International Conference on Renewable Energies and Power Quality (ICREPQ'18)
Salamanca (Spain), 21th to 23th March, 2018
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.16 April 2018

VATES. Optimal operation of power systems with consideration of production forecasts in systems with high wind and solar penetration.

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Abstract-- **From 2010 many countries are changing their power generation mix from hydro and fuel-fired generators to hydro, wind and solar energy. In Uruguay's case, in the first quarter of 2017, the installed wind capacity exceeded the average energy load. Uruguay is an example of a working system with a great amount of Variable Energy Resources (VER).**

This work shows how the optimal operation of the system is programmed on a weekly, daily and hourly basis to deal with the VER. The way the forecast of the wind, solar and hydro resources availability are considered and how these uncertainties are used to generate a Spot Signal Price (SSP) that may be used to implement a Demand Response pricing scheme is shown.

The developed tool is called VATES and it is running continuously on ADME's servers. The forecast of the dispatch for the next 72 hours is continuously available at http://vates.adme.com.uy

Keywords-- **Wind and solar integration, optimal operation of power systems, modeling and simulation, electrical generation forecast.**

Introduction

This work shows a software tool called VATES, which was developed to continuously forecast the optimal operation of a power system with great amount of Variable Energy Resources (VER). The tool was built in cooperation with the Instituto de Ingeniería Eléctrica (IIE) of the Facultad de Ingeniería of the Universidad de la República (UdelaR) Oriental del Uruguay and the Administración del Mercado Eléctrico (ADME) of Uruguay.

VATES is running continuously on ADME's servers and the forecast of the dispatch for the next 72 hours is available at http://vates.adme.com.uy

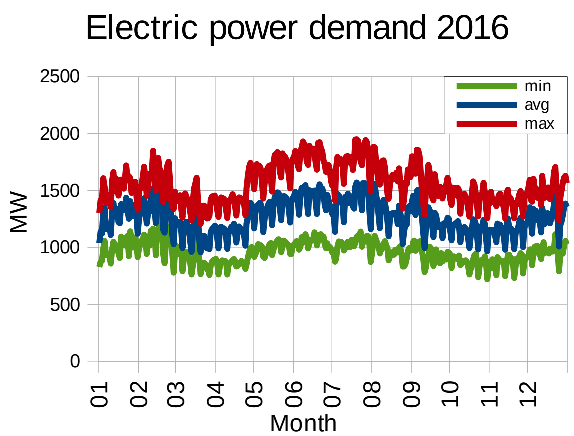

Fig. 1: Uruguayan electric power demand for 2016. Daily minimum, average and maximum.

The expected demand of electrical energy of Uruguay for 2017 was about 11000 GWh. The daily minimum, average and maximum power profiles of 2016 are shown in Fig.1.

In October 2017, Uruguay had 1500 MW of hydro-electric, 1450 MW of wind, 225 MW of solar, 160 MW of biomass and 900 MW of fuel-fired installed capacity.

The rainfall regime is tropical with the consequence of consecutive dry and rainy years. The hydro-electric subsystem is capable of generating 10000 GWh in a rainy year and less than 2500 GWh in a dry year. So, hydro-electric generation may be near the total demand or less than a quarter. There are two lakes associated to the hydro-electric power plants and the largest has a storage capacity of about 600 MW x 136 days over the Negro river and the other over the Uruguay river has a storage capacity of about 900 MW x 7 days. It is obvious that this storage capacity is not sufficient to filter the tropical rainfall variability but it is very suitable to filter the variability of wind and solar resources.

From Fig.1 and considering the 1675 MW of wind plus solar installed capacity it is easy to understand that, occasionally, the wind plus solar power available is greater than the country's demand. This fact was considered in the optimal design of the generation mix. It was considered that under some circumstances the energy from VER is spilled in the same way that happens with the hydro-electric generation.

The country's interconnections are 2000 MW with Argentina (both 50 Hz systems) and 570 MW with Brazil (60 Hz). These interconnections allow to export the energy surplus. Fig. 2 shows an example of the power generation at one instant where the country's demand is 1266 MW and the system is exporting 508 MW to Brazil and 22 MW to Argentina.

For the optimal operation, the stored water is valuated using a classical dynamic programming algorithm (see references: [1-3]) implemented in the SimSEE platform [4]. The developed tool, VATES, is a shield over a SimSEE based simulator of the Uruguayan system following the scheme of Fig. 3. As it can be seen, the idea is very simple. VATES implements a loop that begins in a process where the information coming from the VER's forecast is assimilated together with the real-time information such as the units availability, the lakes' level, etc. into a simulator of the optimal operation of the system (built in SimSEE). Then the result of the next 72 hours is available for the users and the computation starts over after an idle sleep time.

Stochastic process consideration

SimSEE has a powerful tool to deal with stochastic processes called CEGH [5]. A CEGH model of a process can be viewed as a set of lens that, when used, permit to see the process' signals in a Gaussian world. In these Gaussian space the process memory (temporal correlations) and cross correlation between signals can be modeled using linear systems. Then the stochastic process' State, in the sense of the information from history needed to compute the future, can be incorporated to the dynamic programming optimization in a straightforward manner. In the linear model it is also easy to incorporate forecasts in the way of shifts in the noise inputs to fix the trajectory of 50 % of probability of the linear system and the way in that the variance of the process opens from zero (deterministic trajectory) to the full variance corresponding to the process without a forecast.

A specific CEGH model was built for hydro-stream and for wind and solar resources.

The model for hydro-stream is the presented in [6] and for wind and solar generation is the developed in [7].

These models where trained using historical time-series of water stream-flows, wind velocity and solar radiation.

In order to generate the forecast needed to fill the models at each iteration, ADME uses information from a meteorological forecast company at each location that is updated twice a day and the real-time information received directly from the wind and solar generation plants. This information is a set of time-series such as wind velocity and direction, power generation and units availability. Using this information (forecast plus real-time) a detailed model of each generation plant is used to generate the generation forecast for the next hours and all these series are introduced in the VATES loop of Fig. 3.

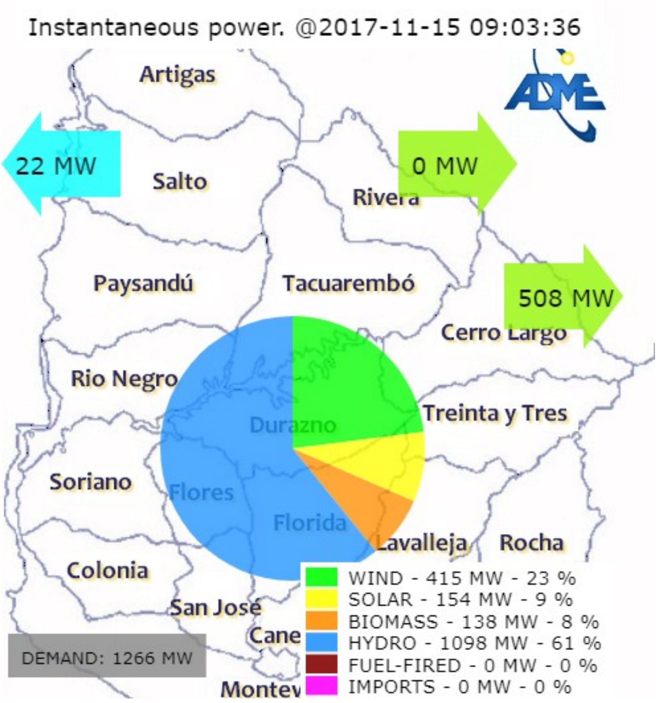

Fig. 2: Instant Power Mix. Uruguay Nov. 15 2017 9:03:36.

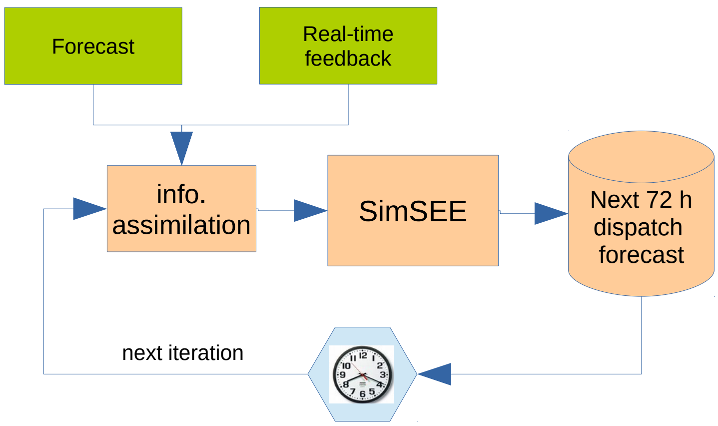

Fig. 3: VATES computation loop.

Wind and Solar Power Generators model

A meteorological forecast is provided by a meteorological service twice a day with a 168 hour forecast of wind speed and solar radiation among other quantities at the wind and solar farm's geographic coordinates. In order to forecast the wind and solar power generation, mathematical models are used to convert the forecasts provided by the meteorological forecast company into electrical power. The model used for the wind power generation as a function of the wind velocity is:

$$P(v)=\begin{cases} 0 & if \quad v \leq v_{min} \\ \dfrac{P_0}{1+e^{-\alpha(v-v_m)}} & if \quad v_{min} < v \leq v_{max} \\ \dfrac{v_{th}-v}{v_{th}-v_{max}} P_0 & if \quad v_{max} < v < v_{th} \\ 0 & if \quad v \geq v_{th} \end{cases}$$

The parameters for this model (P_0, α, and v_m) were calibrated for each wind farm using the previous forecasts and the power time series from the SCADA system. For v_{min}, v_{max}, and v_{th}, the values of 0.2 m/s, 20 m/s and 25 m/s were used, this represents the cut-in and cut-out speeds and a linear transition for the cut-out.

For the solar farms the model used was:

$$P_1(E)=max\{0 \ , \ (4.47\times10^{-7}E^2+9.76\times10^{-4}E-7.32\times10^{-3})P_0\}$$
$$P=min\{P_1, P_0\}$$

Which was calibrated to fit a quadratic model. All solar farms forecasts are calculated with this model and the effective installed power capacity is used for P_0.
A 7 day forecast vs the real power generated time series are shown in Fig. 4, this forecast is calculated twice a day and the generated power is overlapped as the data is available. The last forecast is always available at http://pronos.adme.com.uy/svg and the previous ones can be consulted along with the actual power generated.

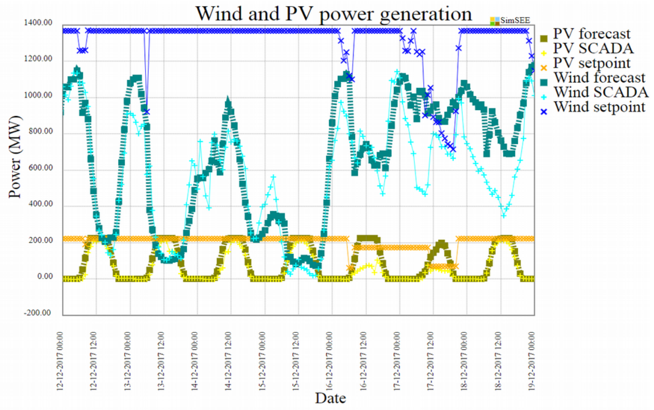

Fig.4: Wind and PV power forecast vs SCADA

These forecast are an input of the VATES program and the cost associated with these energy sources is considered to be 0 USD/MWh.

Hydro-fuel model and water's value

The electrical system is modeled in SimSEE as a dynamical system, thus the past of the system can be represented in a sate vector $X=\{x_1, x_{2,..}, x_n\}$ (e.g. the levels of the reservoirs can be represented as state vector elements). In the optimization process, the state vector's space is explored and for each possible state transition the Future Cost (FC) is calculated. The optimal operation of the system is then the one which minimizes the FC function. This cost for a given state trajectory is calculated by the following equation:

$$FC_k=\sum_{j=k}^{j=\infty}(fc_j+dc_j+ic_j-ei_j)q^{j-k}$$

Where fc is the fuel cost, dc is the deficit cost (cost of not being able to supply the demand, fixed by law), ic is the energy import cost, ei is the energy export income and q is a depreciation factor. All these parameters depend on the state's trajectory. The parameter q is strictly less than 1 so the series is assured to converge and because it is a contraction, the value as j approaches infinity does not influence the value at j = k. The FC function is then constructed backwards starting with some arbitrary value and at some time far away enough from the starting time so that the influence of the initial value is negligible.

The value of any particular resource x can then be calculated as:

$$v_x=-\frac{\partial FC(x,k+1)}{\partial x}$$

In particular the water's value is calculated in this manner and in this way it can be known what benefit can be obtained if the hydro power station produces power at a given time or if it is less costly for the future to burn fuel in that moment and use the water later.

Order of dispatch, Marginal Price and Spot Price

The way to value the different resources has been established in the previous sections. The self dispatched biomass generators that produce power as part of their industrial processes, wind and PV farms are considered with a cost of 0 USD/MWh, the hydro-electric stations' cost is calculated with the FC function and the fuel-fired ones have a fixed price which mainly depends in fuel cost and finally the resources are dispatched to cover the demand at the lowest possible cost and respecting physical restrictions such as minimum power for some generators or minimum flow for navigability in the rivers. This cost is known as the Marginal Cost of Generation (MCG) and can be interpreted as the cost of producing one extra MWh with that resource. The Spot Price (SP) is the minimum between 250 USD/MWh and the MP of the most expensive dispatched resource. This SP can be used as a signal for a Responsive Demand. With the FC an Operation Policy (OP) is built, i.e. a guideline for the system's operator for dispatching the resources in order to minimize the costs.

The VATES loop

The VATES program takes the wind and PV power forecasts, the system's state, and other forecasts used in the CEGHs (e.g. temperature, flow contributions to the rivers' basins, power demand, El Niño's anomalous) as inputs and runs a SimSEE optimization and simulation process. In the optimization process the FC function and OP are calculated and in the simulation process several possible realizations of the stochastic processes are drawn and the OP is applied to each one. The results of the simulation are then are averaged and other statistical quantities are calculated (e.g. probabilities of exceedance) and published in the website as graphs and spreadsheets. The program runs on an hourly basis and the previous forecasts can also be consulted. All the files needed to run the simulation are available at ADME's website and all the source code for SimSEE is free under GNU-GPL v3 license.

Results

VATES is running continuously and the forecast for the next 72 hours of the optimal operation can be seen at http://vates.adme.com.uy.

As an example of the results, Fig. 5 shows the forecast for the next 72 hours of the system's SP. This signal can be used for retailers to build a signal price for Demand Response products. Processes such as EV charging, crop watering and water heating could be relocated to less costly hours.

VATES is also used to calculate the prices and amount of energy offered to the neighboring countries, by knowing the expected VER energy availability and the expected Uruguayan demand, the energy surplus can be estimated and by knowing the estimated SP the price of the offer can be fixed.

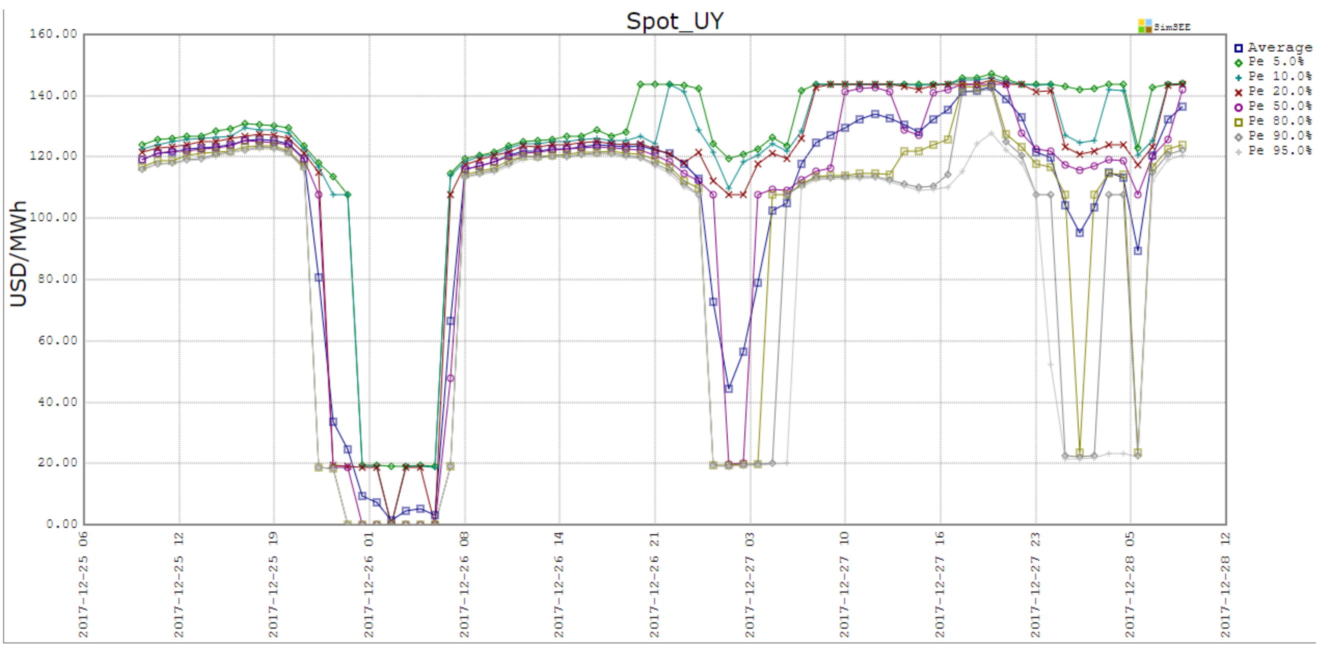

Fig. 5: Spot Price's Forecast for the next 72 hours.

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