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Energy dispatching based on predictive controller of an off-grid wind turbine/photovoltaic/hydrogen/battery hybrid system

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A B S T R A C T

This paper presents a novel energy dispatching based on Model Predictive Control (MPC) for off-grid photovoltaic (PV)/wind turbine/hydrogen/battery hybrid systems. The renewable energy sources supply energy to the hybrid system and the battery and hydrogen system are used as energy storage devices. The denominated "hydrogen system" is composed of fuel cell, electrolyzer and hydrogen storage tank. The MPC generates the reference powers of the fuel cell and electrolyzer to satisfy different objectives: to track the load power demand and to keep the charge levels of the energy storage devices between their target margins. The modeling of the hybrid system was developed in MATLAB-Simulink, taking into account datasheets of commercially available components. To show the proper operation of the proposed energy dispatching, a simpler strategy based on state control was presented in order to compare and validate the results for long-term simulations of 25 years (expected lifetime of the system) with a sample time of one hour.

1. Introduction

The current situation of the energy sector with a continuous increase in the energy demand, together with the Greenhouse gas emissions and the exhaustion of the fossil fuel reserves have enhanced the combination of renewable energy sources for distributed generation. This combination is denominated Hybrid Renewable Energy Systems (HRES) or simply Hybrid Systems (HS) which are composed by one or more renewable energy sources and energy storage systems (ESS). ESS allow adapting the unregulated power generated by the renewable sources to a specific demanded power. This HS can work in stand-alone [1,2] or grid-connected mode [3–7].

The correct design of the energy dispatching for HS is essential for their operation. energy dispatching strategies are designed to track the load power satisfying secondary objectives such as keeping the charge level of the energy storage devices within their operational limits, minimizing the generation costs, operating the system at high efficiency, reducing the fuel consumption, etc. The papers related to energy dispatching can be classified according to these objectives [8].

Depending on the objectives to meet by the energy dispatching there are two kinds of simulations that can be carried out: short-term and long-term simulations. Short-term simulations are focus on the dynamics of the sources which compose the system and take them into account to face the net power variations due to the changes in load power or disturbances in the renewable energy sources. The length of this kind of simulations goes from 200 s to one day [9–11]. Long-term simulations are used when the main objective is to show the proper operation of the system during a considerable period of time (from months to the whole life of the system) [12–15]. In this case, the dynamics of the energy sources are neglected and they pay attention to other parameters such as operation costs, degradation of the sources, level of charge of the storage devices, etc. Model Predictive Control (MPC) has been widely used in the energy dispatching design because of its ability to deal with constraints in a systematic and straightforward manner. In Ref. [16], the HS was composed by wind turbine, PV, electrolyzer and fuel cell. The energy generated by the renewable sources (both controlled by Maximum Power Point Tracking – MPPT-algorithms) was stored as hydrogen. Depending on if the

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Nomenclature

A, B, C	matrices of the HS state space model
$A_{\rm bat}$	exponential zone amplitude of the battery, (V)
$B_{\rm bat}$	exponential zone time constant inverse of the battery, $(\rm Ah)^{-1}$
$c_{1,\ldots,6}$	power curve coefficients of the wind turbine, (−)
C_P	power coefficient of the wind turbine, (%)
D_c	duty cycle, (pu)
$E_{\rm low,H_2}$	lower heating value of hydrogen, (J/kg)
$E^0_{\rm bat}$	battery constant voltage, (V)
$E^{\rm cycle}_{\rm fc}$	energy supplied by the fuel cell which reduces the level of the hydrogen tank from 100% to 20%, (Wh)
$E^{\rm cycle}_{\rm lz}$	energy supplied to the electrolyzer which increases the level of the hydrogen tank from 20% to 100%, (Wh)
$E^{\rm char}_{\rm bat}$	charge energy that the battery must absorb with the EMS, (Wh)
$E^{\rm dis}_{\rm bat}$	discharge energy that the battery must deliver with the EMS, (Wh)
$E^{\rm year}_{\rm bat}$	energy that the battery is expected to deliver during a year, (Wh)
$E^{\rm dis}_{\rm fc}$	energy that the fuel cell must deliver with the EMS, (Wh)
$E^{\rm char}_{\rm lz}$	energy that the electrolyzer must absorb with the EMS, (Wh)
$E^{\rm char}_{\rm net}$	total net charge energy, (Wh)
$E^{\rm dis}_{\rm net}$	total net discharge energy, (Wh)
ESS	energy storage system
F	Faraday constant, (C/kmol)
H_C	control horizon
H_P	prediction horizon
HRES	hybrid renewable energy systems
$I_{\rm ph}$	solar-induced current, (A)
$I_{\rm ph0}$	solar-induced current at a temperature of 300K, (A)
$I_{\rm sat}$	saturation current of the diode, (A)
i^*	battery filtered current, (A)
$i_{\rm bat}$	battery current, (A)
$i_{\rm bat}t$	actual battery charge, (Ah)
$i_{\rm lz}$	electrolyzer current, (A)
K	Boltzmann constant, $(\rm JK^{-1})$
K_0	constant depending on the characteristics of the PV, (−)
K_1	constant depending on the characteristics of the PV, (−)
K_b	battery polarization constant, (V/(Ah))
k	sampling time
$M_{\rm H_2}$	total hydrogen mass consumption, (kg)
MPC	model predictive control
MPPT	maximum power point tracking
N	quality factor of the diode of the PV model, (−)
$n_{\rm H_2}$	produced hydrogen, (mol/s)
$n_{\rm lz}$	number of electrolyzer cells in series, (−)
$P_{\rm fc}$	fuel cell power, (W)
$P_{\rm load}$	power demanded by the load, (W)
$P_{\rm lz}$	electrolyzer power, (W)
$P_{\rm net}$	net power, (W)
$P_{\rm pv}$	power generated by the PV system, (W)
$P_{\rm rnw}$	power generated by the renewable energy system, (W)
$P_{\rm turb}$	power captured by the wind turbine blades, (W)
$P_{\rm wt}$	power generated by the wind turbine, (W)
PEM	proton exchange membrane
PV	photovoltaic
PWM	pulse width modulation
$P^{\rm char}_{\rm bat}$	battery charge power, (W)
$P^{\rm dis}_{\rm bat}$	battery discharge power, (W)
$p_{\rm H_2}$	hydrogen partial pressure, (Pa)
$p_{\rm H_2O}$	water partial pressure, (Pa)
$p_{\rm O_2}$	oxygen partial pressure, (Pa)
q	elementary charge of an electron, (C)
Q	battery capacity, (Ah)
$q_{\rm H_2in}$	hydrogen input flow to the anode, (kg/s)
$q_{\rm H_2out}$	hydrogen output flow to the anode, (kg/s)
$q_{\rm H_2reac}$	hydrogen flow that reacts in the anode, (kg/s)
$q_{\rm O_2in}$	oxygen input flow to the anode, (kg/s)
$q_{\rm O_2out}$	oxygen output flow to the anode, (kg/s)
$q_{\rm O_2reac}$	oxygen flow that reacts in the anode, (kg/s)
$R_{\rm bat}$	battery internal resistance, (Ω)
R_p	PV parallel resistance, (Ω)
R_s	PV series resistance, (Ω)
SOC	state of charge
SPWF	series present worth factor
T_a	aerodynamic torque acting on the blades, (Nm)
$T_{\rm pv}$	PV operating temperature, (K)
$T_{\rm ref}$	aerodynamic torque reference, (Nm)
$u_{\rm min}$	lower constraints for the model inputs
$u_{\rm max}$	upper constraints for the model inputs
$V_{\rm act}$	fuel cell activation voltage drop, (V)
$V_{\rm bat}$	battery voltage, (V)
$V_{\rm conc}$	fuel cell concentration voltage drop, (V)
$V_{\rm fc}$	fuel cell output voltage, (V)
V_g	band gap voltage of the semiconductor used in the PV, (V)
$V_{\rm irrev}$	fuel cell irreversible voltage, (V)
$V_{\rm oh}$	Fuel cell ohmic voltage drop, (V)
$V_{\rm pv}$	voltage across the solar cell electrical ports, (V)
v_t	wind speed, (m/s)
W_u	input weight factors
W_y	output weight factors
x, r, u, y	model states, setpoints, manipulated variables and model outputs
$y_{\rm min}$	lower constraints for the model outputs
$y_{\rm max}$	upper constraints for the model outputs
η_F	Faraday efficiency, (%)
$\eta_{\rm H_2}$	hydrogen system efficiency
$\eta_{\rm bat}$	battery efficiency
$\eta_{\rm HS}$	HS efficiency
λ	tip speed ratio of the rotor blade tip speed to wind speed, (−)
$\lambda_{\rm O_2}$	oxygen excess ratio, (−)
ρ	air density, $(\rm kg/m^3)$
ω_t	rotational speed, (rad/s)

renewable power was higher or lower than the demanded power, the electrolyzer or the fuel cell worked. Both, the fuel cell and the electrolyzer, had a MPC which generated their reference current subject to their dynamic constrains. The objective of the strategy was to meet the load demand taking into account the dynamic limitations of the energy sources but it was not shown if the strategy is able to maintain the hydrogen level in the tank. Vahidi et al. [17] studied a simple HS for stand-alone applications composed by a fuel cell connected to a load by a DC/DC converter. The fuel cell was assisted by an ultra-capacitor which was directly connected to the DC bus. A MPC generated the reference current of the fuel cell in order to ensure an optimal distribution of current