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Advanced Control for Energy Management of Grid-Connected Hybrid Power Systems in the Sugar Cane Industry ⋆

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Abstract: This work presents a process supervision and advanced control structure, based on Model Predictive Control (*MPC*) coupled with disturbance estimation techniques and a *finite-state machine* decision system, responsible for setting energy productions *set-points*. This control scheme is applied to energy generation optimization in a sugar cane power plant, with non-dispatchable renewable sources, such as photovoltaic and wind power generation, as well as dispatchable sources, as biomass. The energy plant is bound to produce steam in different pressures, cold water and, imperiously, has to produce and maintain an amount of electric power throughout each month, defined by contract rules with a local distribution network operator (*DNO*). The proposed predictive control structure uses *feedforward* compensation of estimated future disturbances, obtained by the Double Exponential Smoothing (*DES*) method. The control algorithm has the task of performing the management of which energy system to use, maximize the use of the renewable energy sources, manage the use of energy storage units and optimize energy generation due to contract rules, while aiming to maximize economic profits. Through simulation, the proposed system is compared to a *MPC* structure, with standard techniques, and shows improved behavior.

Keywords: Disturbance Estimation, Model Predictive Control, Decision System, Microgrids, Renewable Sources.

1. INTRODUCTION

Energy generation in efficient ways is a key element for achieving greater goals aiming sustainable and eco-friendly development. The current foundations on energy generation are about to change in a profound way: affordable fossil fuel reserves are decreasing each year whereas, at the same time, energy demands grow in every country.

Notably, in the instance of this work, the Brazilian energy scenario will be taken into account, for the country has an immensely diversified energy matrix, as seen on Ministério de Minas e Energia (2015). The sugar cane processing plants, studied in González (2011), are, as well, particularly significant to this study, given the importance of sugar-ethanol power plants in the Brazilian energy setting and knowing that these are mostly established in high insolation sites, they become potential candidates to be managed as distributed power plants of hybrid sources, as seen in Costa Filho (2013), considering biomass, biogas, solar and wind power energy.

The optimization of a hybrid energy generation system, with the reuse of the sugar cane residues coupled with the use of other renewable sources, external to the plant, as photovoltaic panels and wind turbines, is discussed herein. The studied energy plant is based on a real sugar cane power plant and has to attend to process electric and steam demands and, also, ensure a pre-established multi-objective energy sales contract with the local Distribution Network Operator (*DNO*).

The control of hybrid generation and storage, including renewable and non-renewable sources, is a significant issue to be studied in order to allow the optimal management and operation, carrying out a coordination between legal standards, minimal environmental standards and state of the art techniques Ferrari-Trecate et al. (2004). Recent works have brought to light *MPC*-based control structures used for energy management of microgrids (a set of generators, loads and storage units that operate together, in isolated mode, or connected to the main grid) with renewable sources. Valverde et al. (2013) shows a *MPC*-controlled hydrogen-based domestic microgrids; Garcia-Torres and Bordons (2015) also refer to optimal generation for renewable microgrid; Mendes et al. (2016) propose *MPC* structure for energy management of experimental microgrids, coupled with hydrogen storage systems.

Solar radiation and wind speed present frequent changes due to climatic issues, and its stochastic behavior repre-

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sents an additional challenge to energy management in renewable energy based power systems. Estimation of the future behavior of these variables is also important to the studied hybrid generation system. The importance of disturbance estimation is thoroughly discussed on Pawlowski et al. (2010) and Pawlowski et al. (2011).

In this work, a two-layer advanced control strategy is proposed to deal with the system's operational requirements and find an optimal operating point. The top level consists of a process supervision and decision layer and is responsible for deciding the monthly energy sale goal, while the second layer is composed by a *MPC* algorithm that aims to provide a stable operating point according the control goals and system constraints. The advanced control structure must be able to deal with the effect of the non-dispatchable disturbances predictions on the system operation conditions. By this, this study deals with the estimation of disturbances with long-term prediction horizons, as depicted on Reikard (2009), based on time-series methods, seen on Brockwell and Davis (2002).

This paper is organized as follows: section 2 presents the studied power plant discrete model and the respective energy contract rules, section 3 describes the process supervision and decision layer, depicting the optimization problems that have to be solved and detailing the *MPC* control structure, section 4 presents the disturbance forecasting methods used to estimate wind speed and solar radiation. Finally, section 5 shows simulations of the proposed control strategy. The paper ends with conclusions.

2. THE STUDIED PROBLEM

The hybrid generation energy system herein studied is based upon a sugar cane processing plant, that produces sugar, ethanol and electric power. This system is composed by the following subsystems: two boilers, with different efficiencies; two steam turbines, with different efficiencies; a combined heat and power system, denoted as *CHP*; a water chiller; a hot water tank; photovoltaic panels; water heating solar panels; a wind turbine; two pressure reduction valves; one heat exchanger; stocks of bagasse, straw and compressed biogas and a battery bank. This plant is interesting from an economic and sustainable point-of-view, as it proposes the use of renewable sources and the recycling of the sugar cane residues, aiming to use the best possible technology for sustainable energy generation.

This plant has four demands to satisfy: electric power demand, due to ethanol and sugar production process; middle and low pressure steam demands, defined by the process, and refrigeration (chilled water) demands, used to cool down generators, oil tanks and water for fermentation units. It is important to mention that satisfying each demand alone is not adequate, as they are inextricably linked.

2.1 Hybrid Energy Plant Model

It is important to depict the studied hybrid generation energy plant more minutely, as seen in Morato et al. (2016). Figure 1 shows the outline of the studied plant and table 1 details the used nomenclature; Q_E^A and Q_E^B represent the biomass (bagasse and straw) input flows, measured in $(\frac{t}{h})$.

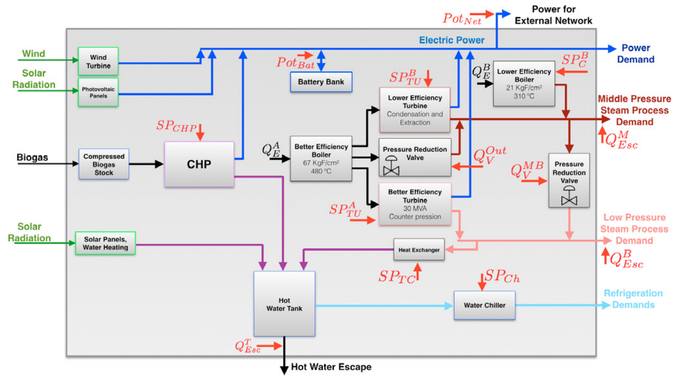

Fig. 1. Studied Hybrid Generation Energy Plant

Table 1. Manipulated Variables

Symbol	*MV*	Unit
SP_C^B	Lower-Efficiency Boiler's Set-Point	$(\frac{t}{h})$
SP_{TU}^B	Lower-Efficiency Turbine's Set-Point	(kW)
SP_{TU}^A	Better-Efficiency Turbine's Set-Point	(kW)
Pot_{Bat}	Energy Flow to the Battery Bank	(kW)
SP_{CHP}	*CHP*'s set-point	(kW)
SP_{ch}	Water Chiller's Set-Point	$(\frac{m^3}{h})$
SP_{TC}	Heat Exchanger's Set-Point	$(\frac{m^3}{h})$
Q_V^{Out}	High-middle Press. Reduc. Valve's *SP*	$(\frac{t}{h})$
Q_V^{MB}	Middle-low Press. Reduc. Valve's *SP*	$(\frac{t}{h})$
Q_{Esc}^{Tank}	Hot Water Escape Flow	$(\frac{m^3}{h})$
Q_{Esc}^M	Middle Pressure Steam Escape Flow	$(\frac{t}{h})$
Q_{Esc}^B	Low Pressure Steam Escape Flow	$(\frac{t}{h})$
Pot_{Net}	Electric Power Available to Network	(kW)

The studied energy plant is composed of internal stocks, put as system states. The use of intermediate storage units allows the system to accumulate energy (or biomass, that can be converted into energy) when the renewable generation is high and use fit when there is no renewable production. From a discrete time standpoint, a state x_s, at sampling time $k+1$, depends on the state at previous sample k and on the total exchanged flow $\breve{u}_s^E(k)$ during the period ΔT, ranging from k to $k+1$, assuming $\breve{u}_s^E(k)$ to remain constant during ΔT - this is: $x_s(k+1) = A_s x_s(k) + \breve{u}_s^E(k)\Delta T$.

As described in Geidl (2007), the discrete *state space* representation model of the studied plant can be put as in (1). This mathematical model was obtained and validated through simulation and with the use of experimental data; to see full details refer to Morato et al. (2016) and Mendes (2016).

$$\left\{ \begin{array}{l} x(k+1) \ = Ax(k) \ + Bu(k) \ + Cz(k) \\ \quad y(k) \quad = Dx(k) \ + Eu(k) \ + Fz(k) \end{array} \right\} \qquad (1)$$

The system state vector is defined as on (2), where each entry represents the normalized percentage of each stock: battery bank, bagasse stock, straw stock, biogas stock and hot water tank. The system's manipulated variables are continuous and are put in table 1. The *set-points* will be treated by lower level internal controls. The complete manipulated variables vector is seen on (3). In terms of the system's outputs, the output vector is defined as on (4),