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Co-evolution entropy as a new index to explore power system transition: A case study of China's electricity domain

Yan Nie, Tao Lv*, Jian Gao

School of Management, China University of Mining and Technology, No. 1 Daxue Road, Xuzhou 221116, Jiangsu, China

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ABSTRACT

Power systems are bound to experience a long transition process, which involves not only changes in technology but also changes in user practices, regulations, industrial networks, infrastructures, and cultures. There are conflicts among these factors on account of the mutual uncoordinated changes, which would hinder the development of power systems. Therefore, keeping permanent coordination of numerous factors is a great challenge for the power system evolution. Current evaluation methods of power system evolution do not pay sufficient attention to the co-evolution of factors, particularly for technology, society, finance and policy, as well as insight from innovation studies and the sociology of technology. Hence, we propose a new index: co-evolution entropy, which can indicate the positive-negative entropy interaction coordinating system evolution. Then, based on socio-technical system, we identify 14 factors participating in the evolution of power system from three layers: landscape, regime and niche. Finally, we apply this index to China's electricity domain for identifying the evolution obstacles of non-coordinates, and propose a strategy to improve the system's co-evolution. Results show that (1) the change in co-evolution entropy from different layers has different characteristics; for example, the landscape mainly possesses negative entropy, but the regime holds positive entropy. (2) The power system's co-evolution entropy changes from 0.043 to −0.154, and reaches the maximum (0.054) in 2000s, which indicates that China's power system begins the coordinated development through a run-in. (3) The co-evolution of the power system is hindered by too much policy intervention; however, technology innovation and electricity market opening could enhance its co-evolution. We also derive strategic policy recommendations from the analysis result and present a co-evolution concept to improve the socio-technical system.

1. Introduction

Power systems, a significant soft power, ensure the safety and stability of whole societies. Accordingly, the power system must have experienced several periodical evolutions in order to satisfy the demand of different countries in different periods, which is aimed at improving the factor's function for national development. However, these factors are not coordinated enough in the evolutionary process due to information imbalance, technical imperfection, and path-locking, which may cause obstacles and prolong the process of evolution.

Coordination refers to the coherence between every element, and its essence means value creation based on interactive qualitative changes. Coordination plays an important role in the whole evolutionary process. However, more obstacles may unexpectedly hinder the evolution of the power system if the evolution is non-coordinate. In view of this, from China's perspective, we present partial obstacles related to a lack of coordination between factors in the evolutionary process. Specifically, quite a few areas in China still have new plans for thermal power plants in spite of coal's overcapacity. The Haze days and social appeals to renewable energy are rising together; furthermore, the amount of “Abandoned wind, photovoltaic and water” also continues to grow (the wind-abandoned rate in Gansu (2016), has reached 43% (Business.sohu.com, 2017), an increase of 4% compared to 2015 (www.xny365.com, 2017)). Although the Chinese government strives to promote distributed power generation, energy storage, and electric vehicles, these solutions cannot increase expected effects in light of mismatched infrastructure.

Hence, coordination is regarded as an essential qualification for evolution, and co-evolution is a significant criterion to measure the

* Corresponding author.
E-mail addresses: nieyan1988@163.com (Y. Nie), taocumt@cumt.edu.cn (T. Lv), 15162143863@163.com (J. Gao).

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evolution effect. However, there is little research on whether the factors are coordinated in the evolutionary process of power systems, partly because the factors are difficult to select and the interactions of factors are more complicated to describe.

To fill this gap, this work aims to create a new index: co-evolution entropy for evaluating the co-evolution effect on power systems. From a perspective of socio-technical system, we first select the main factors of power systems from three layers and construct the factors' relationship graphs at different stages through the collected data, including the government work reports etc. Then, we propose co-evolution entropy by adopting the Dissipative Structure theory and Brusselator model, which is applied to China's power system to reveal its co-evolution characteristics in three stages. Finally, we propose that reducing the government intervention and reforming the financial system could enhance the co-evolution of power system. In addition, we analyze the obstacles of co-evolution and raise a co-evolution concept to improve the socio-technical system.

This paper is organized as follows: Section 2 reviews the previous research of power system evolution, especially on co-evolution. Section 3 creates a new index: co-evolution entropy based on the Dissipative Structure Theory and the Brusselator Model. Section 4 identifies the total 14 factors who participated in the evolution of power system based on socio-technical system. Section 5 describes the correlation graph of China's power system at three stages based on the collected data. Section 6 illustrates the analysis results of co-evolution entropy to reveal the law of co-evolution and presents a co-evolution framework to improve the socio-technical system. Section 7 concludes the main findings and derives strategic policy recommendations. Fig. 1 shows the research framework of this study.

2. Literature review

The research of power system evolution has been a concern since power systems began to face the challenge of renewable energy and supply side reform. The representative research presented a concept of power system co-evolution to indicate that the evolution of power systems involves not only technical updates but also coordinated change in user practices, regulations, industrial networks, infrastructures, and cultures (Hofman et al., 2004). Additionally, in this work, socio-technical system theory is the basis on which evolutionary factors of power systems are selected; Dissipative Structure Theory and the Brusselator Model provide a theoretical basis for the design of co-evolution entropy. Therefore, we introduce some research results from three aspects: evolution of power systems, particularly in co-evolution, socio-technical system transition theory, and Dissipative Structure and the Brusselator model.

2.1. Intelligent evolution of power system

The evolution of power grid undergoes a complicated and long process, which is evolving from simplicity to complexity to the intelligent power system at this stage (Farhangi, 2010). Various countries are trying to analyze the evolutionary targets and characteristics in the intelligent power system. Sarwat et al. introduced a method for reliability assessment of the intelligent power system considering variable weather condition to enhance the reliability (Sarwat et al., 2015); Boroojeni et al. presented a novel oblivious routing economic dispatch algorithm for intelligent power system aimed at minimizing the emission by optimizing the total power generation (Boroojeni et al., 2016). In addition, recent studies on the positive impacts of power system evolution highlight contributions for the intellectualization, including providing tremendous operational benefits for power utilities (Fan and Borlase, 2009), self-decision making for load management (Amini et al., 2013), and strengthening consumer participation (Cardenas et al., 2014). Afterwards, the micro grid appears to promote the intellectual evolution of power system, which is in favor of coordinated integration of the increasing share of distributed generation units (Ravichandran et al., 2013). Meanwhile, distributed generation and energy shortage associated with the power system infrastructure are also problems for most micro grid projects, posing economic costs and lack of coordination of power supply and demand (Gopalan et al., 2014). Therefore, a number of researchers are devoted to analyzing the micro grid framework, which could

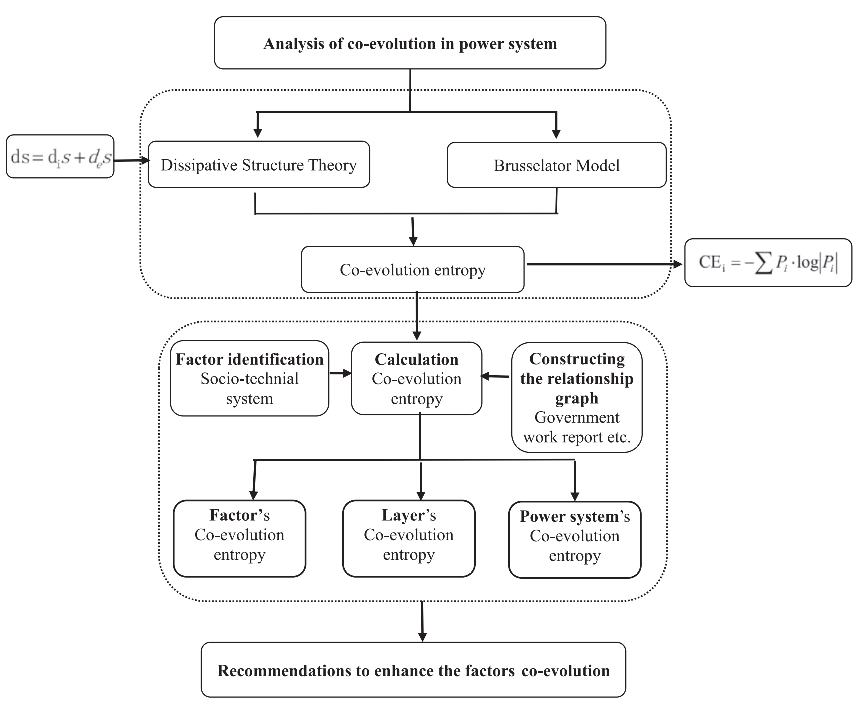

Fig. 1. Research framework of this study.