

Teniendo a la vista el carácter aleatorio de las variables involucradas el costo marginal de abastecimiento en el intervalo **n** representará el valor esperado que tendrá la siguiente expresión (ver Figura 1):

$$\bar{\mu}_n = (1 - p_n)\, \tilde{\mu}_n + p_n\, D_n \qquad (4\text{-}1\text{-}1)$$

donde:

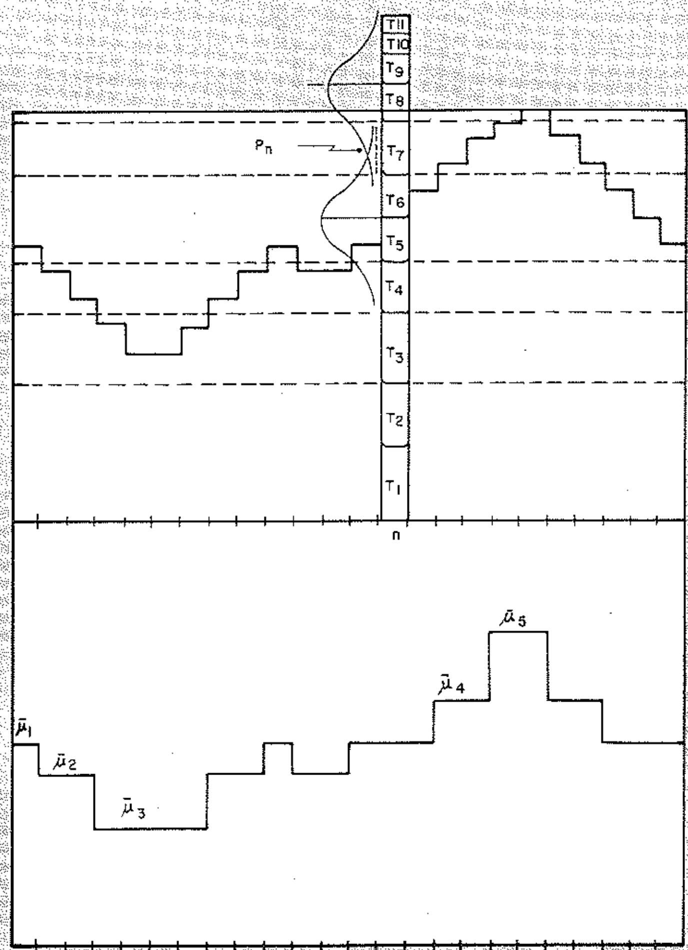
p_n = probabilidad de déficit en el intervalo **n**.

μ_n = costo esperado del déficit en el intervalo **n**.

FIGURA 1

ESTRUCTURA DE COSTOS MARGINALES ESPERADOS

$$\bar{\mu}_n = (1 - p_n)\,\tilde{\mu}_n + p_n D_n$$



$\tilde{\mu}_n$ = costo esperado del combustible de las plantas térmicas a ser utilizadas en **n** para atender el suplemento de consumo.

$\bar{\mu}_n$ = costo marginal esperado del abastecimiento suplementario en el intervalo **n**.

D_n = costo marginal esperado del déficit en el intervalo **n**.

Si consideramos **T** el conjunto de intervalos **n** del año que p_n es significativo, entonces el costo marginal esperado anual será:

$$\sum_{n=1}^{N} \bar{\mu}_n = \sum_{n=1}^{N} \tilde{\mu}_n + \sum_{T} p_n (D_n - \tilde{\mu}_n) \quad (4\text{-}1\text{-}2)$$

El crecimiento del consumo a lo largo del tiempo hará que el fragmento $\sum_{T} p_n (D_n - \tilde{\mu}_n)$ aumente llegando a un punto tal que la construcción de una nueva planta se vuelve inevitable. Llamando "Ca" al costo anual de la anticipación por unidad de producción de la nueva planta (costo representado por: depreciación de la inversión, gastos financieros calculados a una tasa de actualización y gastos de operación) el punto ideal para colocarla en operación ocurrirá cuando:

$$Ca = \sum_{T} p_n (D_n - \tilde{\mu}_n) \qquad (4\text{-}1\text{-}3)$$

con el siguiente significado:

Costo anticipado de 1 KW garantizado
=
Beneficio neto en el sistema por el aumento de la disponibilidad

El uso adecuado de las expresiones (4-1-2) y (4-1-3) permite determinar la estructura de costos marginales para un sistema puramente térmico. Basta disponer de un modelo de gestión del parque de generación, de las previsiones de la curva de carga y de la planta alternativa a ser construida. Por la expresión (4-1-3) se tiene el punto óptimo para instalar la nueva unidad y por el modelo de gestión las variaciones de los costos marginales a lo largo del día, semana, mes y año conforme a la precisión del mismo. Si el costo del déficit no es conocido basta fijar la probabilidad de déficit aceptable y por la expresión (4-1-3) estimar implícitamente el costo del déficit.

4.2 Sistema Puramente Hidroeléctrico

En un sistema puramente térmico es palpable la asociación de costos marginales horario-estacionales con combustible de la térmicas. En los sistemas hidráulicos esto no sucede.

Conocida la curva de carga en valores probabilistas, dividida en intervalos **n**, y la posición del agua en los embalses ¿cómo será atendido un consumo suplementario en el intervalo **n**?.

La posición del agua en los embalses definirá la potencia disponible en el sistema en función del rendimiento de las máquinas, de la altura de caída y del flujo turbinado.

$$P_j = n_T^j \, n_G^j \, g \, H_L^j \, Q^j \qquad (4\text{-}2\text{-}1)$$

$$P_S = \sum_{j=1}^{U} P_j \qquad (4\text{-}2\text{-}2)$$

donde:

- j = planta hidráulica j
- U = número total de plantas existentes
- P = potencia disponible
- n_T = rendimiento medio de las turbinas
- n_G = rendimiento medio de los generadores
- g = aceleración de gravedad; $g = 9{,}81\ m/seg^2$
- H_L = altura neta de caída
- Q = flujo turbinado

Dos situaciones podrán ocurrir al presentarse un suplemento de consumo:

a) La potencia disponible es insuficiente y existirá un déficit en el sistema.

b) La potencia disponible en el sistema es suficiente y algunos metros cúbicos suplementarios de agua son turbinados para la atención del consumo adicional.

En el primer caso el costo para la colectividad será igual al costo del déficit.

En el segundo caso se gastó un poco más de agua con costo aparentemente nulo frente al carácter aparentemente gratuito de su disponibilidad. En términos energéticos, sin embargo, el agua acumulada en los embalses es la única garantía real de mantenimiento de continuidad del abastecimiento de energía eléctrica.

Así, el uso de los metros cúbicos adicionales significan en términos económicos una reducción de garantía del abastecimiento. En otras palabras la "descapitalización" de la reserva ocasiona un crecimiento en el riesgo del déficit futuro. Esto significa que el kilovatio-hora suplementario, almacenado en un sistema de energía eléctrica puramente hidráulico posee un valor económico perfectamente definido e igual al costo esperado del déficit que será capaz de economizar en el futuro.

Teniendo en cuenta el carácter aleatorio de la posición del agua en los embalses, de la afluencia a los mismos y de la curva de consumo, se puede determinar el costo marginal esperado en el intervalo **n**:

$$\bar{\mu}_n = (1 - p_n)\,\tilde{V}_n + p_n D_n \qquad (4\text{-}2\text{-}3)$$

donde:

- $\bar{\mu}_n$ = costo marginal esperado de atender un consumo adicional en el intervalo **n**.
- p_n = probabilidad de déficit en el intervalo **n**.
- D_n = costo marginal esperado del déficit en el intervalo **n**.
- $\tilde{V}_n$ = valor marginal esperado del agua en el intervalo **n** (su cálculo exige evidentemente un modelo de gestión del parque, capaz de calcular el déficit economizado en el futuro por el mantenimiento en el presente de un KWh marginal almacenado).

Es preciso reconocer que el concepto de "valor del agua" en general es mal comprendido, no por su significado económico, pero si por el hecho de precisarse cierta sofisticación en los modelos de gestión para su cálculo. Es tradicional en sistemas hidráulicos con complementación térmica, operar estas últimas antes que las reservas hidráulicas se agoten. De la misma forma las nuevas centrales son colocadas en operación cuando aún existe agua en los embalses. El mecanismo implícito de las dos decisiones arriba citadas es evidente: "El agua todavía disponible posee un valor económico mayor que el combustible de la térmica operada, en otras palabras, mayor que el costo de la planta adicional puesta en operación". Siendo natural el uso del "valor del agua" como factor implícito de las decisiones, debería ser natural también el cálculo de su valor económico explícito, lo que en general no ocurre por falta pura y simplemente de un metodología adecuada para su determinación.

Para un intervalo de tiempo que deberá ser escogido conforme las características del sistema se puede escribir, como en el caso de sistemas térmicos:

$$\sum_{n=1}^{T} \bar{\mu}_n = \sum_{n=1}^{T} \tilde{V}_n + \sum_{n=1}^{T} p_n (D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}4)$$

El punto óptimo para instalar una nueva central ocurrirá cuando:

$$Cap = \sum_{n=1}^{T} p_n (D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}5)$$

$$Cab = \sum_{n=1}^{T} p_n (D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}6)$$

donde:

- Cap = costo de anticipación de una planta de punta;
- Cab = costo de anticipación de una planta de base;
- p_n = probabilidad de déficit (para una planta de punta se refiere a horas de carga máxima y para planta de base se refiere a déficit por falta de agua en los embalses)

4.3 Sistemas Hidrotérmicos

El desarrollo metodológico de los puntos anteriores es perfectamente aplicable a sistemas de energía eléctrica con fuentes de producción hidráulica y térmica. En este caso, siempre que el valor esperado de agua fuera menor que el costo del combustible de una planta térmica, el agua estará siendo utilizada con prioridad.

Con el esquema óptimo de operación arriba mencionado, durante un intervalo **n** de tiempo puede ocurrir que el suplemento del consumo este siendo atendido por una planta térmica o por una planta hidráulica. Con las hidráulicas en la base ocurrirán intervalos **n** en que la disponibilidad p_n del sistema hidráulico no sea suficiente para atender un suplemento de consumo, entonces una térmica es operada y el costo marginal será igual al costo del combustible de esta térmica. Si las térmicas están en la base (valor del agua superior al combustible) el suplemento será atendido por una planta hidráulica y el costo marginal del abastecimiento suplementario será igual al valor del agua.

La estructura de costos marginales, por lo expuesto, es un poco más difícil de ser determinada, pero existen técnicas conocidas y probadas que permiten solucionar el problema con cierta facilidad.

5. TRANSICION DE LA ESTRUCTURA DE COSTOS MARGINALES A LA ESTRUCTURA DE REFERENCIA

Los conceptos desarrollados anteriormente permiten definir la estructura de costos marginales a nivel de producción, estableciendo la estructura hora-estacional de tarifas.

Determinando las variaciones marginales del consumo en los diversos nudos de la red eléctrica es posible encontrar el costo marginal de interconexión y distribución. Estos costos, de acuerdo con los diversos tipos de consumidores, serán asignados entre demanda y energía y en los diferentes puntos tarifarios determinados. Este paso no siempre es muy simple, pues exige el conocimiento de la curva de carga de los consumidores, de las características físicas del sistema y de la caracterización de los parámetros causantes de costos.

Experiencias obtenidas en el sistema eléctrico brasileño dieron los siguientes resultados:(2)

a) La atención de una unidad marginal de energía en las horas pico (18-21h de los días hábiles) cuesta en valor esperado más el sistema que el suministro de la misma unidad marginal en las horas de carga media. Este hecho puede ser explicado por la necesidad de repartir grupos térmicos para pasar las horas pico, principalmente en los períodos del año en que los embalses están abatidos y con pérdida de potencia en las plantas hidráulicas.

b) No existe diferencia del costo marginal en la atención de una unidad suplementaria de energía en las horas de carga media. Este resultado era de cierta forma esperado ya que la atención de estos períodos se realiza con la reserva hidráulica sin necesidad de fraccionar grupos térmicos adicionales.

c) El costo marginal de producción posee una estacionalidad acentuada a lo largo del año, que acompaña la estacionalidad de las aportes hidráulicos.

Como resultado del efecto estacional y de la diferencia de costos entre generación en la punta y fuera de la punta fueron distinguidos cuatros puntos tarifarios para el sistema brasileño: **Punta, Fuera de la Punta, Período Húmedo o Período Seco.** El período de punta es definido como el que engloba las horas más cargadas de los días hábiles (18:00, 19:00, 20:00); en cuanto al período fuera de punta comprende las otras horas de los días hábiles y los fines de semana. El período húmedo comprende los meses de diciembre y enero hasta abril; el período seco, los meses de mayo a noviembre.

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Tariff Structure and Levels and Marginal Costs

*Izaltino Camozzato**

1. INTRODUCTION

Pricing based on marginal costs is one of the most outstanding approaches used to set prices for electric power.

The well-known marginal cost analysis elaborated by economic theory and economists was introduced to the electric power sector as a basis for setting prices by Electricité de France, a pioneer in the practical application and theoretical organization of its principles.

The purpose of this study is to present, in an organized fashion, the marginal cost reasoning behind the pricing of electricity tariffs, clarifying certain principles, explaining some definitions, and discussing some results.

2. STRUCTURE AND TARIFF LEVEL

When a supplier of electricity requests tariffs that are compatible with its economic and financial equilibrium, it is focusing on the total earnings stemming from the tariff and not on the price of each consumer category. The tariff levels are at stake, not their structures.

When a particular category of consumers requests lower tariffs, they are focusing on their expenditures and not on the expenditures of other consumer categories. The tariff structure is at stake, not the tariff levels.

The tariff level has to do with the total earnings. The overall amount of earnings collected is an element for negotiation in almost all countries, in view of the monopolistic nature of the electric power system. By means of this negotiation, the concession granter prevents the monopolistic concession holder from exploiting consumers and, at the same time, prevents consumers from threatening the economic and financial balance of the supplier by paying low prices.

The tariff structure should not be an object of negotiation; on the contrary, it should be equitable, since it deals with the price relativity between consumer categories. The structure will come close to being ideal when all consumer categories are convinced that they are paying fair prices for the services they receive and when they do not sense that the price paid by other categories is unfair to them.

Electric power is a service which throughout its entire chain (production, transportation, distribution) is valued by adding up its costs. The voltage level at which it is delivered represents a commercial figure of the supplied power. Thus, the kilowatts per hour delivered at different voltage levels consists of different commercial products, with different uses and costs. Therefore, a fair tariff structure should be based on supply costs.

We can repeat here the arguments of Electricité de France:

> "The marginal cost, as a tariff reference for new consumptions and not the average cost of plants already in service, is the one element that correctly informs users of the economic consequences of their consumption actions and proposes a price where all marginal decisions made will cost them what it costs the producer-distributor, that is, the entire community. It will indicate once and for all to consumers the savings for the community if they decrease their consumption, if they consume beyond their ceiling, or if they completely eliminate consumption.
> The minimum marginal cost is justified as a reference for former consumers, in view of the fact that all consumption can be considered as additional, since the decision to give it up may be made at

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any time; it is apparent that a decrease in supply to one consumer allows meeting the increased consumption needs of another one, which would require the construction of a new source of generation.

A tariff structure based on marginal costs is a fair, stable, and rational structure, since it is "neutral," "equitable", and "effective". **Neutral** because it leads to billing each service provided at the real cost for the community; **equitable** because it makes each consumer pay for the cost he causes, eliminating any hidden subsidy, discrimination, or play of influences; **effective** because the resulting tariff optimally guides consumption expansion, for the hours and in the places where the supply supplement is, as a whole, least burdensome for the nation."(1)

3. PRICING BASED ON MARGINAL COSTS

The main objective of pricing based on marginal costs is to get each consumer to pay for the actual cost incurred by the system (community) to serve him.

In terms of costs for the system, it can be stated that no two electric power supplies are identical. Tariff theory and practice would therefore have to define which of the supplies can be aggregated and dealt with in a similar fashion.

Application of the tariff neutrality principle, which is implicit in the main objective of pricing based on marginal costs, involves the following:

a) A careful distinction should be made between the periods in the year where marginal costs are different.

b) The parameters that characterize the consumer load curve and that best explain the formation of costs should be identified.

The above-mentioned considerations mean that a tariff based on marginal costs stems from the balance between supply and demand systems and should take into account the characteristics of both sides. This equilibrium is not easy to achieve, because as soon as the electric utility becomes a product seller (capacity per period P_i and consumption per period C_i), the buyer (consumer) becomes a purchaser of a "service" that electricity provides through installations. It is therefore evident that for a perfect balance between consumers and producers, both have to view electric power under the same angle.

The parameters P_i and C_i that users will consumer are extremely relevant for the production costs of a power unit. The fact that these two products are linked—that is, one cannot exist without the other—complicates the problem to a certain extent, although it does not eliminate the consumer's need to know exactly how his use of electricity affects production costs. The resulting tariffs will allow the consumer to visualize on his bill the costs that he is generating in the system, thus enabling him to contribute to rationalizing consumption, with the consequent reduction of the overall costs for the community.

In addition to the above-mentioned concerns, the final tariff proposal should have a structure that is sufficiently simple, in order to ensure that collective benefit stemming from its implementation cost can be evaluated.

These considerations reduce the problem of tariffs based on marginal costs to a problem of establishing the marginal cost structure without creating a complete pricing process.

4. HOURLY-SEASONAL MARGINAL COST STRUCTURE

4.1 Exclusively Thermal System

Let us assume that the load curves of the various types of consumers, both by consumer category and voltage level, are known and possible to forecast. With these curves, it is possible to build one equivalent curve, which is supposed to be located next to the production system. The incorporation of transportation and distribution costs can be done later, in view of the fact that, in an optimal operation, power flows from the points where it is cheaper to those where it is more expensive.

Bearing in mind the random nature of the variables involved, the marginal cost of supply during interval **n** will represent the expected value, which is expressed as follows (see Figure 1):

$$\bar{\mu}_n = (1 - p_n)\,\tilde{\mu}_n + p_n D_n \qquad (4\text{-}1\text{-}1)$$

where:

p_n = probability of shortage during interval n.

μ_n = expected cost of shortage during interval n.

$\tilde{\mu}_n$ = expected cost of fuel of the thermal plants to be used in n to cover the consumption supplement.

$\bar{\mu}_n$ = expected marginal cost of additional supply during interval n.

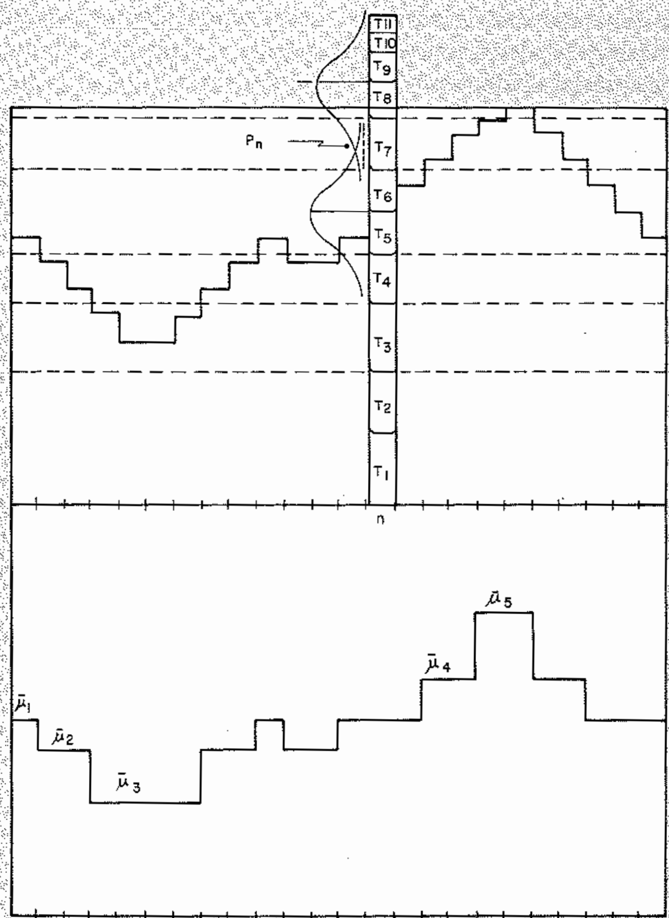
D_n = expected marginal cost of the shortage during interval n.

If we consider **T** to be the set of intervals **n** during the year that p_n is significant, then the expected annual marginal cost will be:

FIGURE 1

STRUCTURE OF EXPECTED MARGINAL COSTS

$\bar{\mu}_n = (1 - p_n)\, \tilde{\mu}_n + p_n D_n$



$$\sum_{n=1}^{N} \bar{\mu}_n = \sum_{n=1}^{N} \tilde{\mu}_n + \sum_{T} p_n (D_n - \tilde{\mu}_n) \quad (4\text{-}1\text{-}2)$$

Consumption growth in time will make fragment $\sum_{T} p_n (D_n - \tilde{\mu}_n)$ increase, reaching a point where the construction of a new plant becomes unavoidable. By designating "Ca" as the annual anticipation cost per production unit of the new station (this cost is represented by: Investment Depreciation, Financial Expenses calculated at a discount rate and Operating Expenditures), the ideal point to begin operating it will occur when:

$$Ca = \sum_{T} p_n (D_n - \tilde{\mu}_n) \qquad (4\text{-}1\text{-}3)$$

with the following meaning:

Expected cost of 1 guaranteed kilowatt
=
Net benefit in the system due to increased availability

The adequate use of equations (4-1-2) and (4-1-3) allows one to establish the marginal cost structure for an exclusively thermal system. All one needs is a management model for generation facilities, the forecasts of the load curve, and the alternative plant to be constructed. Equation (4-1-3) provides the optimal point for installing a new unit, and the management model provides the marginal cost variations throughout the day, week, month, and year, depending on its precision. If the shortage cost is unknown, all one has to do is set the acceptable shortage probability and through equation (4-1-3) implicitly estimate the shortage cost.

4.2 Exclusively Hydropower System

In a purely thermal system, the association between hourly-seasonal marginal costs and the fuel used by thermal plants is evident. This, however, is not apparent with the hydro systems.

Once the load curve is identified in probabilistic values and divided in **n** intervals, and the water level of the reservoirs has been determined, the question is how is an additional consumption dealt with in interval **n**?

The water level of the reservoirs will define the system's available capacity in accordance with the performance of the machines, the drop height, and the turbined flow.

$$P_j = n_T^j \; n_G^j \; g \; H_L^j \; Q^j \qquad (4\text{-}2\text{-}1)$$

$$P_S = \sum_{j=1}^{U} P_j \qquad (4\text{-}2\text{-}2)$$

where:

j = hydro plant j
U = total number of existing plants
P = available capacity
n_T = average performance of the turbines
n_G = average performance of the generators
g = gravity celerity; $g = 9.81$ m/sec²
H_L = net height of drop
Q = turbined flow

Two situations could occur if an additional consumption arises:

a) The available capacity may be insufficient and there will be a shortage in the system.
b) The available capacity in the system is sufficient and some supplementary cubic meters of water are turbined to handle the additional consumption.

In the first case, the cost for the community will be equal to the shortage cost.

In the second case, a little more water was used at apparently no cost at all, due to the evidently free character of its availability. In power terms, however, the water accumulated in the reservoirs is the only true guarantee of maintaining the continuity of electric power supply.

Thus, the use of additional cubic meters in economic terms mean a reduction of supply security. In other words, the "capital loss" of the reserve increases the risk of future shortages. This means that the supplementary kilowatt-hour stored in a purely hydraulic electric power system has an economic value that is perfectly well defined and equal to the expected shortage cost that it will be capable of saving in the future.

Bearing in mind the random nature of the water level in the reservoirs, the inflows to these reservoirs, and the consumption curve, the expected marginal cost in interval **n** can be determined as follows:

$$\tilde{\mu}_n = (1 - p_n)\,\tilde{V}_n + p_n\, D_n \qquad (4\text{-}2\text{-}3)$$

where:

$\tilde{\mu}_n$ = expected marginal cost of handling an additional consumption during interval **n**.
p_n = probability of shortage during interval **n**.
D_n = expected marginal cost of shortage during interval **n**.
$\tilde{V}_n$ = expected marginal water cost during interval **n** (this calculation evidently requires a management model for the installations, which is capable of calculating the shortage economized in the future due to the conservation in the present of one stored marginal KWh).

It should be acknowledged that the concept of "water value" in general is poorly understood, not because of its economic value but rather because its calculation requires a certain amount of sophistication in the management models. In hydraulic systems with complementary thermal units, it is customary to start operating the latter before the hydro resources are depleted. Likewise, the new stations are put into operation while there is still water in the reservoirs. The reasoning behind both of the abovementioned decisions is evident: "The water that is still available has a greater economic value than the fuel for the thermal plant put into operation, in other words, greater than the cost of the additional plant put into operation." Since it is natural to use the "water value" as an implicit factor for decision making, the calculation of its explicit economic value should also be natural, although this generally does not occur simply because there is no suitable methodology for determining this value.

For a time interval that should be chosen according to the system's characteristics, one can write, as in the case of thermal systems:

$$\sum_{n=1}^{T} \tilde{\mu}_n = \sum_{n=1}^{T} \tilde{V}_n + \sum_{n=1}^{T} p_n\,(D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}4)$$

The optimal point to install a new plant occurs when:

$$Cap = \sum_{n=1}^{T} p_n\,(D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}5)$$

$$Cab = \sum_{n=1}^{T} p_n\,(D_n - \tilde{V}_n) \qquad (4\text{-}2\text{-}6)$$

where:

Cap = expected cost of a peak plant;
Cab = expected cost of a base plant;
p_n = probability of shortage (for a peak plant, it refers to maximum load hours and for a base plant it refers to a shortage due to the lack of water in the reservoirs)

4.3 Hydrothermal Systems

The methodological development of the previous items is perfectly applicable to electric power systems with hydro and thermal production sources. In this case, as long as the expected water value is lower than the fuel cost for a thermal plant, priority will be given to the use of water.

With the above-mentioned optimal operation scheme, during interval **n** the additional consumption could be covered by either a thermal or a hydro plant. With the hydro plants at the base, **n** intervals will occur in which the availability p_n of the hydro system is not sufficient to handle an additional consumption. Therefore, a thermal unit is put into operation, and the marginal cost will be equal to the fuel cost of this thermal unit. If the thermal plants are meeting base demand (water value higher than fuel), the supplement will be covered by a hydro plant and the marginal cost of the additional supply will be equal to the water value.

According to what has been presented here, the marginal cost structure is a bit more difficult to establish, although there are well-known and proven techniques that allow the problem to be resolved with a certain facility.

5. SHIFT FROM A MARGINAL COST STRUCTURE TO A REFERENCE STRUCTURE

The concepts developed above enable the marginal cost structure to be defined at the production level and to establish an hourly-seasonal structure.

Once the marginal consumption variations in the different nodes of the electric network are determined, it is possible to calculate the marginal interconnection and distribution costs. These costs, depending on the characteristics of the various types of consumers, will be allocated between demand and power and to the different determined tariff points. This move is not always simple, since it requires knowing what the consumer load curve is, as well as the physical characteristics of the system and of the cost parameters.

Experiences obtained from the Brazilian electric system have produced the following results: (2)

a) The service delivered by a marginal power unit during peak hours (18:00-21:00 on working days) costs, in terms of expected value, more for the system than the service of the same marginal unit during average load hours. This fact can be explained by the need to distribute thermal groups in order to cover peak hours, especially during those periods in the year when the reservoirs are emptied, with a power loss for the hydro plants.

b) No difference exists in terms of the marginal cost in dispatching an additional power unit during average load hours. To a certain extent, this is to be expected, since the service during these periods is provided by using hydro reserves, without any need to fragment additional thermal groups.

c) The marginal production cost has a seasonality that increases throughout the year, which accompanies the seasonality of water inflows.

As a result of the seasonal effect and of the difference between peak and off-peak generation costs, four tariff categories were identified for the Brazilian system: **peak, off-peak, humid period,** and **dry period.** The peak period is defined as comprising the most loaded hours during work days (18:00, 19:00, 20:00). The off-peak period consists of the other hours during working days and weekends. The humid period covers the months of December and January through April, whereas the dry period covers the months from May to November.

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