OPTIMISATION OF THE HYDRAULIC VARIABLE INERTIA FLYWHEEL FOR SPECIFIC ENERGY

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Introduction

The control of the European electricity grid currently relies on conventional inertia provided by rotational masses connected to the grid via synchronous generators [1]. The kinetic energy (E_{kin}) stored within these rotating generator units responses inherently, opposing power imbalances (ΔP) [2]. Power imbalances lead to a change in the frequency (f) of the electricity grid. The instantaneous Rate of Change of Frequency $(RoCoF)$ can be derived from equation (1), where S_{sys} and H_{sys} are the apparent power and the inertia constant of the power grid [3, 4].

$$RoCoF = \frac{\Delta P \cdot f}{2 \cdot \underbrace{S_{sys} \cdot H_{sys}}_{E_{kin}}} \tag{1}$$

It becomes apparent that the kinetic energy stored in the power grid (E_{kin}) is crucial to keep the $RoCoF$ within manageable limits [3]. The transition towards 100% renewable energy is rapidly reducing conventional inertia, as synchronously rotating generation units are replaced by inverter-based renewables [2]. This can be supplemented by frequency measurements from Thiesen et. al. 2021 [5] that show an increase in $RoCoF$ in the continental European electricity grid from 2016 to 2022, see Figure 1.

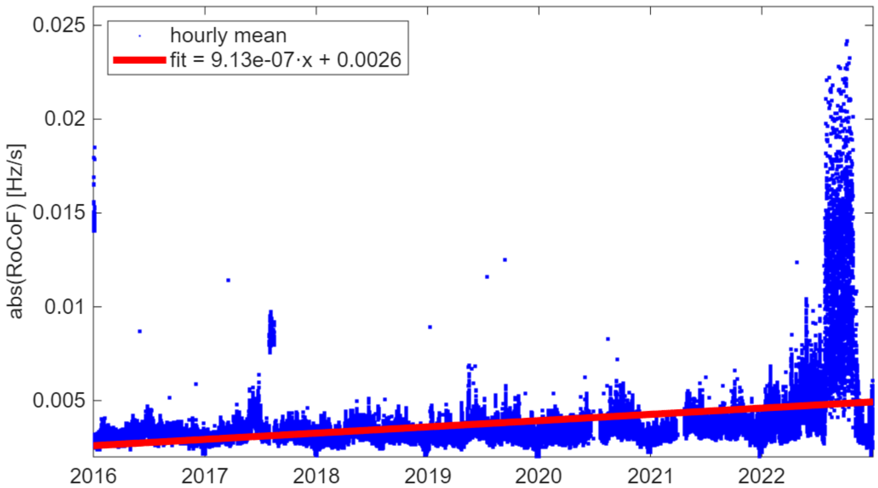

Figure 1: Hourly mean of the absolute RoCoF in the continental European electricity grid from 2016 to 2022. The data points (blue) are fitted with a linear function (red) over the entire data series.

For maintaining a stable frequency control in a future European electricity grid, additional synthetic inertia together with alternative spinning reserves is required [2]. The Hydraulic Variable Inertia Flywheel (HVI-FW) [6] represents such an alternative spinning reserve [6, 7]. It is a synchronously rotating flywheel that can store energy in the change of its rotational speed, in the change of its moment of inertia and in the compression of gas [6]. Thus, the HVI-FW is offering a greater specific energy (Wh/kg) compared to conventional flywheels (CFWs), making it a good addition for providing inertia to the electricity grid (see Figure 3). This novel flywheel therefore addresses a critical need in a future continental European electricity grid by offering distributed, fast-responding, inherent inertia. In order to show which geometric configurations of the HVI-FW are best suited for this task, this paper introduces a design tool developed for this purpose.

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Results

To find favourable dimensions of the HVI-FW for providing inertia (i.e. kinetic energy) to the electricity grid, the diameter of its inner and outer cylinders, as well as its height are varied. During a generation loss, the frequency can drop from 50 Hz to 47.5 Hz before an impermissible grid frequency is reached [7]. Hence, for each geometric configuration, the energy provided by the HVI-FW during a frequency drop from 50 Hz to 47.5 Hz is calculated. To find the optimal geometric configuration and to reduce the material consumption compared to CFWs, the specific energy is derived. The design tool indicates that both the hollow cylinder radius (width) and height of the HVI-FW should be as large as possible to maximize specific energy (see Figure 2). Because the same trend applies to CFWs, Figure 3 compares the specific energy of the optimal geometric configurations of the HVI-FW with that of CFWs. For the CFWs, a CFRP rim with identical energy content, height, and outer diameter as the HVI-FW is considered. Figure 3 shows, that the HVI-FWs achieve significantly higher specific energy, particularly at small radii. However, this advantage decreases continuously as the radius of the hollow cylinder increases and even reverses. Consequently, the design tool emphasises HVI-FW configurations with small hollow cylinder radii and thus relatively low power. This makes the HVI-FW a good choice for providing inertia to the electricity grid by coupling it to small synchronously rotating electrical machines, which are spatially well distributed and abundantly available.

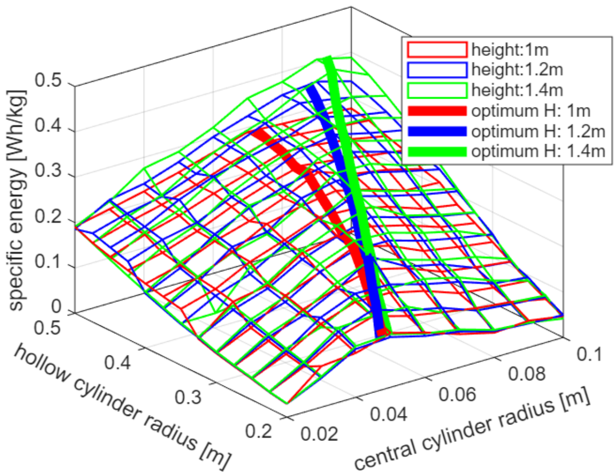

Figure 2: Specific energy of the HVI-FW in regard to its central cylinder radius, hollow cylinder radius and height (red for height = 1m, blue for height = 1.2m, green for height = 1.4m)

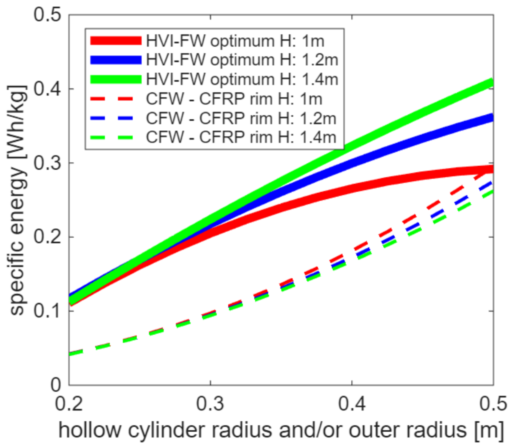

Figure 3: Specific energy for the optimal geometric configurations of the HVI-FW compared to the specific energy of CFWs

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