Electricity transmission network optimization model of supply and demand – the case in Taiwan electricity transmission system

Miao-Sheng Chen [a]

Chien-Liang Wang [b,c,*]

Sheng-Chuan Wang [d,e]

[a] *Taichung Branch*
Graduate Institute of Management Sciences
Nanhua University
Taiwan
R.O.C.

[b] *Graduate Institute of Management Sciences*
Tamkang University
Taiwan
R.O.C.

[c] *Taichung Branch*
Power Supply Department of Taiwan Power Company
Taiwan
R.O.C.

[d] *Department of Finance*
Asia University
Wufong, Taichung
Taiwan
R.O.C.

[e] *Department of Industrial Management*
National Yunlin University of Science and Technology
Touliu, Yunlin
Taiwan
R.O.C.

[*] *E-mail*: henry_w@edirect168.com

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Abstract

The electricity system can be divided into power generation, transmission and distribution subsystems from the structure point of view. Electricity business is positioned as a public business and regulated by pricing and quantities due to the high publicly utilization. The power transmission system is responsible for power transmission from power generation plants to the areas of power utilization. Since there is the characteristic that electricity needs to produce and sell with immediate and instant balance, it is required to construct the complete power transmission network in charge of the power dispatching in order to provide stable electricity. The price of purchases and sales is closely related with the necessity of power supply and demand. The purpose of this paper is to introduce the optimization model of power supply and demand in the independent power transmission network for the maximization of consumer and producer's surplus in the liberalization of electricity business. We apply this model to discussing the relationships of electricity quantity and price of purchases and sales. In addition, the sensitive analysis is introduced as well. We conclude that the maximal profit of power transmission network will be decreased when quantity of power utilization, cost of power generation and maintenance cost of transmission network are increasing. Instead, the maximal profit of power transmission network will be increased when power transmission rate is increasing.

Keywords and phrases : *Electricity system, publicly utilization, power transmission network, consumer and producer's surplus, liberalization of electricity business.*

1. Introduction

Power generation and sales are the enormous and complicated production-demand supply chain systems. As referring to the electricity liberalization countries in the world, the electricity business is horizontally divided into three sectors, i.e. generation, transmission and distribution (including electricity sale). The generation and distribution business are open competition for electricity multi-supply. The transmission network is defined as monopolistic public system and restricted by the effective regulation. It provides a fair electricity transmission environment with supply and demand in order to eliminate the defect of interacting subsidy and enhance efficiency market operation with classified into mandatory and voluntary pool that combine with producers and consumers' contract. Each power generation sector can be produced powers independently. Each distribution sector can be taken charge of power marketing and distribution in its own area. Both of them are relatively

independent and operated businesses individually. The transmission sector is responsible for the long-distance power transmission from each power plant to each distribution sector and kept electricity instantly balanced. It will cause power shutdown when power supply and demand are not balanced (supply is larger than demand or demand exceeds to supply). The transmission network is regarded as public fair institution to operate the power market equitably since there is economy of scale and monopoly in the whole world. However, most of the past researches focus on the pricing of generation and distribution system and less of transmission system. The transmission system is one of the key factors in the entire power system that treats as the channel role in the electricity supply chain system. This research is to propose the electricity supply and demand optimization model for transmission system and discuss its pricing and quantity's relationship of power acquisition and sales.

Most of the past researches are adopted unitary pricing approach except during peak load. However, it is unreasonable that consumers should not only pay unit variable cost but also share producers' fixed cost in the industry with average cost decreasing. It will be the unfavorable influence for element of production and allocation of earning if the electricity pricing is base on margin cost and fixed cost exclusively. Moreover, the demand curve can't be estimated accurately so that it causes producer's loss. Two-part tariffs refer to that producer charges fixed utilization fee and variable product price. It includes fixed cost and avoided producer bankruptcy crisis whose pricing adapts marginal cost pricing. It is based on the cost and profit pricing in most of world-wide companies including Taiwan Power Company. The electricity price adjustment of Taiwan Power Company concerns about the factors of fuel cost and price index. Some scholars, such as Christodoulopoulos [1], Lindblom and Andersson [4], and Joskow and Kahn [3], have discussed the production and competitive pricing strategy of each power generation plant and relative issues after power market liberalization.

There is the characteristic of power system that different raw materials can be produced the same electricity. And the same electricity will create various utilizations by different applications. For example, hydropower, thermal power or nuclear power plants can produce the same electricity such as frequency and voltage with different row materials. The same electricity can provide industrial production materials with different

utilization or end-users' consumption. From the management point of view, there is the characteristic of same supply function and various utilizations with different usage for power supply and demand.

In addition, electricity business is featured by high public utilization, consistency of production and marketing, economy of scale and technology. In the power supply and demand system, generation sectors produce power as much as possible in order to operate the invested equipments effectively and gain maximum profits. And distribution sectors provide power with high quality and low price in order to enhance users' will of usage and satisfy users' requirement of quality and price. Transmission network plays the role to connect with generation and distribution sectors. It is responsible for power transmission and regulation with power generation and distribution. It also undertakes the cost and power loss during transmission process. Therefore, the quality, reliability and pricing decision of transmission network affect whole electricity system, cost structure and electricity pricing.

The power dispatching is responsible for Independent System Operator (ISO) after electricity market deregulated in California, U.S.A [6]. Power generating regulation has withdrawn and price is depended on market competition. In England, the transmission affair is responsible for National Grid Company (NGC). The power generation companies sign Pooling & Settlement Agreement (PSA) with NGC. PSA in England is transmission system of central enforcement combining transmission network, electricity trade with dispatching. In the electricity trade system, consumers can choose power providers when the quantity is higher than 100kw. It can be shown reasonable power price through the competition of electricity retailer market.

In Australia, electricity liberalization affair are responsible for National Grid Management Council (NGMC). It is divided into power generation, transmission and distribution business into the competitive mechanism. Electricity transmission network is operated for Victoria Power Net (VPN). Power dispatching and exchange are responsible for Victoria Power Exchange (VPE). The electricity pooling in Australia is monopolistic and all powers from generation plants must be dispatched by VPE except small plants that electricity generating is under 30mw. The power transmission is in charge of Trans Grid (TG).

The electricity revolution in New Zealand is to provide the best welfare via competition of power generation sector, users' option opening and contract exchange system with producers and consumers. They regard the market surveillance committee as an independent institute to supervise power market operation, and implement relative regulation, and play the role of coordination with argument for all participants. New Zealand Trans-power (NZT) of state-own enterprise is in charge of transmission network and power dispatching. The power transmission price is referred to the conditions of transmission network limitation and utilization by NZT. Electricity Corporation of New Zealand (ECNZ) announces power transmission price and the condition of network utilization once per two hours in order to decide power demand and price that are willing to pay according to given information.

In Taiwan, the power supply and demand changes from regulatory synthesis electricity business into open generating business company. The private generation plants sell electricity to synthesized electric business company with political contract, which doesn't calculate costs separately for power generation, transmission and distribution. Considering the specialization and evolution in Taiwan power market and referring to liberalization model of electricity business in the whole world [2], [5], [7], [8], [9], [10], [11], we assume that Taiwan power business is divided into generation, transmission and distribution sectors. Power transmission sector is the monopolized public independent department.

The purpose of this paper is focus on the Taiwan power transmission system. We consider Taiwan power transmission network independent and monopolistic. And we develop the optimization model of the electricity transmission network that discusses supply and demand relationship of power generation, distribution and transmission system with customer and producer's surplus maximum point of view. And the sensitivity analysis is introduced with decision variables and optimization solutions.

2. Construct optimization model of electricity transmission supply anddemand

2.1 *The perspective of consumer's surplus*

According to supply and demand theory of economics, demand curve is declined from upper left to lower right in which means the vari-

ation of price is opposite direction with purchase quantity. And supply curve is extended from lower left to upper right in which means the supply quantity will increase when the price is rising. The relationship of demand and supply is shown in Figure 1.

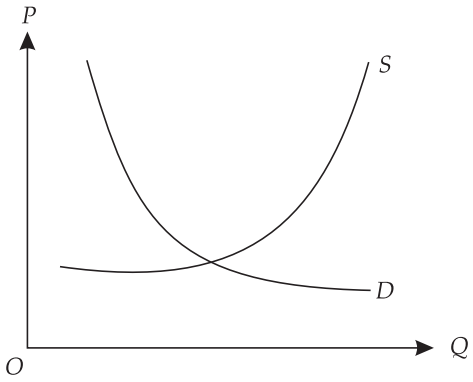

Figure 1
Supply (*S*) and demand curve (*D*)

Consumer's Surplus (CS) refers to the difference between the maximum price a buyer is willing and able to pay for a good or service and the price actually paid. When P_0 is a market price that is in the demand curve D, demand volume is response to Q. The area of P_0OQ_0E is the price that consumers actually pay. The area of AOQ_0E is the price that consumers are willing and able to pay. The difference between both is area AP_0E that means customer's surplus. The relationship of demand curve and CS is shown as following.

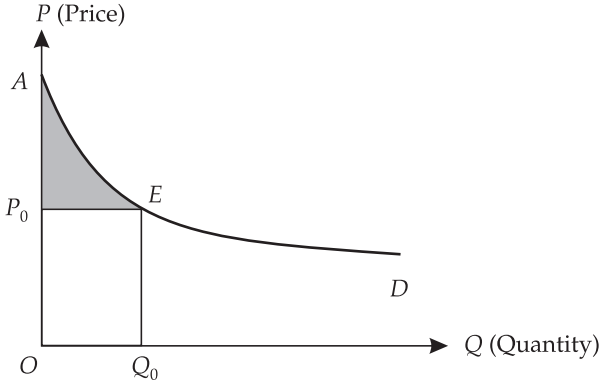

Figure 2
Relationship of demand curve and consumer's surplus

In economic theory, the final product and service's price is decided by supply and demand of market in the completely competition environment. The final purpose of all economic activities is to consume. So consumers are the main decision maker in the whole activities. The direction of economic activities is decided by consumers' will and producers play the role offering a good service. There are features that electricity can't be stored and requires for immediate sales after generation in the electricity market. The successful operation of electricity market should be proceed and coordinated with power generation, transmission and end-user consistently. The end-user is willing to consume electricity that is determined by the needs of timing and the timing price. The power generation plant is willing to produce electricity that is determined how many profits it can get in the timing price. The power transmission network concerns about the balance of all necessary expenses and revenues. Therefore, timing pricing of power transmission network has an impact on the price of demand (P_d) and price of supply (P_s) for power generation plants, and regulated difference between the volume of power generation and consumption.

The power supply and demand's balance is that the volume of electricity supply (including all kinds of power supply) should satisfy the user's demand (including all kinds of demand) adequately. Otherwise, the power shortage or overloading will be happened. However, there will be power loss during the transmitting in the transmission network. We define r means the effective power transmission rate in transmitting, then we can get: $0 < r < 1$,

$$\begin{aligned}&\text{The power demand of user's market } (q_d)\\ &= \text{The power supply of generation market } (q_s)\\ &\quad \times \text{effective power transmission rate } (r).\end{aligned}$$

The user's price in time t for users is $q_d(P_d(t))$. The sale's price in time t for generation plants is $q_s(P_s(t))$. It means the power regulation organization should adjust volume of power supply and demand according to the price of supply $P_s(t)$, price of demand $P_d(t)$ and unit price of power transmission y in different time t. The purpose of the paper is to analyze the relationship of supply and demand of power generation, transmission and distribution market.

2.2 *Model assumption and notation*

This paper is to discuss the relationship of electricity supply and demand for power generation, transmission and distribution in period of time. The assumption and notation is as following:

$P = f(Q)$: Demand function of power distribution market, where f is the continuously strict decreasing concave function of Q, i.e., $f'(Q)$ so and $f''(Q) < 0$ $\forall\, Q$, $f(0) - C'(0) > 0$.

r : Power effective transmission rate, where $0 < r < 1$. i.e., the effective unit power volume that is transmitted from generation to distribution market.

Q : Power consumption volume of distribution market.

$\frac{Q}{r}$: Power generating volume of generation market.

y : Power transmission cost paid to power transmission network that the unit power volume of generation market (which is equal to r unit power volume of distribution market) transmits to distribution market.

$\frac{y}{r}$: Power transmission cost paid by the unit power volume of distribution market.

$p_1 = C'\left(\frac{Q}{r}\right)$: Supply function of power generation market (excluding transmission cost).

$p_2 = C'\left(\frac{Q}{r}\right) + \frac{y}{r}$: Supply function of power distribution market (including transmission cost).

Where, C is the continuous strict increasing convex function and satisfies the following conditions:

$$C'\left(\frac{Q}{r}\right) > 0\,, \quad C''\left(\frac{Q}{r}\right) > 0\,, \quad C'''\left(\frac{Q}{r}\right) > 0\,, \quad \forall\ Q,$$

$$f(0) > C'(0), \text{ or } \frac{C'}{(Q)} > 0,\ \frac{C''}{(Q)} > 0,\ \frac{C'''}{(Q)} > 0\ \forall\ Q\,.$$

A : Power transmission cost of transmission network, including the apportion cost of facilities assets revaluation in existing transmission network, cost of equipments replacement, interest and maintenance cost.

As the relationship of consumer's surplus, producer's surplus and unit transmission cost is shown as Figure 3.

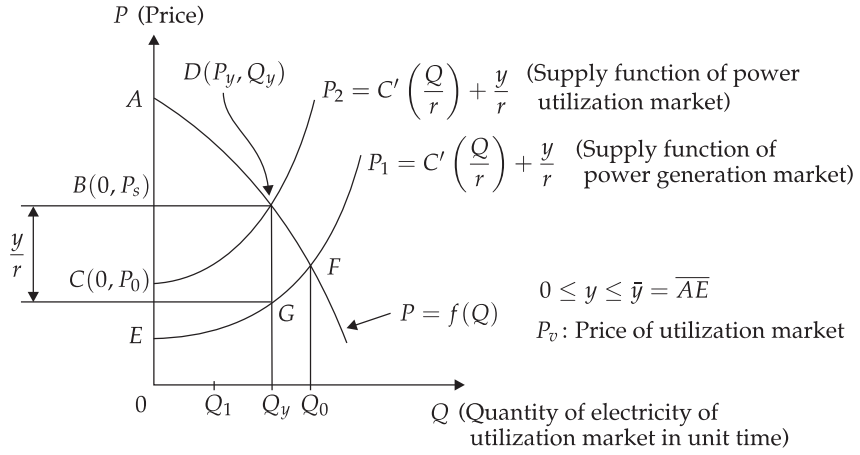

Figure 3

Relationship of consumer's surplus, producer's surplus and decision variable y of transmission network

In Figure 3:

Value of area ABD is the consumer's surplus corresponded to "y".

Value of area BCD is the producer's surplus corresponded to "y".

Value of area $CEGD$ is power transmission earning for Power Regulation Organization of transmission network.

Value of area ACD is the value of social welfare corresponded to "y" (i.e., sum of consumer's surplus and producer's surplus).

As we know: the greater of y, the less of Q_y. Therefore, area ACD is the increasing function of Q_y (i.e., area ACD is the decreasing function of y). Moreover, the closer Q_y approached to Q_0, the greater area ACD corresponded to Q_y. It means the power transmission earning may not increase since the will of production and consumption is decreases when y increases.

2.3 *The optimization model of consumer's surplus and producer's surplus maximum when the earning of power transmission network is achieving to* A

The purpose of liberalization is to deregulate the state-owned enterprise that is restricted by government regulation and poor performance in order to enhance cooperation competitiveness. Take Taiwan power market for example. Taiwan Power Company (TPC, the state-owned company which monopolizes the Taiwan power market) needs to revaluate assets, and calculates apportion cost of facilities, interest, maintenance cost and equipment replacement cost for the base of power transmission cost A. In addition, power transmission network is established by government what is independent and fair institution. It should be supervised by Congress (Legislative Yuan) and required to pay in surplus to the state treasury. Therefore, the surplus should be considered when A is calculated. As above assumption, we construct the transmission model that is maximized the weighted average of consumer and producer's surplus as following:

The Objective function

$$\begin{aligned}\underset{0\le y\le y}{\text{Max}}\ \pi(Q_y) &= \underset{0\le Q\le Q_0}{\text{Max}}\ \pi(Q)\\ &= w_1\int_0^Q [f(Q)-C'(Q)]dx\\ &\quad + w_2\int_0^Q \left[f(Q)-C'\left(\frac{Q}{r}\right)-\frac{f(Q)-C'\left(\frac{Q}{r}\right)}{r}\right]dx \qquad (1)\end{aligned}$$

Subject to $\pi(Q)=Q\left[f(Q)-C'\left(\frac{Q}{r}\right)\right]\ge A$.

Where Q_y is the strict decreasing function of y (as shown in Figure 3). Weight w_1 and w_2 are nonnegative constant.

The optimal solution of this model shall be:

Assume y^* and Q^* are the optimal solution of Formula (1). And let $Q^*=Q_{y^*}$. From

Formula (1), we have:

$$\pi(Q)=g(Q)-w_1\left(\frac{1}{r}-1\right)\pi(Q). \qquad (2)$$

Where, $g(Q)=w_1\int_0^Q [f(x)-f(Q)]dx+w_2\int_0^Q\left[C'\left(\frac{Q}{r}\right)-C''\left(\frac{x}{r}\right)\right]dx$.

Since $g'(Q) = w_1 \int_0^Q -f'(Q)dx + w_2 \frac{1}{r} \int_0^Q \left(\frac{Q}{r}\right) dx > 0$.

So $g(Q)$ is the strict increasing function of Q. (3)

From Formula (1) and (2), we have the relationship $\pi(Q)$ and Q shown in following:

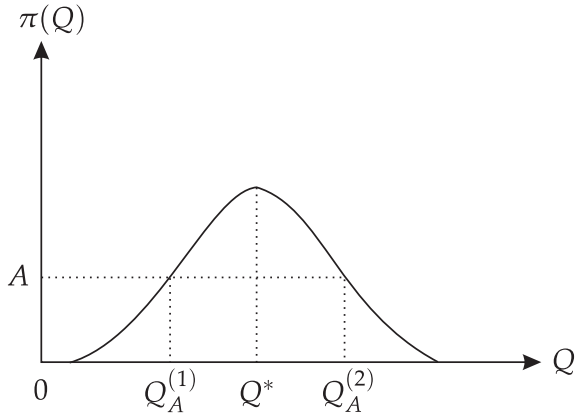

Figure 4
Relationship of objective function $\pi(Q)$ and volume Q

From Figure 4, Q is satisfied the constraint of this model: $\pi(Q) = Q\left[f(Q) - C\left(\frac{Q}{r}\right)\right] \geq A$, the necessary and sufficient condition of Q is: $Q \in [Q_A^{(1)}, Q_A^{(2)}]$. Any Q in $[Q_A^{(1)}, Q^*]$ is written as Q_1. One of Q in $[Q^*, Q_A^{(2)}]$ is written as Q_2 and let $\pi(Q_1) = \pi(Q_2)$.

From Formula (2) and (3), we have:

$$\begin{aligned}\pi(Q_2) &= g(Q_2) - w_2\left(\frac{1}{r} - 1\right)\pi(Q_2) \\ &> g(Q_1) - w_2\left(\frac{1}{r} - 1\right)\pi(Q_1) = \pi(Q_1).\end{aligned}$$

It means the optimal solution Q_2^* of this model should be satisfied $Q_2^* \in [Q^*, Q_A^{(2)})]$.

In addition, from the Formula (2), (3) and Figure 4, we have:

$$\pi'(Q) = g'(Q) - w_2\left(\frac{1}{r} - 1\right)\pi'(Q) > 0 \quad \forall\ Q \in [Q^*, Q_A^{(2)}] \qquad (4)$$

i.e., $\pi(Q)$ is the strict decreasing function of $[Q^*, Q_A^{(2)}]$. Therefore, the optimal solution Q_2^* of this model is satisfied the following:

$$\pi(Q_2^*) = Q_2^* \left[f(Q^*) - C' \left(\frac{Q_2^*}{r} \right) \right] = A \,.$$

It means

$$Q_2^* = Q_A^{(2)} \,. \tag{5}$$

If $\pi(Q_2^*) > A$, then $\delta > 0$ is existed, we can get $\pi(Q_2^* + \delta) > A$. $Q_2^* + \delta$ is the feasible solution of this model and we can get the in equation $\pi(Q_2^* + \delta) > \pi(Q_2^*)$ from Formula (4).

Since it is contradicted with assumption that Q_2^* is the optimal solution of this model, so we have Formula (5) proved.

3. Sensitivity analysis

3.1 *Influence of demand function f changes*

The electricity transmission network should regulate the supply and demand of electricity and set reasonable time's prices $(P(t))$ for reference of generation plant and end-user in order to balance supply and demand in the whole system. Timer's price affects the investment and operation of generation plants and will of end-users. It is necessary to consider power generation cost (k), maintenance cost of transmission network (A), transmission expense of unit quantity for distribution market (y), power loss $(1 - r)$ and the right of consumers in order to reach the maximal welfare when transmission network determines the time's price. The maintenance cost of power transmission network (A) includes apportion of transmission facilities' depreciation and regularly maintenance expense. In the electricity system, generation plants are suppliers when transmission network is demander. Transmission network is supplier when all kinds of end-users (including different power utilization) are demanders. From figure 3 we have:

$$p = f(Q) = f_1(Q) + f_2(Q) + f_3(Q) \,.$$

Where, f_1, f_2, and f_3 are demand functions of power utilization for industry, commercial and household.

Different timing and timer's prices can generate different quantity of power demand for different kinds of utilization. For example, the power utilization for industry is consumed different quantities of power in different seasons and timing for different industries. The demand for commercial utilization is also various with different commercial activities and different time. So does the quantity demand for the household utilization quantities. Generally, the power utilization of household is less from midnight to early morning. This is the difference of peak and off-peak time for power supply and demand. Therefore, the timer's prices are necessary to be considered in power pricing. The discussion and analysis of Figure 3 is based on the time interval, that is, the curve f is different caused by different time.

When f is increasing to f_1, that is $f_1 > f$, the optimal power quantity is increasing from Q_f^* to $Q_{f_1}^*$ in Formula (5). Figure 5 illustrates the relationship as following:

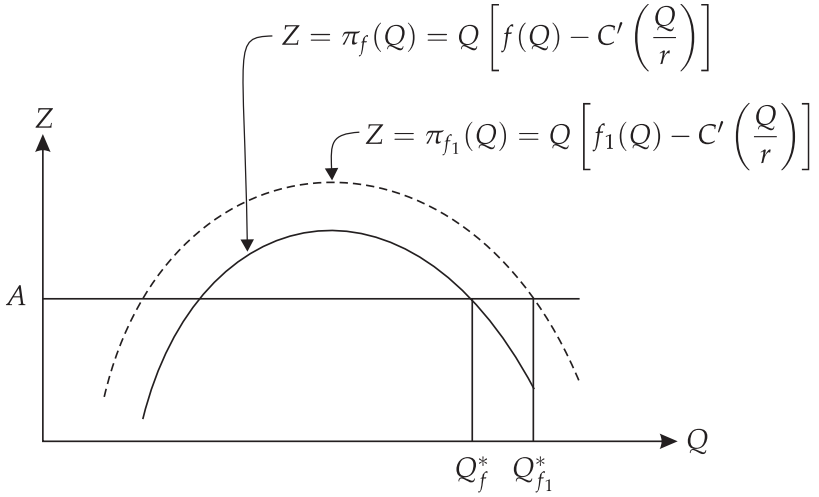

Figure 5

The optimal solution Q^* moves from Q_f^* to $Q_{f_1}^*$ when f is increasing to f_1

In addition, the margin cost power generation is increasing from $C'\left(\frac{Q_f^*}{r}\right)$ to $C'\left(\frac{Q_{f_1}^*}{r}\right)$ from Figure 5.

Figure 6 illustrates the relationship of power utilization quantity and power transmission cost as following. When the quantity of power

utilization is from Q_f^* to $Q_{f_1}^*$ the cost of power transmission will be changed from $\frac{y_f}{r}$ to $\frac{y_{f_1}}{r}$.

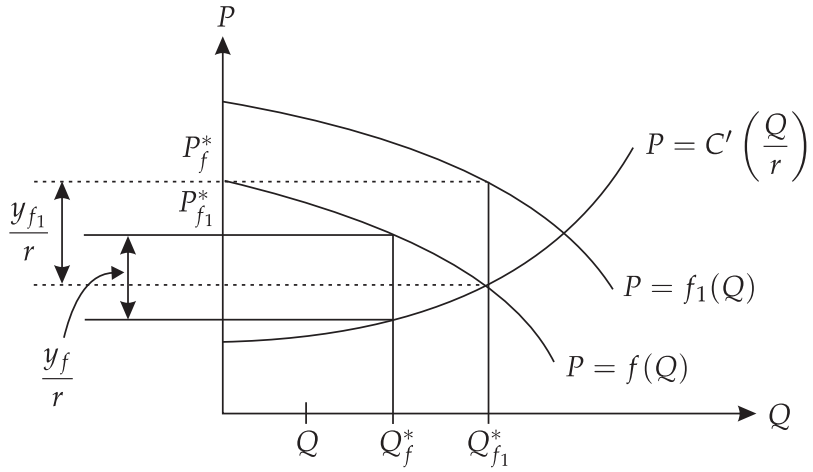

Figure 6

Influence when both demand function f and marginal demand function f_1 increase

The value of optimal transmission unit cost y^* and electricity price p^* for distribution market depend on f, C and r.

3.2 *Influence of optimal solution for power transmission efficiency r changes*

The power transmission efficiency is higher when transmission efficiency is less that r is greater. Generally speaking, transmission efficiency is related with the transmission distance, resistance of transmission wire and network structure. When power transmission efficiency r is increasing to r_1, that is $0 < r \leq r_1 < 1$, we have $Q_r^* < Q_{r_1}^*$ from Figure 5 and $P_r^* > Q_{r_1}^*$ shown in Figure 7.

3.3 *Influence of optimal solution when lower limit of transmission cost A is increasing to A_1*

We have $Q_{A_1}^* < Q_A^*$ from Formula (5) and Figure 6. Then we can get $P_A^* > P_{A_1}^*$ and $\frac{y_A^*}{r} > \frac{y_{A_1}^*}{r}$, that is $y_A^* > y_{A_1}^*$, from Figure 8.

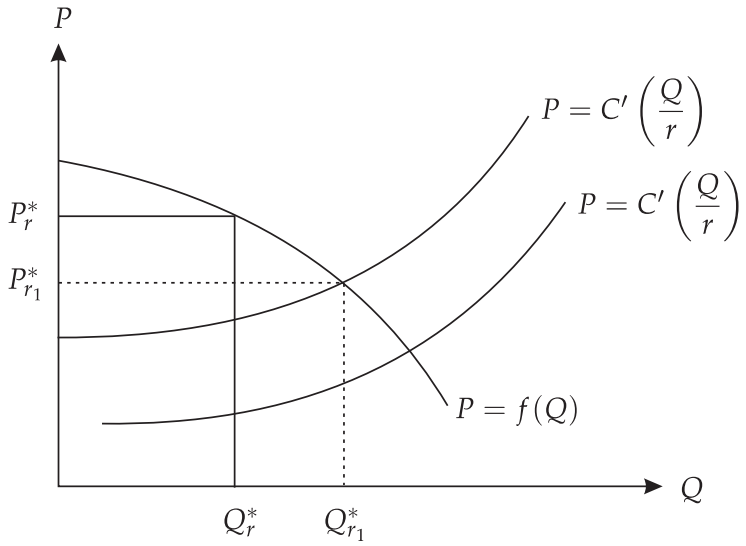

Figure 7
Influence of optimal solution when r is increasing to r

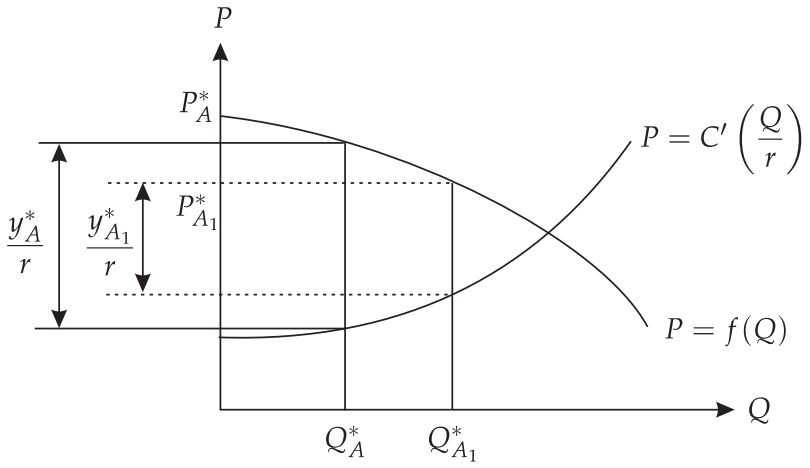

Figure 8
Influence of Q^* and y^* when the lower limit of transmission cost A is increasing to Q^*

3.4 *Influence of power generation margin cost when C' is increasing to C_1'*

If the relationship of power generation margin cost is as following:

$$C' < C_1', \quad C'' < C_1''.$$

Since $\frac{d\pi(Q)}{dQ}$ is the strict decreasing function of Q and C is the total cost of power transmission system, $\pi(Q)$ must decrease when the power transmission cost increases.

3.5 *Relationship of the decisive variable and optimal solution*

What the quantity Q changes affects the volume P from Formula (5). The demand curve $P = f(Q) = f_1(Q) + f_2(Q) + f_3(Q)$ is the strict decreasing function and $f' < 0$. Therefore, $f(Q)$ is decreasing when Q is increasing. $\pi(Q)$ is increasing when r increases, that is effective power transmission rate. $\pi(Q)$ is decreasing when power generation quantity C increases. The total welfare is decreasing when power transmission network revenue A Increases.

As the discussion mentioned, we have the conclusion what $\pi^*(Q)$ and y^* change shown as following table when f is increasing to f_1, r is increasing to r_1, C' is increasing to C'', and A is increasing to A_1.

Table 1
The variation of optimal solution when variables change

Variable	$f \to f_1$	$r \to r_1$	$C' \to C_1''$	$A \to A_1$
$\pi^*(Q)$	–	+	–	–
y^*	+	+	–	–

NOTE: "+" means increasing, "–" means decreasing

4. Conclusion

The industrial liberalization is a trend and electricity liberalization is unavoidable in electricity market. The electricity business operated by each division is the efficient approach to achieve liberalization. As we review the references in the whole world and our discussion in this paper, the business of power generation and distribution are suitable to be liberalized and operated independently. However, liberalization of power transmission business, which is special of structure, can't promise stable of power transmission and achieve the maximum goal of society welfare. As the discussion mentioned in this paper, there are some conclusions and recommendations as below:

(1) We introduce the supply and demand optimization model of power transmission network and analyze the relationship of decisive variables.

(2) In the model we construct, we fix power generation cost C and analyze power demand f_1, f_2 and f_3 in different time periods. We can apply this model to peak and off-peak time periods of power utilization.

(3) The contribution of this paper focuses on the supply and demand of power transmission system which is not familiar with scholars. We think there are the characteristics of monopolization and uniqueness for power transmission system. It is not suitable for liberalization and requires a fair organization responsible for regulation. Nevertheless, the liberalization can be promoted both for supply price in the generation market and demand price in the utilization market. However, the supply price in power generation market and demand price in power utilization market can be liberalized.

(4) The transmission sector should be an independent institute to adjust electricity while the generation and distribution sectors should be liberalized. However, the synthesized electric business includes the three sectors. Therefore, synthesized electric business doesn't reach the utmost efficiency. So synthesized electricity business is not suitable for liberalization.

(5) Taiwan power transmission business isn't suitable for liberalization under consideration of the existent environment and transmission network structure.

(6) We suggest setting up the Power Regulation Organization (PRO) in charge of the power dispatching and to define the electricity price of purchases and sales for power transmission network in order to regulate the balance and stability of power supply and demand.

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