Energy for Sustainable Development 43 (2017) 100–113

Contents lists available at ScienceDirect

Energy for Sustainable Development

Modeling for the regional integration of electricity markets

Johan Manuel Redondo[a,*], Gerard Olivar[b], Danny Ibarra-Vega[c,*], Isaac Dyner[d]

[a] Universidad Católica de Colombia, Bogotá, Colombia
[b] Universidad Nacional de Colombia, Manizales, Colombia
[c] Universidad Sergio Arboleda, Bogotá D.C., Colombia
[d] Universidad Jorge Tadeo Lozano, Bogotá D.C., Colombia

ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form 28 November 2017
Accepted 19 December 2017
Available online xxxx

Keywords:
National electricity market
Systems Dynamics
Piecewise smooth dynamical systems
Energy policies
Modeling

ABSTRACT

The regional integration of electricity markets has been established as desirable among the South American nations to meet demands through the possible consolidation of a unified competing market in the medium term (CAN, 2010). However, what remains to be defined are rules of the game with satisfactory benefits for all parties that have been demonstrated. In this paper we propose a model of power integration based on the Market Coupling scheme, which starts with the modeling of the national markets using the System Dynamics modeling methodology. As a result, the expected behavior of the system is obtained, except in the case of exports, in which, because of the assumption of an infinite transmission capacity between nations, it is seen to surpass the real values found in the market. The work presented in this document (based on two nations, Colombia and Ecuador) allows experimentation for the formulation of the rules of the game necessary in the regional integration of markets.

1. Introduction

Throughout the world, the electricity industry is currently undergoing significant restructuring towards deregulation and competition and market integration (Boffa & Sapio, 2015). The spatial organization of the electricity industry is key in the current policymaking debate in many parts of the world regarding market integration (Ramos, 1999). In the agreement CAN 536 on the general framework for the subregional interconnection of electrical systems and intracommunity exchange of electricity approved in December 2002 (Comunidad Andina de Naciones, 2010), the member countries of the Andean Community established as desirable the development of interconnected regional systems and the future functioning of an integrated energy market among the Andean Community member countries, giving important benefits to member countries in economic, social and environmental terms, which could also lead to the optimum use of their energy resources and to security and reliability in the electrical supply of the region. This paper presents a model for the regional integration of electricity markets built under the dynamics of systems assuming that the transmission that connects the markets of the different nations is of infinite capacity. We present some simulations in which we can see significant results of the model.

The regional integration of electrical markets translates into taking advantage of the excess supply that exists in some countries; into an increase of competition in the sector, which can lead to a decrease in prices and an improvement in quality, and an increase in the scale of production, which seeks to increase the reliability and security of supply; and into harnessing the benefits in economic, social and environmental terms brought about by exchanges (Tobón & Valencia, 2005). In this way, electricity exchanges are important for increased investment, for economies of scale and for the market to benefit users with lower prices.

The CAN 536 agreement established, as a general principle, that member countries should ensure competitive conditions in the electricity market, with prices and tariffs that reflect efficient economic costs, avoiding discriminatory practices and abuses from a dominant position. Rules were also established, such as the following:

- The economic dispatch of each country will consider the supply and demand of the countries of the subregion equivalent at the border nodes.
- International short-term electricity transactions will not be conditional on the existence of surpluses and will only be limited by the capacity of international links.
- Short-term international electricity transactions (TIE) will be considered in the allocation and payment of the capacity

* Corresponding authors.
E-mail addresses: galileonp@hotmail.com (J.M. Redondo), ingdanny09@hotmail.com (D. Ibarra-Vega).

https://doi.org/10.1016/j.esd.2017.12.003
0973-0826/

charge under conditions similar to the internal agents of each country. In this sense, the importer or exporter will receive or pay, respectively, the capacity charge.
- For the definition of electricity prices on each side of the border, all charges in the electricity sector in each system should be considered and expressed in US dollars.

In this way, the challenge is twofold: on the one hand, to reconcile the market mechanisms of each country, and on the other, to advance in the design of an institutional structure that can resolve conflicts, generate incentives and establish clear and credible long-term rules (Tobón & Valencia, 2005).

This article is organized as follows: In Section Modeling of a national electricity market we present the process of modeling a national electricity market and that will be used in the regional integration scheme. We find in Subsections Causal diagram and Forrester diagram and model the construction of the model from the identification of causalities of the system to the obtainment of a 4−dimensional system of first-order ordinary differential equations. Section Calibration and validation of the national model performs the calibration and validation of the model using the historical data of two South American markets. Section Modeling integration presents a model for the regional integration of electricity markets and the structure of the international electricity transactions TIE, Subsection International Transactions of Electricity, methods for congestion management, Subsection Methods to manage congestion, the construction of the model for integration, Subsection The proposed integration model, and the validation of the integration scheme, Subsection Validation of the integration of two nations. Finally, the conclusions are presented in Section Conclusions. The nations of the scheme are Colombia (A) and Ecuador (B).

2. Modeling of a national electricity market

This section presents the process of modeling a national electricity market, with calibration and validation with information from a nation. The integration model is presented in Section Modeling integration.

In (Dyner et al. (2011) and Redondo (2013)), three-dimensional mathematical models are presented for a national electricity market. For the integration, a work was realized that is presented in Ochoa (2010) . These models were developed using System Dynamics methodology. System Dynamics is a methodological approach derived from systems thinking, which is aimed at facilitating learning in complex, feedback, multi-loop, multi-state and non-linear systems (Cardoso de Sales, Celestino, & Guimarães, 2016; Ibarra-Vega, 2016).

2.1. Causal diagram

The dynamic hypotheses H considered for the construction of the model are based on the ideas presented in (Dyner et al., 2011), can be seen in Fig. 1 and are explained next.

- H_1: The reserve margin determines the price of electricity to be paid by the consumer, so that if the reserve margin increases, the price decreases.

  The reserve margin is defined as the relationship between the power supply of the electricity generating plants (represented by the installed capacity available in the market) and the demand for power by the users of the service, so that a large reserve margin indicates an oversupply of power in the system and a corresponding decrease in the price of electricity, while a small reserve margin indicates a decrease in the supply with respect to the demand that must be taken care of and, therefore, an increase in the price is produced, so that the demand diminishes and can be invested in increasing the capacity.
- H_2: An increase in the price of electricity leads to a decrease in power demand, after a delay. The increase in price evidently reduces demand. The delay is due to the fact that in this market, users do not immediately know the price changes in the market, which are recorded on average in monthly energy bills.
- H_3: An increase in power demand results in a decrease in the reserve margin. This hypothesis follows from the definition of reserve margin.
- H_4: An increase in the price of electricity leads to an increase in the expected return on investment in generation plants.

  Since the hydroelectric generation cost is almost nil and the generation costs of other sources are not very variable, the increase in the price implies an increase in the income, which, when making a difference with the costs, produces an increase in the expected return on the investment.
- H_5: An increase in the expected return on investments implies an increase in investments in generation plants.

  This hypothesis is based on the annual increase in demand, which requires that the installed capacity is always greater than the demand, to provide an efficient electrical service. The money to build the new capacity must come out of the expected return of the market so it does not become a burden on the government. In this way, the increase in the expected return implies an increase in investments.
- H_6: Increased investments lead to increased capacity to generate electricity under construction.
- H_7: Generating capacity under construction generates installed generation capacity, after a delay.
- H_8: An increase in installed generation capacity increases the system's reserve margin.

In Fig. 1 we see two negative feedback loops. The feedback loop on the left represents the demand for power, in which we see that the increase in the price of generation electricity leads, after a delay, to a decrease in power demand. If demand increases, then the reserve margin decreases. Finally, we see that if the reserve margin increases, the generation price decreases.

The feedback loop on the right represents the power supply of the market. In this loop we see how the reserve margin determines the price of electricity. If the reserve margin decreases, then the price of electricity increases, which in turn increases the expected return on investment by producing increased investment. When the investments become effective, the construction of new generating capacity begins, which, after a delay, increases the effective generating capacity. If the installed generation capacity increases, the system?s reserve margin also grows.

2.2. Forrester diagram and model

The Forrester diagram implemented from Fig. 1 (Redonodo, 2013) is of dimension three, whereas the one presented in this document is of dimension four. To see the proposed Forrester diagram presented in this paper see Fig. 2.

In our model we have taken as state variables the following: the installed generation capacity *IC*, the generation capacity under construction *BC* and the power demand *D* wich are given in megawatts (*MW*), and the delayed price *DP* given in pesos over Kilowatt-hour. The currency of the system may be defined as necessary, but in this work, we have taken the Colombian peso as referring to a work that was sustained in this country.

From the stock and flow diagram are established the time evolution equations of the state variables. The rate of change of the installed generation is given by:

$$\frac{d}{dt}GI = PT - Dep, \tag{1}$$