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A series hybrid "real inertia" energy storage system

J.P. Rouse[a,*], S.D. Garvey[a], B. Cárdenas[a], T.R. Davenne[b]

[a] Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham, Nottinghamshire NG7 2RD, United Kingdom
[b] Rutherford Appleton Laboratory, Didcot OX11 0QX, United Kingdom

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ABSTRACT

The wide scale market penetration of numerous renewable energy technologies is dependent, at least in part, on developing reliable energy storage methods that can alleviate concerns over potentially interrupted and uncertain supplies. Many challenges need to be overcome, not least among them is allowing capacity for the wide range of time scales required to ensure grid stability. In thermal power plant, high frequency/short duration demand fluctuations, acting at the milliseconds to several seconds time scale, are addressed passively by the inertia of the grid. Here, grid inertia can be thought of as the mechanical inertia of spinning steel in steam and gas turbines. This allows time for active control measures to take effect at the tens of second to hours time scale and for the system to recover without a supply frequency deviation that is noticeable to the customer. It is of paramount importance that, as thermal plant is retired, renewable energy generation and storage systems account for the loss of this inertia. In the literature, strategies to address the loss of "real" inertia have often relied on emulation rather than actual replacement. The present work focuses on the preliminary development of a novel energy storage system that makes use of real inertia to address short term supply/demand imbalances while simultaneously allowing for extended depths of discharge. The concept looks to combine flywheel and compressed fluid energy stores in order to power a synchronous generator. By combining these energy storage technologies through a differential drive unit, DDU, it is anticipated that the benefits of high system inertia can be exploited in the short term while allowing energy to be continually extracted from the flywheel in the long term during storage discharge. The use of a DDU makes the present design particularly novel and distinct from other hybrid systems. In essence, this inclusion allows energy to be extracted entirely from the flywheel, inducing "real" inertia, or entirely from the secondary store, inducing "synthetic" inertia, or some combination of the two. Fundamental sizing calculations for a 50 MW system with 20 MWh of storage capacity are presented and used to design a suitable control system that allows for the operation of both primary flywheel and secondary compressed fluid energy stores. The transient behaviour of the system is simulated for several charge/discharge time profiles to demonstrate response stability for the system. Comments on system turnaround efficiency, which is dependent upon loading history but for the intended applications can be considered to be greater than 90% are also made here, along with a case study application to an isolated Californian solar powered grid.

1. Introduction

The intermittent and irregular nature of renewable energy sources necessitates at least some form of energy storage if uninterrupted supply is to be achieved [1]. Mismatches in supply and demand need to be accounted for on a wide range of time scales, from the order of weeks or months as a result of diurnal and seasonal variations [2], to seconds and milliseconds. In order to ensure a stable grid, it is critically important that a balance is maintained between consumption and generation in real time over this wide range of time scales [3]. The inertia response of an energy system limits the rate of change of frequency, known as RoCoF, when a sudden change in load is encountered [3]. Systems such as thermal energy storage and pumped hydroelectric have very little associated inertia and may be thought of as providing slow response energy storage. Slow energy storage in the present context may be thought of as reactions to grid imbalances that take place over time periods greater than several minutes. Conversely, fast energy storage addresses momentary load imbalances on the millisecond to second time scale.

In thermal power plants, the inertia of a turbine passively controls the rate of the change in speed to the synchronous machine it is coupled to. This action buys time for active control systems to take effect and

* Corresponding author.
E-mail address: James.Rouse@nottingham.ac.uk (J.P. Rouse).

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Nomenclature

ω	rotational speed (rad/s)
ω_{FW}	flywheel rotational speed (rad/s)
$\hat{\omega}_{FW}$	flywheel burst rotational speed (rad/s)
ω_D	flywheel design rotational speed (rad/s)
ω_{SM}	synchronous machine rotational speed (rad/s)
$\overline{\omega}_{SM}$	synchronous machine nominal rotational speed (rad/s)
$\hat{\omega}_{SM}$	synchronous machine target rotational speed (rad/s)
ω_{SMLL}	synchronous machine rotational speed lower limit (rad/s)
ω_{SMUL}	synchronous machine rotational speed upper limit (rad/s)
E_K	kinetic energy (J)
ΔE_{FW}	change in flywheel store energy (J)
ΔE_{HY}	change in secondary store energy (J)
E_{Trans}	transaction energy (J)
J	moment of inertia (kg m^2)
J_{FW}	flywheel moment of inertia (kg m^2)
J_{SM}	synchronous machine moment of inertia (kg m^2)
m	flywheel mass (kg)
R_I	internal flywheel radius, bore radius (m)
R_O	external flywheel radius (m)
R_{EP}	elastic/plastic transition radius (m)
r	radial coordinate (m)
ρ	flywheel material density (kg/m^3)
σ_r	radial stress component in flywheel (MPa)
σ_θ	hoop stress component in flywheel (MPa)
A, B, C	integration constants in flywheel stress expressions
σ_Y	flywheel material yield stress (MPa)
σ_{UTS}	flywheel material ultimate tensile strength (MPa)
$\Delta\sigma$	"Endurance" alternating stress, fully reversed condition (MPa)
σ_e	flywheel material endurance limit (MPa)
S_A	alternating stress for a particular loading condition (MPa)
S_M	mean stress for a particular loading condition (MPa)
N_f	number of cycles to failure
α, β	Basquin model parameters
p_i	hydraulic fluid working pressure (bar)
ΔP	hydraulic machine pressure differential (bar)
P_{Atmos}	atmospheric pressure (bar)
p	number of machine poles
f	frequency (Hz)
G	synchronous machine basic rating (MVA)
H	synchronous machine inertia constant (MJ/MVA)
G_C	PID controller transfer function
K_P	proportional gain (kg m^2/s)
K_D	differential gain (kg m^2)
K_I	integral gain (kg m^2/s^2)
ω_n, ζ, k	DDU transfer function parameters
T	instantaneous DDU torque (Nm)
T_R	DDU rated torque (Nm)
T_C	controller torque (Nm)
T_W	windage torque (Nm)
θ_{EM}	electromechanical load angle (°)
$\hat{\theta}_{EM}$	electromechanical load angle at rated synchronous machine power (10°)
K_{SM}	synchronous machine spring constant (Nm/°)
err	rotational speed error, difference between instantaneous synchronous machine speed and target speed (rad/s)
t	simulation time (s)
t_s	total simulation time (s)
P_{PV}	photovoltaic cell power (MW)
P_{Demand}	total demand power (MW)
P_{Gen}	total generated power (MW)
P_{Base}	total baseline power (MW)
$\hat{P}_{SM}$	rated synchronous machine power (MW)
C_W	windage loss coefficient
η_G	generator efficiency
η_M	motor efficiency
η_P	pump efficiency
η_{PV}	photovoltaic cell efficiency
η_{INV}	inverter efficiency
η_T	total system efficiency
h_{pv}, p_{pv}, q_{pv}, m_{pv}, r_{pv}, s_{pv}, u_{pv}	photovoltaic cell model coefficients
θ_{PV}	photovoltaic cell temperature (°C)
θ_{Air}	instantaneous air temperature (°C)
$\hat{\theta}_{Air}$	peak air temperature (°C)
t_{rise}	time of sunrise
t_{set}	time of sunset
$t_{\hat{\theta}_{Air}}$	time of peak air temperature
M_{Air}	normalised air mass
G_β	global solar irradiation (W/m^2)
ψ_Z	zenith angle (°)
d_n	day number
C_s, C_v, C_f	hydraulic machine model coefficients
$Q_{P/M}$	pump/motor flow rate (m^3/s)
$T_{P/M}$	pump/motor torque (Nm)
D	hydraulic machine displacement (cc/rev)
x	hydraulic machine displacement fraction
A_L	loading cycle amplitude (MW)
t_L	loading cycle period (s)
$RoCoF$	rate of change of (grid) frequency (Hz/s)

stabilise the system frequency by adjusting prime mover inputs. Note that prime mover adjustment may not be required for a particular load imbalance scenario if, for example, sufficient kinetic energy can be extracted from synchronous machine rotors. Renewable energy sources on the other hand are commonly connected to the grid via power converters rather than synchronous generators. As such they operate to generate maximum available power and do not respond to system load directly. Power converters require control technology in order to keep line frequencies, voltages and power oscillations within acceptable tolerances while also guarding against power circulation [4]. Renewable energy sources typically have little in the way of intrinsic inertia in the first instance. Wind turbines (for example), have relatively low inertia constants, 2–6 s [5], and it is debatable as to whether or not this inertia is truly seen by the grid due to the interconnecting power electronics. For comparison, turbo generators used in conventional steam power plants have inertia constants of 7–9 s [6]. Inertia constants may be expressed as the ratio of stored kinetic energy in a system, rotating at rated speed, to the rated electrical power of the system. Inertia constants have time units and indicate how long it would take for a rotating mass to de-accelerate to stationary if continuously discharged at rated power [6].

The present work proposes an electricity in/electricity out (EIEO) storage system that bridges the gap between the extremes of energy storage time scales, with sudden load imbalances addressed through the introduction of "real system inertia" (in a flywheel) and secondary energy stores (compressed fluid) exploited for sustained delivery over longer time periods. Real inertia is distinct to emulated or synthetic inertia, and may be thought of as energy storage that acts in an entirely passive manner. That is to say, the transfer of energy is determined completely by the reluctance of the system to change speed. By way of example, a 50 MW system with a capacity of 20 MWh is sized here with the view that such a design could form part of the energy storage requirement for an offshore wind farm.

Numerous techniques have been proposed for emulating inertia in