The Research on Multi-Order Parameters' Stable Value of Electricity Market Operation Efficiency Based on Complex System

Sun Jingqi, Yan Li, and Li Chunjie

Abstract—**Electricity market is a complex system involving multi-factors and multi-links, together with typical characteristics of self-organization. In order to evaluate the efficiency of its operations dynamically, this study established the co-evolution model and revealed the dynamic evolution of the internal mechanism. Three order parameters were found: declared supply and demand ratio, reserve rate of generation and market clearing price. PJM data and the adiabatic elimination of Synergetic are used here. By solving the order parameter equations, this study found and analyzed the stability of the steady state solution.**

Index Terms—**Self-organization, co-evolution, complex system, order parameter**

I. Introduction

Electricity market reform is a systems engineering, even with diverse ways, it is always about 'enhance efficiency, lower cost and optimize the resources allocation'. How to assess the efficiency of electricity market operation and figure out the factors affecting it becomes the main concern. If its operation efficiency is put into study, the market environment, trade mechanisms and firm behavior all need to be considered. Worldwide scholars have done lots of research on how to enhance the efficiency of electricity market operation based on factors above, such as the research on market structure, firm behavior and policy with SCP theory, the research on the relationship between market trade mechanisms and efficiency, the research on the development trend and equilibrium of the power market based on game theory and the research on the assessment of market efficiency from regulatory perspective etc [1]-[7]. So far, all these studies about the electricity market efficiency didn't fit to the characteristics of complex system.

Self-organization theories study the complex self-organization system. These kinds of system can evolve and improve the organizational behavior structure itself, which means to form new structure and function through the evolution under environmental interaction [8]. Synergy drives the complex system to evolve as well as self-organization, and the Synergetics will reveal the dynamic mechanism by studding the co-evolution model and the order parameter.

This paper used self-organization theory to construct co-evolution model of electricity market and found the order parameter that described the system dynamic operation state. As a result, the stationary solution of the order parameters had been given through equations, but it was not necessarily the stable solution. In that case, this paper used Jacobian Eigenvalues to analyze the stability of stationary solution, which finally led to the stable solution for the effective electricity market operation state.

II. The Co-Evolution Model of Electricity Market Operation

A. The Principle of Synergetics

Synergetics, founded by Haken, a German physicist, is the self-organization theory which studies synergistic effect produced by the nonlinear interaction among subsystems of one complex system and how it leads system structure to evolve in order. In synergetics theory, when system trends towards critical point, its stability will be destroyed and at that point, system's status variables should be divided into two categories: one is fast variable with quick change varied with time and short relaxation time; the other is slow variable which is also called order parameter. It varies with time slowly and takes long or even infinite relaxation time to reach new stationary state. When the system is in disorder, the order parameter value is zero. However it varies with the outside conditions, when reaching the critical point, order parameter increases to maximum, meanwhile system emerges a type of orderly macrostructure.

Order parameter describes a system's macroscopical degree of order. It dominates and defines the degree of order, its evolvement and the structure performance of a macroscopical system [9]. Therefore, electricity market's order parameter is the key to assess whether the operation is effective. The mathematical equation of synergy complex system evolution is generally expressed as Lagevin equation:

$$\dot{u} = K(u, s) + F \tag{1}$$

where $\dot{u}$ denotes the status variable's change rate; u denotes status variable which could be microscopic quantity or macroscopic quantity; s denotes control parameter; F denotes random fluctuation. The evolution model consists of u and its various orders derivatives which are differential equation or simultaneous differential equations.

B. The Selection of ELECTRICITY market's Status Variable

The 'Structure, Conduct and Performance' (referred to as

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SCP), which is analytical paradigm of industrial organization represented by Harvard school, expounds the relationship of market structure, firm behavior and market performance, laying the solid foundation for industrial organization theory. This paper used this paradigm's principle to divide electricity market operation into structure, behavior and performance subsystems. Considered both the former researches [10-13] and the complex properties of electricity market, this paper selected the five variables for the study. $X_1(t)$ declared supply and demand ratio; $X_2(t)$ reserve rate of generation; $X_3(t)$ transaction charge; $X_4(t)$ market clearing price; $X_5(t)$ transmission congestion costs.

TABLE I: DESCRIPTION OF THE STATE VARIABLES OF ELECTRICITY MARKET OPERATION

Status variable		Definition	indicators
declared supply and demand ratio	$X_1(t)$	The ratio of generation side and purchasing side's declared power; It implies the supply and demand state of electricity market.	Indicators for structure subsystem
reserve rate of generation	$X_2(t)$	(the available outcome of power generation-power demand)/the available outcome of power generation; It implies the advanced supply capacity of generation.	
transaction charge	$X_3(t)$	The actual transaction charge of power generation market after bidding; It depends on the trade behavior of both sale and purchase sides.	Indicators for behavior subsystem
market clearing price	$X_4(t)$	The electricity prices that won the bid in generation market biding; It implies the stability of market and the benefit of both sale and purchase sides at some extend.	Indicators for performance subsystem
transmission congestion costs	$X_5(t)$	The loss caused by transmission congestion; It affects the economical efficiency and reliability of system operation and implies market development.	

C. The Co-Evolution Model of Electricity Market

According to electricity market subsystem's nonlinear interaction and its co-evolution model (1), the electricity market operation system' co-evolution model should be expressed as:

$$\frac{dX_i(t)}{dt} = a_i X_i(t) + b_i X_i^2(t) + \sum_{j=1, j\neq i}^{5} (a_{ij} X_j(t) + b_{ij} X_j^2(t)) + f_i(t) \qquad (2)$$

a_i Denoted relaxation coefficient of X_i, reflecting decay rate for factor i. Fast variable accompanied with large relaxation coefficient decays quickly and vice versa.

b_i, a_{ij}, b_{ij} denoted the nonlinear coupling coefficient among variables.

$f_i(t)$ Denoted random fluctuation from internal or external system. It not only drove the power system away from original track or state but also indicates the deviation to electricity market operation system's equilibrium, which triggered system to evolve.

This paper only considered the primary and secondary items for each status variable's internal or external synergy, and the term of higher order would be verified in subsequent context.

III. THE CO-EVOLUTION MODEL OF ELECTRICITY MARKET OPERATION IN REGION PJM

This paper utilized electricity market operation data from 2008 to 2009 in region PJM to establish co-evolution model as following steps:

1) Normalized the data due to different dimensions

$$X_i^{(0)}(t) = \frac{X_i(t) - \min_t X_i(t)}{\max_t X_i(t) - \min_t X_i(t)}, \text{ (i=1, …, 5; t=1,2,…,24)} \qquad (3)$$

2) Accumulated results above to get $X_i^{(1)}(t)$ (weaken the random of original series)

$$X_i^{(1)}(k) = \sum_{t=1}^{k} X_i^{(0)}(t), \text{ (k=1, 2,…, 24)} \qquad (4)$$

3) For convenience, this paper assumed $f_i(t) = 0$, and calculated a_i, b_i, a_{ij}, b_{ij} in equation (2) by least square method. Due to $\frac{dX_i(t)}{dt} = X_i^{(1)}(t) - X_i^{(1)}(t-1) = X_i^{(0)}(t)$, substituted it into equation (2) got the result as:

$$X_i^{(0)}(t) = a_i X_i^{(1)}(t) + b_i (X_i^{(1)}(t))^2 + \sum_{j=1, j\neq i}^{5} (a_{ij} X_j^{(1)}(t) + b_{ij} (X_j^{(1)}(t))^2) \qquad (5)$$

Substituted t=2,…, 24 into equation (5), then:

$$\begin{cases} X_i^{(0)}(2) = a_i X_i^{(1)}(2) + b_i (X_i^{(1)}(2))^2 + \sum_{j=1, j\neq i}^{5} (a_{ij} X_j^{(1)}(2) + b_{ij} (X_j^{(1)}(2))^2) \\ X_i^{(0)}(3) = a_i X_i^{(1)}(3) + b_i (X_i^{(1)}(3))^2 + \sum_{j=1, j\neq i}^{5} (a_{ij} X_j^{(1)}(3) + b_{ij} (X_j^{(1)}(3))^2) \\ \cdots\cdots \\ X_i^{(0)}(24) = a_i X_i^{(1)}(24) + b_i (X_i^{(1)}(24))^2 + \sum_{j=1, j\neq i}^{5} (a_{ij} X_j^{(1)}(24) + b_{ij} (X_j^{(1)}(24))^2) \end{cases} \qquad (6)$$

Sorted equation (6), then got: $y_{iN} = B_i P_i$.

Due to the 23×10 matrix B_i, this paper got following under least square method:

$$P_i = (B_i^T B_i)^{-1} B_i^T y_{iN} \qquad (7)$$

Utilized the normalized data to calculate B_i, substituted B_i and y_{iN} into equation (7), got equation (8):

$$\begin{cases} \frac{dX_1^{(1)}(t)}{dt} = 0.0261X_1^{(1)}(t) - 0.0172(X_1^{(1)}(t))^2 + 0.4324X_2^{(1)}(t) + 0.3795X_3^{(1)}(t) \\ \quad -0.2303X_4^{(1)}(t) + 0.1947X_5^{(1)}(t) - 0.0249(X_2^{(1)}(t))^2 + 0.0164(X_3^{(1)}(t))^2 \\ \quad -0.0137(X_4^{(1)}(t))^2 - 0.0288(X_5^{(1)}(t))^2 + f_1(t) \\ \frac{dX_2^{(1)}(t)}{dt} = -0.2115X_2^{(1)}(t) - 0.0033(X_2^{(1)}(t))^2 - 0.5103X_1^{(1)}(t) - 0.3597X_3^{(1)}(t) \\ \quad -0.1805X_4^{(1)}(t) + 1.1468X_5^{(1)}(t) + 0.0537(X_1^{(1)}(t))^2 + 0.0189(X_3^{(1)}(t))^2 \\ \quad +0.0045(X_4^{(1)}(t))^2 - 0.0438(X_5^{(1)}(t))^2 + f_2(t) \\ \frac{dX_3^{(1)}(t)}{dt} = -1.3004X_3^{(1)}(t) + 0.0448(X_3^{(1)}(t))^2 - 0.7607X_1^{(1)}(t) + 0.2376X_2^{(1)}(t) \\ \quad -0.5158X_4^{(1)}(t) + 2.7274X_5^{(1)}(t) + 0.0007(X_1^{(1)}(t))^2 + 0.0581(X_2^{(1)}(t))^2 \\ \quad +0.0469(X_4^{(1)}(t))^2 - 0.2338(X_5^{(1)}(t))^2 + f_3(t) \\ \frac{dX_4^{(1)}(t)}{dt} = -0.5625X_4^{(1)}(t) + 0.0185(X_4^{(1)}(t))^2 - 0.0328X_1^{(1)}(t) + 0.1993X_2^{(1)}(t) \\ \quad +0.114X_3^{(1)}(t) + 1.2635X_5^{(1)}(t) - 0.0019(X_1^{(1)}(t))^2 + 0.0089(X_2^{(1)}(t))^2 \\ \quad -0.0104(X_3^{(1)}(t))^2 - 0.1314(X_5^{(1)}(t))^2 + f_4(t) \\ \frac{dX_5^{(1)}(t)}{dt} = 1.5432X_5^{(1)}(t) - 0.1505(X_5^{(1)}(t))^2 - 0.0143X_1^{(1)}(t) - 0.3014X_2^{(1)}(t) \\ \quad -0.4845X_3^{(1)}(t) - 0.4447X_4^{(1)}(t) - 0.0103(X_1^{(1)}(t))^2 + 0.0323(X_2^{(1)}(t))^2 \\ \quad +0.029(X_3^{(1)}(t))^2 + 0.0401(X_4^{(1)}(t))^2 + f_5(t) \end{cases} \tag{8}$$

4) Calculated $f_i(t)$

Supposed that mean value for original status variable was $\bar{X}_i(t)$ and $f_i(t) = X_i(t) - \bar{X}_i(t)$. According to reference [14], this paper considered the fluctuation of electricity market operation as periodic function:

$$f_i(t) = \alpha_{i1}\sin t + \cdots + \alpha_{ik}\sin kt + \beta_{i1}\cos t + \cdots + \beta_{ik}\cos kt \tag{9}$$

This paper fitted equations to equation (9) through Eviews, finding that when $k > 2$, the goodness-of-fit didn't change. Hence only the part of $k \le 2$ was taken into consideration to calculate the fluctuation:

$$\begin{cases} f_1(t) = -0.2345\sin t + 0.0189\sin 2t - 0.0938\cos t - 0.0077\cos 2t \\ f_2(t) = -0.0327\sin t - 0.0965\sin 2t + 0.0893\cos t - 0.0357\cos 2t \\ f_3(t) = 0.3192\sin t + 0.0085\sin 2t - 0.0302\cos t - 0.003\cos 2t \\ f_4(t) = 0.0109\sin t + 0.0228\sin 2t + 0.0418\cos t - 0.023\cos 2t \\ f_5(t) = 0.0648\sin t - 0.0065\sin 2t + 0.0355\cos t + 0.0016\cos 2t \end{cases} \tag{10}$$

Equation (8) and (10) were the co-evolution model of electricity market operation in region PJM.

IV. The Solution of Order Parameter Stable Value

A. The Determination of Order Parameter

The relaxation coefficients for status variables were given by equation (8):

$a_1 = 0.0261$, $a_2 = -0.2115$, $a_3 = -1.3004$,

$a_4 = -0.5625$, $a_5 = 1.5432$

Through the judgments of relaxation coefficient, this paper selected three order parameters for electricity market, declared supply and demand ratio, reserve rate of generation and market clearing price.

B. The Establishment of Order Parameter Equations

This paper used adiabatic elimination technique to eliminate fast variables, and then solved the slow variables' differential equations. The process as follow:

Set the equation of fast variable equal with zero, and took slow variable $X_1^{(1)}(t)$ $X_2^{(1)}(t)$ $X_4^{(1)}(t)$ to denote fast variable $X_3^{(1)}(t)$ $X_5^{(1)}(t)$ as:

$$\begin{cases} X_3^{(1)}(t) = 0.0335(X_2^{(1)}(t))^2 + 0.4626X_4^{(1)}(t) \\ X_5^{(1)}(t) = 0.0112(X_1^{(1)}(t))^2 + 0.8798X_4^{(1)}(t) - 0.0233(X_4^{(1)}(t))^2 \end{cases} \tag{11}$$

Substituted result above into the equation of slow variable to get order parameter equations (12):

$$\begin{cases} \frac{dX_1^{(1)}(t)}{dt} = 0.026X_1^{(1)}(t) - 0.015(X_1^{(1)}(t))^2 + 0.432X_2^{(1)}(t) - 0.012(X_2^{(1)}(t))^2 \\ \quad +0.117X_4^{(1)}(t) - 0.037(X_4^{(1)}(t))^2 \\ \frac{dX_2^{(1)}(t)}{dt} = -0.510X_1^{(1)}(t) + 0.066(X_1^{(1)}(t))^2 - 0.212X_2^{(1)}(t) - 0.015(X_2^{(1)}(t))^2 \\ \quad +0.662X_4^{(1)}(t) - 0.052(X_4^{(1)}(t))^2 \\ \frac{dX_4^{(1)}(t)}{dt} = -0.033X_1^{(1)}(t) + 0.012(X_1^{(1)}(t))^2 + 0.199X_2^{(1)}(t) + 0.013(X_2^{(1)}(t))^2 \\ \quad +0.602X_4^{(1)}(t) - 0.115(X_4^{(1)}(t))^2 \end{cases} \tag{12}$$

C. Stationary Solution and Stability Analysis

Set order parameter equations (12) equal with zero and got the stationary solution:

$X_1^{(1)}(t)=X_2^{(1)}(t)=X_4^{(1)}(t)=0$ or $X_1^{(1)}(t)=9.282$

$X_2^{(1)}(t)=8.330$ $X_4^{(1)}(t)=8.570$

Stationary solution is a solution when the order parameter equations equals with zero, which also is the extreme point. Stable point suggests that the system is in stable state at that point and will return to that point automatically after disturbance. Not every stationary solution is the stable point; therefore judgment needs to be done. The determination for the stable point of single order parameter model could be completed through the potential function theory. However, for the multi-order parameter model, it is told through the type of eigenvalues for Jacobian matrix of the order parameter equations [15], [16].

Supposed that order parameter equations as:

$$\begin{cases} \frac{dX_1^{(1)}(t)}{dt} = F_1(X_1^{(1)}, X_2^{(1)}, X_4^{(1)}) \\ \frac{dX_2^{(1)}(t)}{dt} = F_2(X_1^{(1)}, X_2^{(1)}, X_4^{(1)}) \\ \frac{dX_4^{(1)}(t)}{dt} = F_3(X_1^{(1)}, X_2^{(1)}, X_4^{(1)}) \end{cases} \tag{13}$$

The Jacobian matrix of equations (13) was:

$$A = \begin{bmatrix} \frac{\partial F_1}{\partial X_1^{(1)}} & \frac{\partial F_1}{\partial X_2^{(1)}} & \frac{\partial F_1}{\partial X_4^{(1)}} \\ \frac{\partial F_2}{\partial X_1^{(1)}} & \frac{\partial F_2}{\partial X_2^{(1)}} & \frac{\partial F_2}{\partial X_4^{(1)}} \\ \frac{\partial F_3}{\partial X_1^{(1)}} & \frac{\partial F_3}{\partial X_2^{(1)}} & \frac{\partial F_3}{\partial X_4^{(1)}} \end{bmatrix} = \begin{bmatrix} 0.026 - 0.030X_1^{(1)} & 0.432 - 0.024X_2^{(1)} & 0.177 - 0.074X_4^{(1)} \\ -0.510 + 0.132X_1^{(1)} & -0.212 - 0.030X_2^{(1)} & 0.662 - 0.104X_4^{(1)} \\ -0.033 + 0.024X_1^{(1)} & 0.199 + 0.026X_2^{(1)} & 0.602 - 0.230X_4^{(1)} \end{bmatrix} \tag{14}$$

1) When $X_1^{(1)}(t)=X_2^{(1)}(t)=X_4^{(1)}(t)=0$

Jacobian matrix as $A = \begin{bmatrix} 0.026 & 0.432 & 0.117 \\ -0.510 & -0.212 & 0.662 \\ -0.033 & 0.199 & 0.602 \end{bmatrix}$

Through calculation, the eigenvalues were:

$\lambda_1 = -0.1312 + 0.3684i$, $\lambda_2 = 0.1312 - 0.3684i$, $\lambda_3 = 0.6784$

According to stationary solution stability theory, as long as one eigenvalues has a positive real part, the stationary solution is unstable.

Hence solution $X_1^{(1)}(t)=X_2^{(1)}(t)=X_4^{(1)}(t)=0$ was rejected.

2) When $X_1^{(1)}(t)=9.282$, $X_2^{(1)}(t)=8.330$, $X_4^{(1)}(t)=8.570$

Jacobian matrix as $A=\begin{bmatrix} -0.252 & 0.232 & -0.517 \\ 0.715 & -0.462 & -0.229 \\ 0.190 & 0.416 & -1.369 \end{bmatrix}$

Through calculation, the eigenvalues were

$\lambda_1=-0.2490$ $\lambda_2=-0.4974$ $\lambda_3=-1.3366$

Same as above, all eigenvalues are negative real number, hence it is the stable point. $X_1^{(1)}(t)$, $X_2^{(1)}(t)$, $X_4^{(1)}(t)$ tends to return to the stationary solution after $X_1^{(1)}=9.282$, $X_2^{(1)}=8.330$, $X_4^{(1)}=8.570$ is disturbed.

Because the data was normalized and accumulated, the solution for order parameter equations wasn't the initial stable value and it needs accumulated subtraction and reduction.

$X_1(t)=0.978$ $X_2(t)=18.96\%$ $X_4(t)=56.57$

The calculation indicated that the operation efficiency of electricity market complex system was led by multi- order parameter. When declared supply and demand ratio is 0.978, reserve rate of generation is 18.96% and market clearing price is 56.57$/MWH, the electricity market in that area is in the best state of operation efficiency, which operates at supreme order degree and most stable state.

V. Conclusion

This paper established the co-evolution model of electricity market operation system based on Synergetics which is a branch of self-organization theory. It found the declared supply and demand ratio, reserve rate of generation and market clearing price among multi-status variables as the order parameters which led the system to evolve. It used the adiabatic elimination method to construct the equations to calculate the stationary solution and the characteristic for Jacobian matrix eigenvalues to analyze stability of stationary solution. Ultimately, it calculated the order parameter value at the supreme order degree for electricity market operation system and explored new entry point to evaluate electricity market operation efficiency dynamically.

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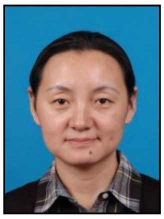

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