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The PAR(p) Interconfigurations model used by the Brazilian Electric Sector

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ABSTRACT

This study discusses the characteristics of the Periodic Autoregressive model, PAR(p), which is used to generate synthetic series of inflow energies that serve as entries for computer platforms that implement the planning and expansion of the operations of the BES – the Brazilian Electric Sector (SEB – Sistema Elétrico Brasileiro). The methodology for the design of a generating plant is presented in addition to the fundamentals of the "PAR(p) Interconfigurations" Model, which is referred to as the Inflow Energy Generation Model (IEGM) in this study. The major contribution of this study is to provide the first scientific discussion of the representation of multiple configurations using the PAR(p) model. For this purpose, several topics related to the time series are discussed, such as the definition of the model order, the matter of stationarity and the need to address possible *outliers*. Finally, a case study is presented, wherein the results of the estimation and generation of the described model's scenarios are demonstrated.

Introduction

The Brazilian Electric Sector (BES) is ranked 9th globally in terms of energy generation, producing approximately 470 TW h per year [21]. In 2011, the generation, distribution and transmission sectors generated approximately R$ 15 billion in revenue [1], and electricity is a utility that currently services the homes of more than 99% of Brazilians.

To support the sizable BES that has arisen from a history of effective use of natural resources for the generation of energy, the National Interconnected System (Sistema Interligado Nacional – SIN) was developed. The SIN, which is of continental scope, allows energy generated anywhere in the country to be consumed by many consumers in different regions, depending on certain technical configurations. This interconnection among regions results in better use of resources. The resultant BES is large and complex, and computational models are (necessary) tools to support the planning and operation of the SIN [24,17].

To plan the expansion and operation of the system and to determine the short-term price of electrical energy, the Brazilian Electric Sector developed a chain of computational models; in these models, as the planning horizon becomes narrower, the stochasticity of the inflows to the hydroelectric plants decreases, and the representation of the physical characteristics increases.

The long-term model for this chain is the NEWAVE model, in which the Periodic Autoregressive (PAR(p)) model is used to generate synthetic scenarios that consider the stochasticity of the inflows to hydroelectric plants. NEWAVE is used to determine the long-term operational strategy, i.e., the planning for the repartitioning of hydraulic or thermal generation. For this purpose, NEWAVE applies algorithms of stochastic optimisation.

Among the many techniques that are available in the literature, the Stochastic Dual Dynamic Programming (SDDP) algorithm is used, which also determines a future cost function (FCF) that is used to couple the short- and long-term decisions evaluated by the other models in the chain [19,25].

This optimisation process uses the synthetic scenarios of the Natural Inflow Energy (NIE) as a stochastic variable, which is generated by a Periodic Autoregressive (PAR(p)) model (adjusted based on the estimated parameters from the NIE history) [29,13,22].

In this context, the objective of this study is to discuss the characteristics of the PAR(p) model used by the BES to facilitate the NEWAVE module in the synthetic-series generation phase; in this study, the PAR(p) model is referred to as the Inflow Energy Generation Model (IEGM). Throughout this study, concepts such as the design of generating-plant configurations and the "PAR(p)

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Interconfigurations" (PAR(p)-IC) Model are explicitly presented for the first time.

The remainder of this paper is divided as follows: the next section concerns the Inflow Energy Generation Model (IEGM), the following section presents a discussion of the modelling results for the Southeast/Midwest subsystem, and the final section presents the conclusions and a perspective on future research.

The Inflow Energy Generation Model (IEGM)

According to [16], the inflow-history series, which is the only available real-world data, does not constitute a sample of sufficient size to estimate the risk indices with acceptable uncertainties in the operation planning and expansion of the SIN. To address this problem, models based on the historical series are generated, and equally probable scenarios that are capable of reproducing the characteristics of the historical series are produced. Hence, the information contained in the historical series can be extracted in a more complete manner, allowing for the evaluation of the risks and uncertainties that affect a hydrothermal system.

To produce an energy series to use as an input in the NEWAVE module's optimisation stage, the IEGM is divided into three major components: (i) the transformation of the series of streamflow expressed as the Natural Inflow Energy [29,7], in which they are aggregated by subsystem to "assemble" the historical series of energies corresponding to the generating-plant configurations; (ii) the adjustment of the "PAR(p) Interconfigurations" model; and (iii) the generation of the synthetic series (Fig. 1).

Although the first task (the "assembly" of the historical energy series corresponding to the generating-plant configurations) does not rely on statistical or time-series concepts, it is fundamental to the understanding of the subsequent analysis because the BES approach to the PAR(p) model differs from the *mainstream* approach described in the literature [13,30].

With regard to component (ii) of the IEGM, the underlying concept of the "PAR(p) Interconfigurations" model is discussed along with points related to Box–Jenkins theory and the SDDP algorithm. Finally, some questions related to the generation of scenarios and their behaviour under the assumption of log-normal noise are discussed.

The assembly of the generating-plant configurations

BES technical activities are executed by the following parties: the Energy Research Company (Empresa de Pesquisa Energética – EPE), which is responsible for the planning of sector expansion; the National System Operator (Operador Nacional do Sistema – ONS), which is responsible for the planning and programming of operations; and the Electrical Energy Chamber of Commerce (Câmara de Comercialisação de Energia Elétrica – CCEE), which is responsible for facilitating commercialisation activities [10].

Every month, the CCEE provides the Monthly Operation Program (MOP)[1] on its website; the MOP is elaborated by the ONS and lists which plants will begin operations during the planning period, along with their generation capacities and productiveness. During the operation start-up phase of a plant, three stages can be identified: the dead-volume-filling period, the under-motorisation period and the complete motorisation period.

During the dead-volume-filling period, only the impact of the beginning of operation of the plant's reservoir is considered in the optimisation process because part of the inflow to the hydroelectric plant is required for reservoir filling and because there is no generation of electrical energy.

In the under-motorisation period, the reservoir's dead volume is already full and the plant generates energy for the SIN; however, because the number of operating machines is not sufficient for the plant to generate its "assured energy",[2] the plant is said to not have reached its base potential and therefore remains under-motorised. During the under-motorisation period, the plant is not yet considered in the optimisation process, and its average projected generation is deduced from the energy market to be fulfilled that month.

Starting with the month in which the plant begins to operate with a sufficient number of machines to generate its assured energy, the plant is said to be motorised, and it begins to be considered in the optimisation process.

Therefore, the conclusion is that for each month in which new hydroelectric generating units begin operation, there is a new hydroelectric configuration of the system; i.e., a new entry in the historical NIE series for the period between January/1931 to December/2011, for example, will be added when a new configuration is identified. Hence, during the start-up of a new plant, the historical NIE series is altered because the topological configuration of the system is changed.

Once there is an established history of streamflow and the generation capacity of the plant ensemble is known month by month (plants that are already in operation and plants that will begin operation), the IEGM calculates the NIE histories for each one of these configurations.

In summary, in the context of the IEGM module, each configuration is an energy-history series that corresponds to a given fixed period of time (for example, January/1931 to December/2011). If a new plant begins operation, then the energies that correspond to the new plant are added to the entire time period, creating a new generating-plant configuration. The combination of all configurations forms a set of configurations that can contain a maximum of 60 configurations (total number of months in the operation planning period, which is 5 years). Hence, the number of configurations will be equal to the number of months in which new configurations were identified.

In the same configuration context, there are two relevant terms defined by the BES: the pre-study and the post-study. The pre-study essentially corresponds to the first configuration and acts as the "starting point" for the estimation of the models. The post-study is the final system configuration of the planning period, and the models defined in this configuration are replicated if there is the desire to create scenarios for ten/thirty years ahead, for example, to address the finite-horizon effects that can lead to difficulties in the SDDP algorithm [6,28].

In the context of the NEWAVE module, the pre-study and post-study periods are periods in which the configuration of the generating plant and the demand information are considered to be constant. These periods help to eliminate the effects of the initial state (pre-study) and to obtain information concerning the FCF in the period of interest (FCF different than zero). These periods are used in expansion planning and in operation planning. The difference is that in the case of expansion planning, the purpose is to define the generating-plant configurations for the entire planning period, which comprises 10 years or more, whereas in operation planning, the configuration is supposedly known.

To illustrate the previous definitions, an academic example is provided here. From Table 1 and Fig. 2, which summarise the introduction or lack of introduction of new plants into the generating plant, in the months of January and February 2013 (configuration 1), no introduction of any new operating plant is found. In contrast,

[1] Available at http://www.ccee.org.br.

[2] Contract limit determined by the Brazilian Electricity Regulatory Agency (Agência Nacional de Energia Elétrica – ANEEL) for the system's hydroelectric generators.