The Stability Analysis of the Strategic Transaction in a Deregulation Environment

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Abstract:

In a deregulation system, the transaction may happen at any participant of the power pool. That will result in the complexity of the power exchange. The supervisor is necessary to inspect the system stability. In the paper, we derive the dynamic equations for the three distinct deregulation policies, uniform policy, UK (United Kingdom) policy, and discriminatory policy. The dynamic equation can deal with the strategic bidding and permit the distinct buying price. According to the simulation results, it is obvious that the unstable priority is uniform, UK, and discriminatory policy. Beside that, we also portray the unstable region in the power exchange region. They are useful for congestion management of ISO (Independent Power Operator).

Keyword: ISO, power pool, deregulation, SMP, clearing price.

I. Introduction

In a deregulation system, each participant tries to acquire the most benefit through the spot power market. It is very different from the conventional economic dispatch that the object is the entire minimum operation cost. In the deregulation system, power company may lose some member's profit to make transmission line congested. Moreover, its other member will bid the more expensive price to compensate the deficient power and so more company profits are obtained. This is called congestion benefit. Therefore, the strategic behavior of congestion benefit make the system management more complex. It is necessary to examine the stability of strategic transaction.

Some papers use the game theory [1] to study the strategic benefits. The papers [2,3] discussed that the network imposed additional constraints on the bids, and provider will increase their benefits by using game theory to coordinate bidding strategy. A genetic algorithm is used to evolve the bidding strategies and predicts whether the strategies will be profitable [4]. The strategic bidding is also discussed in a brokerage system [5-8]. The tariff can be used for the reference of strategic behavior [9-11].

Some authors [12-13] use the differential equation to study the market stability. In paper [14], the author establishes the differential algebraic equation (DAE), and examines the stability by analyzing the eigenvalues of its characteristic equation. It is successful to analyze the uniform price and non-strategic system. However, it is hard to analyze the actual power system that strategic behavior and the distinct prices for each transaction often exists. Our purpose is to obtain the dynamic equations that realizes the stability analysis for three distinct deregulation policies, uniform policy, U.K. policy and discriminatory policy.

There are four sections in the paper. In section II, the dynamic equations are derived for the distinct policies to analyze its stability of the steady solution. In section III, we applied our proposed differential equations to IEEE 30-bus [15]. The stability between the policies is discussed. A quantitative description of unstable region supports ISO for congestion management. Finally, a brief conclusion is outlined in section IV.

II. The Stability Analysis of the Distinct Deregulation Policies

To study the subject of the stability, we give the 4-bus example in Fig.1.

Fig.1 : The configuration of 4-bus system

The terminology in the paper:

P_i : Generation by unit i , in MW.

L : Total load , in MW

D : Total delivery power of P_A , P_B and P_C

E_l : Capacity of line l

α : Fraction of A's generation flowing on line 1

β : Fraction of B's generation flowing on line 1

S^{MAX} : Maximum price allowed by pool in \$/MW

S_i : Unit cost of generator i , in MW

P_i^* : Pre-curtailment schedules for generator i , in MW

λ : Pool buying price

b_i : The first order coefficient of generator i marginal cost

C_i : The second order coefficient of generator i marginal cost

T_i : The unit reacting time constant in generator i .

G_i : Provider i , for $i = A, B, C, D$

f_i : The profit of company i

Assume transaction procedure is distinguished into two steps by Line 1 congestion. The interesting providers are G_A and G_B prior the Line 1 congestion. If the line 1 congestion occurs, the pool will curtail some original transaction power and search another provider to compensate the deficient amount. Let the G_C and G_D to fill the deficient amount. Suppose G_A and G_C belongs to the same company 1. The G_B and G_D belongs to company 2 and company 3, respectively. When G_A and G_C use strategy to get congestion benefit, the stability of the distinct policies, described at [16], is studied here.

We will derive the optimal dynamic equation of the different deregulation policies first. Moreover, we append the strategic function into the optimal dynamic equation to make the stability analysis available for the strategic behavior. For all of the policies, we assume the bidding price of G_B is greater than the G_A 's and the Line 1 is more sensitive for G_A than G_B (it is $\alpha > \beta$). In addition, the buying prices of G_C and G_D are $S^{\max}$. There is no reason for them to bid their price lower the $S^{\max}$, because that the pool certainly needs their power to maintain power balance. These dynamic equations are derived as the following.

1. Uniform policy

The buying prices of each provider are the same under the uniform policy. Here, we set λ to denote the buying price. If we neglect the constant term of unit marginal cost, the company profit is expressed as the following:

$$f_1(P_A, P_C) = (\lambda - b_A)P_A - 0.5C_A P_A^2 + (\lambda - b_C)P_C - 0.5C_C P_C^2 \quad (1)$$

$$f_2(P_B) = (\lambda - b_B)P_B - 0.5C_B P_B^2 \quad (2)$$

$$f_3(P_D) = (\lambda - b_D)P_D - 0.5C_D P_D^2 \quad (3)$$

where f_1, f_2, f_3 are the company profits for company 1, 2, 3, respectively. The strategic behavior is explained as the P_A uses the line congestion constraint to make P_C generate. The more P_C amount is expected to obtain more benefits of company 1. The P_C can be expressed as the following:

$$P_C = D - P_A - P_B = (D - E_t / \beta) + \alpha P_A \quad (4)$$

Where $A = -1 + \alpha / \beta$ and D is total delivery power of P_A, P_B , and P_C .

According to Eq.(4), we have the following equation.

$$\partial P_C / \partial P_A = A \quad (5)$$

The constraint equation is the following:

$$P_A + P_B + P_C + P_D = L$$

According to the reference [14], we can express the dynamic and constraint equations as the following compact form:

$$\begin{bmatrix} T_A & 0 & 0 & 0 & 0 \\ 0 & T_B & 0 & 0 & 0 \\ 0 & 0 & T_C & 0 & 0 \\ 0 & 0 & 0 & T_D & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{P}_A \\ \dot{P}_B \\ \dot{P}_C \\ \dot{P}_D \\ \dot{\lambda} \end{bmatrix} = Q \begin{bmatrix} P_A \\ P_B \\ P_C \\ P_D \\ \lambda \end{bmatrix} + B \quad (6)$$

$$Q = \begin{bmatrix} -(C_A + A^2 C_C) & 0 & 0 & 0 & 1 + A \\ 0 & -C_B & 0 & 0 & 1 \\ 0 & 0 & -(C_C + C_A / A^2) & 0 & 1 + 1/A \\ 0 & 0 & 0 & -C_D & 1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -[b_A + A b_C + C_C A (D - E_t / \beta)] \\ -b_B \\ -[b_A / A + b_C - (C_A / A^2) (D - E_t / \beta)] \\ -b_D \\ -L \end{bmatrix}$$

2. U.K policy with Merit-Order Curtailment

The power pool buying prices are two levels due to line congestion in the UK policy. We set two distinct buying prices to denote it, λ_1 for G_A, G_B and λ_2 for G_C, G_D . To avoid the congestion, we will curtail the G_B power.

The matrix form of dynamic and constraint equations are derived as follows:

$$\begin{bmatrix} T_A & 0 & 0 & 0 & 0 \\ 0 & T_D & 0 & 0 & 0 \\ 0 & 0 & T_B & 0 & 0 \\ 0 & 0 & 0 & T_C & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{P}_A \\ \dot{P}_D \\ \dot{P}_B \\ \dot{P}_C \\ \dot{\lambda}_1 \\ \dot{\lambda}_2 \end{bmatrix} = Q \begin{bmatrix} P_A \\ P_D \\ P_B \\ P_C \\ \lambda_1 \\ \lambda_2 \end{bmatrix} + B \quad (7)$$

$$Q = \begin{bmatrix} -(C_A + A^2 C_C) & 0 & 0 & 0 & 1 & A \\ 0 & -C_D & 0 & 0 & 0 & 1 \\ 0 & 0 & -C_B & 0 & 1/(1-A) & 0 \\ 0 & 0 & 0 & -(C_C + C_A / A^2) & 1/A & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -[b_A + A b_C + C_C A (D - E_t / \beta)] \\ -b_D \\ -b_B \\ -[b_A / A + b_C - (C_A / A^2) (D - E_t / \beta)] \\ -K \\ -(L - K) \end{bmatrix}$$

Here we have arranged power vector in the sequence of P_A, P_D, P_B, P_C to prevent singularity when we compute the eigenvalues of the system later. The symbol K is the sum of P_A and P_B .

3.U.K policy with least curtailment:

The pool buying prices are still two levels due to congestion. To avoid the congestion, we have to curtail G_A .

The compensation payment is paid to G_A .

The matrix form of dynamic and constraint equations are derived as follows:

$$\begin{bmatrix} T_A & 0 & 0 & 0 & 0 & 0 \\ 0 & T_D & 0 & 0 & 0 & 0 \\ 0 & 0 & T_B & 0 & 0 & 0 \\ 0 & 0 & 0 & T_C & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{P}_A \\ \dot{P}_D \\ \dot{P}_B \\ \dot{P}_C \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = Q \begin{bmatrix} P_A \\ P_D \\ P_B \\ P_C \\ \lambda_1 \\ \lambda_2 \end{bmatrix} + B \quad (8)$$

$$Q = \begin{bmatrix} -(C_A + A^2 C_C) & 0 & 0 & 0 & 1 & 0 & A \\ 0 & -C_D & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -C_B & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -(C_C + C_A/A^2) & 1/A & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -[b_A + Ab_C + C_C A(D - E_1/\beta)] \\ -b_D \\ -b_B \\ -[b_A/A + b_C - (C_A/A^2)(D - E_1/\beta)] \\ -K \\ -(L - K) \end{bmatrix}$$

4. Discriminatory policy with merit-order curtailment:

The pool buying prices are according to the provider's bidding price and no curtailment compensation is needed to pay. Before congestion, set the bidding prices of P_A and P_B to be λ_1, λ_2 with that λ_1 is lower than λ_2 . After the congestion, it is intuitive that the P_C and P_D will bid the maximum allowable buying price S^{MAX} . So we set the same price to be λ_3 .

The matrix form of dynamic and constraint equations are derived as follows:

$$\begin{bmatrix} T_A & 0 & 0 & 0 & 0 & 0 \\ 0 & T_D & 0 & 0 & 0 & 0 \\ 0 & 0 & T_B & 0 & 0 & 0 \\ 0 & 0 & 0 & T_C & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{P}_A \\ \dot{P}_D \\ \dot{P}_B \\ \dot{P}_C \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} = Q \begin{bmatrix} P_A \\ P_D \\ P_B \\ P_C \\ \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} + B \quad (9)$$

$$Q = \begin{bmatrix} -(C_A + A^2 C_C) & 0 & 0 & 0 & 1 & 0 & A \\ 0 & -C_D & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -C_B & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -(C_C + C_A/A^2) & 1/A & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -[b_A + Ab_C + C_C A(D - E_1/\beta)] \\ -b_D \\ -b_B \\ -[b_A/A + b_C - (C_A/A^2)(D - E_1/\beta)] \\ -K_1 \\ -K_2 \\ -(L - K_1 - K_2) \end{bmatrix}$$

The K_1 is the transaction amount of P_A . The K_2 is the transaction amount of P_B . Assign the three different transaction amounts K_1, K_2 and $L - K_1 - K_2$ correspond to the three different prices λ_1, λ_2 and λ_3 , respectively.

5. Discriminatory policy with least curtailment:

For the merit order curtailment, the G_B power is curtailed and the deficient power is compensated by $(P_C + P_D)^{\text{merit-order}}$. For the least curtailment, the G_A power is curtailed and the deficient power is compensated by $(P_C + P_D)^{\text{least}}$. Then, the two power compensations have the following relation.

$$(P_C + P_D)^{\text{least}} = (\beta/\alpha)(P_C + P_D)^{\text{merit-order}} \quad (10)$$

6. The Stability Analysis:

The general form of the above matrix of dynamic and constraint equations can be written as the following form

$$\begin{bmatrix} T_1 & 0 & 0 \\ 0 & T_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{P}_1 \\ \dot{P}_2 \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} C_1 & 0 & S_3 \\ 0 & C_2 & S_4 \\ S_1 & S_2 & 0 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \lambda \end{bmatrix}$$

Where P_1 is the redundant power vector. Eliminating λ and P_1 yields the following reduced differential equation.

$$\begin{aligned} \dot{P}_2 &= [T_2 + S_4 S_3^{-1} T_1 S_1^{-1} S_2]^{-1} [C_2 + S_4 S_3^{-1} C_1 S_1^{-1} S_2] P_2 \\ &= H P_2 \end{aligned} \quad (11)$$

The stability of the deregulation system is investigated by the eigenvalues of the characteristic matrix H.

7. The modified dynamic equation:

In order to research the desired strategic steady solution, we will modify the optimal dynamic equation. The modified procedure is described as the following.

Set ΔB to be "provider's pricing difference matrix" that is dependent on $\Delta \lambda = \lambda - \lambda^0$. λ^0 and λ are the optimal and desired prices, respectively.

Now we express the optimal dynamic and the modified dynamic equations as the following.

The optimal dynamic equation:

$$\begin{pmatrix} T & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \dot{P} \\ \dot{\lambda} \end{pmatrix} = \begin{pmatrix} Q_1 & Q_2 \\ Q_3 & Q_4 \end{pmatrix} \begin{pmatrix} P^0 \\ \lambda^0 \end{pmatrix} - \begin{pmatrix} B \\ L \end{pmatrix}$$

The modified dynamic equation:

$$\begin{pmatrix} T & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \dot{P} \\ \dot{\lambda} \end{pmatrix} = \begin{pmatrix} Q_1 + \Delta Q_1 & Q_2 + \Delta Q_2 \\ Q_3 & Q_4 \end{pmatrix} \begin{pmatrix} P \\ \lambda \end{pmatrix} - \begin{pmatrix} B + \Delta B \\ L \end{pmatrix} \quad (12)$$

where $(\Delta Q_1, \Delta Q_2)$ is the necessary terms that we must modify the dynamic equation to reach the strategic steady solution $S = (P, \lambda)^T$. By some algebraic manipulations, we obtain the following.

$$(\Delta Q_1, \Delta Q_2) = (\Delta B - Q_2 \Delta \lambda) (S^T S)^{-1} S^T \quad (13)$$

As long as the strategic steady solution S is assigned. Then the $(\Delta Q_1, \Delta Q_2)$ can be obtained by Eq.(13).

III. Simulation Results

We use IEEE-30 bus shown in Figure 6 to demonstrate the proposed method and assign bus 13,10,5,19 to providers A,B,C,D, respectively. The load is at bus 5. Line 1 is the branch between bus 5 and bus 7. For easy comparison, we fixed the following parameters in Table 1.

Table 1: The parameters of simulation

parameter	T_A	T_B	T_C	T_D	b_A	b_B	b_C	b_D
value	3	2	1	2	0.2	0.1	0.2	0.2
parameter	C_A	C_B	C_C	C_D	E_1	L	α	β
value	0.03	0.02	0.05	0.06	0.21	8	0.0502	0.0313

The simulation results of the different policies are summarized in Table 2. According to Eq.(10), we set $(P_C + P_D)^{\text{merit-order}} = 3$, $(P_C + P_D)^{\text{least}} = 1.8705$.

Table 2: Simulation results of the different policies

policy	λ_1 λ_2 λ_3	P_A P_B P_C P_D	f_1	f_2	f_3	Pool cost	Eigen. value
uniform	5 NA NA	2.8307 2.1693 0.7500 2.2500	17.053	10.5826	10.6481	40	0.0207 -0.0021 -0.0215
UK_m	1 5 NA	2.8307 2.1693 0.7500 2.2500	5.7303	1.9053	10.6481	23	-0.0181 -0.0945
UK_l	1 5 NA	0.9601 5.1694 0.7500 1.1205	5.0902	4.3852	5.3407	17.3525	0.0307 -0.0801
Dis_m	0.75 1 5	2.8307 2.1693 0.7500 2.2500	5.0227	1.9053	10.6481	19.2923	-0.1308
Dis_l	0.75 1 5	0.9601 5.1694 0.7500 1.1205	4.1002	4.3852	5.3407	15.2420	-0.1342

The abbreviation of Table 2:

Uniform: uniform policy.

UK_m: U.K policy with merit-order curtailment

UK_l: U.K policy with least curtailment

Dis_m: Discriminatory policy with merit-order curtailment

Dis_l: Discriminatory policy with least curtailment

The uniform policy has only one buying price level. The UK_m and UK_l have two levels of buying price. The Dis_m and Dis_l have three levels of buying price. $S = (P, \lambda)^T$ in the first two columns of Table 2 denotes the strategic results. We notice the index of the eigenvalues. It shows that the uniform and UK_l policies are unstable. The instability means that such transaction is impractical. Its solution will diverse as time increasing.

Next we can use the derived dynamic equations to portray the stable and unstable region within the load $L=8$ range. The feasible region denotes that all of the providers do not supply negative power of steady solution. For the discriminatory policy, the two curtailment methods have the same dynamic equations as mentioned last section. Therefore, we only portray one discriminatory drawing. The drawings are shown in figure 2 to figure 5. The data supports the participant to decide which strategy is practical.

Figure 2: The stability drawing of uniform policy

Figure 3: The stability drawing of UK_m policy

Figure 4: The stability drawing of UK_l policy

Figure 5: The stability drawing of discriminatory policy

IV. Conclusions

Accompany with the progress of power deregulation, the power dispatch center has changed its role from ordering to supervising. The ISO needs to inspect the security of transaction and adopts the necessary curtailment. The paper studies the stability of power transaction. The unstable transaction means that the strategy is impractical. Although there have been several papers dealing with the topic, they have not considered the strategic behavior yet. We successfully use IEEE-30 bus to investigate the stability of distinct policies. It shows that the uniform policy is most unstable. Besides that, the unstable region is available for the congestion management of ISO and the references of participants..

Figure 6 IEEE 30-bus system

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