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Fuzzy logic based power management strategy of a multi-MW doubly-fed induction generator wind turbine with battery and ultracapacitor

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ABSTRACT

Integrating energy storage systems (ESS) with wind turbines results to be an interesting option for improving the grid integration capability of wind energy. This paper presents and evaluates a wind hybrid system consisting of a 1.5 MW doubly-fed induction generator (DFIG) wind turbine and double battery-ultracapacitor ESS. Commercially available components are used in this wind hybrid system. A novel supervisory control system (SCS) is designed and implemented, which is responsible for setting the active and reactive power references for each component of the hybrid system. A fuzzy logic controller, taking into account the grid demand, power generation prediction, actual DFIG power generation and state-of-charge (SOC) of the ESSs, sets the active power references. The reactive power references are proportionally delivered to each element regarding their current limitations in the SCS. The appropriate control of the power converters allows each power source to achieve the operation defined by the SCS. The wind hybrid system and SCS are assessed by simulation under wind fluctuations, grid demand changes, and grid disturbances. Results show an improved performance in the overall response of the system with the implementation of the SCS.

1. Introduction

Coupled operation of ESSs (energy storage systems) together with wind turbines is nowadays a feasible way to reduce intermittency, unpredictability and fluctuations on wind power generation [1–4]. If these issues are addressed, connection to grid of large wind farms becomes safer and more reliable. Due to the recent commercialization of wind turbines in the range of several megawatts equipped with ESS [5], the modeling and control of such devices becomes more necessary.

Different energy storage technologies are available for these purposes. A complete and up-to-date evaluation of the most relevant technologies is presented in Ref. [4]. Each of them presents particular characteristics that make them more suitable for a specific application. In this regard, ultracapacitors (UCs) typically show a fast response and low energy density, thus being able to complete charge and discharge cycles within a few minutes or seconds [6,7]. On the other hand, electrochemical batteries are more adequate for longer charge/discharge periods, since their higher capacity prevails over their response time, which is slower than in the ultracapacitors [7]. Therefore, the wind hybrid system proposed in this paper aims to take advantage of the most remarkable characteristics of both devices.

Wind speed prediction is also a valuable tool for the operation of large grid-connected wind farms [8,9]. Accurate wind forecasts allow the estimation of future wind power generation in a particular location. This analysis can be carried out in different time scales for specific purposes. For instance, short-term estimations can help in the daily generation scheduling [10,11], which is of great importance from the grid operator point of view. In Ref. [10], the authors developed a hybrid wind speed forecasting model which achieved satisfactory accuracy with simple calculation process, thus easing its implementation on wind farms. In Ref. [11], a

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Nomenclature

Acronyms

BESS battery energy storage system
DFIG doubly-fed induction generator
ESS energy storage system
GSC DFIG grid side converter
MPPT maximum power point tracking
PCC point of common coupling
RSC DFIG rotor side converter
SCS supervisory control system
SOC state-of-charge of the energy storage system
UC ultracapacitor
VRLA valve-regulated lead–acid

Parameters

A swept area of the rotor disk
C capacity of the DFIG DC link capacitor
CAP maximum battery capacity
C_p power coefficient of the wind turbine
C_{UC} UC capacity
E_{batt} battery no-load voltage
i_{batt} instantaneous battery current
i_{dr}, i_{qr} direct and quadrature components of the rotor currents
i_{ds}, i_{qs} direct and quadrature components of the stator currents
i_{dg}, i_{qg} direct and quadrature components of the current at the AC side of the GSC
I_s, I_r stator and rotor currents
I_{UC} UC series branch current
L_r, R_r rotor windings electrical inductance and resistance
L_s, R_s stator windings electrical inductance and resistance
L_M DFIG magnetizing inductance
p number of DFIG pole pairs
P_{conv}, Q_{conv}, S_{conv} active, reactive and apparent power of the AC/DC power converters
$P_{exchange}$ compensating power between UC and BESS
P_{dem}, Q_{dem} active and reactive grid power demand
P_g total DFIG active power generation
P_{gsc}, Q_{gsc} active and reactive power through the GSC of the DFIG
P-$P_{BESS\ ref}$ primary active power reference for the BESS
P-$P_{UC\ ref}$ primary active power reference for the UC
P_r active power through the DFIG rotor windings
P_s, Q_s active and reactive power through the DFIG stator windings
Q_{s_ref} reactive power reference for the DFIG stator
$Q_{s\_con\_lim}$ reactive power consumption limit for the DFIG stator
$Q_{con\_lim\_total}$ total reactive power consumption limit for the hybrid system
R_i battery internal resistance
R_{UC} UC internal resistance
slip DFIG rotor slip
S_{s_Ir} stator apparent power according to the limit rotor current
S_{s_Vr} stator apparent power according to the limit rotor voltage
S_{s_Is} stator apparent power according to the limit stator current
SOC_{BESS} battery state-of-charge
SOC_{UC} UC state-of-charge
T_e DFIG electromechanical torque
T_{wt} wind turbine mechanical torque
U_{batt} battery output voltage
U_c voltage at the DC link capacitor of the DFIG
U_s, U_r stator and rotor voltage
u_{dg}, u_{qg} direct and quadrature components of the voltage at the AC side of the GSC
u_{dr}, u_{qr} direct and quadrature components of the rotor voltage
u_{ds}, u_{qs} direct and quadrature components of the stator voltage
U_{UC} UC instantaneous voltage
$U_{UC\ rated}$ UC rated voltage
U_{UC_0} UC initial voltage
v wind speed
V_{B575} voltage at the output terminals of the hybrid system
$V_{dc\ DFIG}$, $V_{dc\ BESS}$, $V_{dc\ UC}$ DC bus voltage of the DFIG, BESS and UC power converter
Z_s, Z_r, Z_m stator, rotor and mutual impedances

Greek

θ blades pitch angle
λ tip speed ratio
ρ air density
φ_{dr}, φ_{qr} direct and quadrature components of the magnetic flux linkages for rotor
φ_{ds}, φ_{qs} direct and quadrature components of the magnetic flux linkages for stator
ω DFIG synchronous speed
ω_r DFIG angular speed
Φ rotor radius

combined wind power and speed forecasting method for time-scales from minutes to an hour was presented. However, this model was not adequate for day-ahead prediction. An hourly average wind speed forecasting method was introduced in Ref. [12]. The proposed approach was proven valid for up to two-days-ahead predictions in some cases. Moreover, the authors used the power curve of a wind turbine to obtain the corresponding power generation forecast. This concept has been adopted in this paper, as it will be stated later on. The previous studies demonstrate the feasibility of performing time-ahead wind power prediction. Nonetheless, the implementation of a forecasting algorithm is not the goal of this paper, and the wind power prediction is considered given by an external system.

Fuzzy logic controllers show a remarkable flexibility in electric power applications. Their performance together with wind power generation and other renewable sources has been analyzed in the literature [13]. In Ref. [14], a fuzzy control was used to enhance wind power stability under fluctuating wind speed. Nonetheless, its combination with ESSs was not addressed. In Ref. [15], the authors showed the improvements achieved with the integration of fuzzy logic and UC in a micro grid, compared to PI (proportional-integral) controllers. However, fuzzy logic and UC were evaluated separately, thus not studying the coupled application of both technologies. Some studies applied fuzzy logic controllers to power control and voltage regulation of wind turbines without any ESSs. Almeida et al. [16] compared PI with fuzzy system to control DFIG