Future Frequency Stabilisation by Innovative Hydraulic Variable Inertia Flywheel

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Abstract: In order to ensure the security of supply of the German power grid as part of the continental European power system in the future, alternative solutions for providing inertia must be used regarding the energy transition and the resulting reduction of conventional power plants. One solution for this is the innovative hydraulic variable inertia flywheel, which was invented at Flensburg University of Applied Sciences. It is characterised by a variable mass moment of inertia, which allows it to exchange energy with the grid while rotating at a quasi-constant speed. As a synchronously connected rotating machine, it offers an inherent grid-forming effect. This article therefore examines the potential for providing inertia through the hydraulic variable inertia flywheel in Germany. Using a design tool, potential power outputs are determined. Assuming that the novel flywheel is connected to all rotating power generators of corresponding rated power in Germany, the inertia potential is calculated. The flywheel can be designed to provide between around 13 and 1,450 kWs during a frequency drop from 50 to 47.5 Hz. Assuming a provision time of 10 s, the power output is between 1 and 145 kW. Additionally, it is assumed that all existing power generators of this size are connected synchronously to the grid and that a hydraulic variable inertia flywheel is connected to all of them. This results in a potential inertia provision of approximately 5 GWs in addition to the 0.2 GWs of inertia provided by the electric machines itself. By attaching this flywheel to those generators, their kinetic energy provided during that frequency decrease can be increased by a factor of 26. It should be emphasised at this point that this result of 5 GWs is based solely on the use of low-scale existing generation-side infrastructure. Additional potential exists in the use of load-side machines. The aim of the HVI-FW is not to cover a major share of inertia demand but to provide a sustainable complementary solution to grid-forming frequency converters by still taking advantage of the grid-forming benefits of synchronously rotating machines.

Keywords: inertia, frequency stabilisation, power grid, energy transition, flywheel

1 Introduction

Driving forward the energy transition to achieve climate targets is a challenge for the energy industry on multiple levels. The expansion of fluctuating renewable energies and the electrification of several sectors are not only leading to an increase in imbalances between electricity generation and demand, but also to a reduction in conventional power plants and thus in the inertia of the system. The result is an increase in frequency deviations [1]. Therefore, frequency stabilisation is one challenge to ensure the security of supply in a future 100 % renewable power system.

Nowadays, the frequency of the continental European electricity grid is inherently stabilised by the inertia provision of conventional technologies due to their inertial mass rotating synchronously connected to the grid. The renewable energies photovoltaic and wind are connected via frequency converters and thus do not provide inherent inertia today. The reduction of conventional power plants and the expansion of renewable, converter-based technologies are consequently leading to a reduction of system's inertia which effects the frequency stability negatively. For this reason, technological, regulatory and economic changes and innovations are needed to ensure the functionality of the power system in future. [1]

This article focuses on an innovation for future frequency stabilisation: the hydraulic, variable inertia flywheel (HVI-FW) [2]. Due to its variable moment of inertia, HVI-FW exchanges energy with the grid while rotating at a quasi-constant speed. Connected to the grid via a synchronous machine of rotating power generator or load, it provides inertia inherently and offers a grid-forming effect. Even though grid-forming frequency converters will play a significant role in providing inertia in the future [3], HVI-FW offers a complementary solution that does not require controls, i.e. software and communication. Hence, it is inherently secure against software bugs, communication network interruptions and cyber-attacks [2].

The aim of this paper is to investigate the potential inertia provision of HVI-FW in Germany when connected to already existing rotating generators of suitable rating.

2 Frequency as an indicator of grid stability

Power generation and demand must be balanced at all times. If power generation and the total consumption due to losses and usage are exactly equal, the frequency of the continental European power grid is 50 Hz and thus stable. Imbalances between generation and consumption lead to frequency fluctuations. The electricity grid can only be operated stably within a frequency band of 47.5 and 51.5 Hz. Particularly problematic are underfrequencies, which in the ultimate case, are tackled with load shedding. In order to keep the frequency stable, energy must therefore be fed into or taken out of the system to compensate for the imbalance. There are various frequency control measurements for this purpose. The first frequency control measure is system inertia, which inherently counteracts fluctuations. Rotating power plants and rotating loads, which are synchronously connected to the electricity grid, inherently provide inertia. Kinetic energy is stored by their rotating masses. Whenever the grid frequency changes, this kinetic energy is inherently and instantaneously provided to the power grid, counteracting the imbalance between generation and demand. Hence, inertia does not stop a drift in frequency, but it retards it, and by doing so, it provides the time necessary for activating control reserves. Not inherently and only after a necessary activation time, control reserves provide the power that is necessary to re-establish a constant and satisfactory grid frequency. [4]

The expansion of renewable energies leads to a reduction in conventional rotating power plants and loads and thus to a reduction in system inertia. Already today, there are stronger frequency fluctuations, which are caused by high renewable feed-in and the decoupling of conventional power plants. [1] For this reason, the German Federal Ministry for Economic Affairs and Energy identifies system stability as a key challenge, especially in the short term. Another reason, besides the continuously decreasing system inertia, is the increase in potentially critical system states. Possible system-splits are an example for those critical system states. The result is an increasing need for additional system inertia. In the past, there was no need for additional inertia because the system had sufficient inertia due to the dominance of conventional power plants with their synchronously connected rotating generators. [5]

3 Frequency stabilisation by the hydraulic variable inertia flywheel

In order to stabilise the frequency and thus the power grid, an inherent inertia provision is necessary. With the aid of grid-forming frequency converters that emulate the behaviour of synchronous machines (virtual synchronous machines), the stored energy from converter-based technologies, such as wind turbines and battery storage systems, can be utilised and provided to the power grid. Wind turbines utilise the energy stored in their rotation. Since photovoltaics do not store energy directly, they cannot be used to provide inertia through grid-forming frequency converters. According to the German Federal Ministry for Economic Affairs and Energy, a significant share of the inertia demand will be provided by grid-forming power converters in the future [3]. Their functionality has already been proven by their use in inverter-dominated island grids. They have also been used successfully in uninterruptible power supply systems [6]. Broad field and pilot tests are required for widespread use [3].

Even though grid-forming frequency converters will play a significant role in frequency stabilisation in the future by covering the majority of demand, it still makes sense to complement them with passive, synchronously connected electric machines, which have kinetic energy storage connected to their shafts. This is because frequency converter-based power grid support has the disadvantage of requiring high-resolution frequency measurements and being vulnerable to cyber-attacks. The hydraulic variable inertia flywheel, developed at Flensburg University of Applied Sciences, is one such technology that can be used to provide inertia as a complement. As a kinetic energy storage device, the HVI-FW is ideally connected to the grid synchronously via a synchronous machine, although a simpler and cheaper induction machine would also work [2]. Since all rotating electric machines are types of magnetic energy storage devices, the HVI-FW also has an inherent grid-forming effect. In contrast to passive rotating masses, it has a variable moment of inertia, which allows it to offer much greater inertia constants assuming the same initial moment of inertia.

The functionality of the HVI-FW is briefly explained in the following. The flywheel consists of two concentric cylinders that rotate around their longitudinal axis. The central cylinder and the hollow cylinder are connected to each other via a double bottom. This double bottom allows the two cylinders to communicate according to the principle of communicating vessels. Pressure is applied to the hollow cylinder to such an extent that initially the fluid is only in the central cylinder. The centrifugal force generated by the rotation causes the fluid to flow through the double bottom into the hollow cylinder towards larger radii. The shift of mass to a larger radius increases the moment of inertia. During this shift, the fluid compresses the gas in the hollow cylinder. If the speed and thus the centrifugal force decreases, the gas pressure in the hollow cylinder prevails, so that the fluid is pushed back into the central cylinder. The reduced moment of inertia results in an accelerating torque. The HVI-FW can thus store energy in the variation of the moment of inertia at quasi-constant speed. Therefore, the HVI-FW is capable of providing inertia and frequency containment reserve. [2]

There are additional benefits. The flywheel is characterised by its simple design. As it does not require any rare materials, it is a sustainable alternative to conventional fossil based machines while offering the same grid-forming effects. It is connected to the power grid via an electric synchronous machine. In addition to providing inherent inertia, those synchronous machines offer several benefits for the power grid: high efficiency, the insensitivity to voltage distortions, vector surges, flicker, providing reactive power, and their favourable short circuit current contribution. While the fault current capacity of grid-forming frequency converters is limited to 1.2 times their rated current, classic synchronous machines can deliver up to seven times their rated current. [7] As HVI-FW does not require a frequency converter or controls, it is secure against cyber-attacks and offers reliable operation. The HVI-FW is particularly suitable for smaller applications in the low-to-medium kilowatt range. When connected to motors of various devices, it provides decentralised support for the power system and thus increases the redundancy of system stabilisation, which is particularly important in the context of possible system-splits [5].

HVI-FW can be made from various materials, which are currently still being investigated. Manufacturing from materials with high specific strength, such as carbon fibre, enables energy storage with high power outputs. Lower power units can be realised using simpler materials, such as steel. In the current research project Inno!Nord-HYDRAD [8], demonstrators are manufactured using 3D printing of polyethylene terephthalate glycol (PETG) and then coated with carbon fibre reinforced plastic (CFRP). The reason for this type of production is that the 3D printing process allows different geometries and sizes to be tested flexibly, cheaply, quickly and independently. Possible designs of HVI-FW are then coated with CFRP so that load tests can be conducted at higher speeds due to the high strength of CFRP.

4 Methodology

In order to identify the potential inertia provision via HVI-FW, a design tool is used to determine suitable geometries and the corresponding energy output for inertia provision [9]. The flywheel consists of a PETG liner coated with CFRP. The material specific parameters are integrated in the design tool. The geometry considered is a cylinder with hemispherical caps.

As the HVI-FW is still being developed, the first step is to determine the amount of inertia that can be provided. The amount of energy stored in the HVI-FW depends on the rotational speed and the size of the flywheel. In addition to kinetic energy, potential energy is also generated by the radial movement of the fluid. Nevertheless, the amount of energy stored is determined by the rotational speed. The rotational speed is set by the synchronous connection to the power grid, where the frequency varies between 47.5 and 51.5 Hz. The HVI-FW should be able to charge and discharge energy within this speed range. Therefore, the design tool considers this frequency range. The power output is calculated as the average over a period of 10 s in accordance with the technical requirements for grid-forming devices of the Verband der Elektrotechnik [10].

The central cylinder volume determines the fluid volume. In order to be able to displace fluid both when the frequency is increased from 50 to 51.5 Hz and when it is reduced from 50 to 47.5 Hz, it is assumed that at a frequency of 50 Hz 37.5% of the fluid is in the central cylinder and 62.5% is in the hollow cylinder. Therefore, the design tool determines the stored energy for positive inertia provision during a frequency drop from 50 – 47.5 Hz and for negative inertia provision during a frequency increase from 50 – 51.5 Hz. To do this, different radii and heights are combined and the respective energy output is calculated. The central cylinder radii are from 0.02 to 0.1 m, the hollow cylinder radii are between 0.25 and 0.6 m. In addition, the HVI-FW is calculated with three different heights: 1.2 m, 1.4 m, and 1.6 m. These geometric ranges were determined with regard to the feasible design of demonstrators based on the current state of research.

Since the aim is to identify suitable geometries for providing inertia, the ratio of the moment of inertia must be taken into account in addition to the amount of energy stored. The following criteria have therefore been established, which the geometries must meet:

1. The movable share of the fluid within the speed range is at least 80%.
2. The average power output is at least 1 kW.
3. The inertia ratio is greater than 1.
4. The specific energy of HVI-FW is greater than that of a conventional flywheel.

A geometry is defined as suitable if these criteria are met. In order to utilise the effect of the variable moment of inertia, it is assumed that at least 80% of the available fluid is displaced. With a frequency drop from 50 Hz to 47.5 Hz, this means that at least 80% of the fluid in the hollow cylinder, i.e. 62.5% of the total fluid volume, is shifted to the central cylinder. Assuming an inertia constant of 10 s, one criterion is a minimum additional stored energy of 10 kWs so that the average power output is 1 kW. Another criterion is whether HVI-FW offers an advantage compared to a conventional flywheel. This is the case if the specific energy of HVI-FW is greater than that of a conventional flywheel storing the same amount of energy at the same outer radius and height. The conventional flywheel was assumed to be a hollow cylinder made of CFRP with the same dimensions.

As described above, if HVI-FWs are connected to different electric machines, they support the system stability in a decentralised manner. In order to use existing infrastructure and to identify the total inertia provision, it is assumed that HVI-FWs are connected to all synchronously rotating electric generators in Germany with suitable rated power. An overview about those power plants is offered by the German core energy market data register [11]. It would also be possible to connect HVI-FW to rotating loads, but this is not considered here due to a lack of available data.

5 Results

First of all, the possible inertia provision of different geometries is examined. Figure 1 shows the energy which can be provided to the electricity grid when the frequency drops from 50 to 47.5 Hz. The taller the flywheel is the more energy can be provided due to the lager fluid volume. In addition, the amount of energy stored increases along larger hollow and central cylinder radii. The same observation can be made for Figure 2 during a frequency increase to 51.5 Hz.

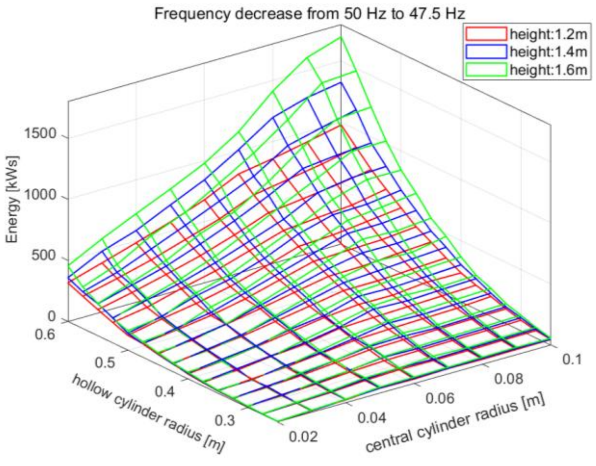

Figure 1: Energy provided during a frequency drop from 50 to 47.5 Hz for different radii and heights

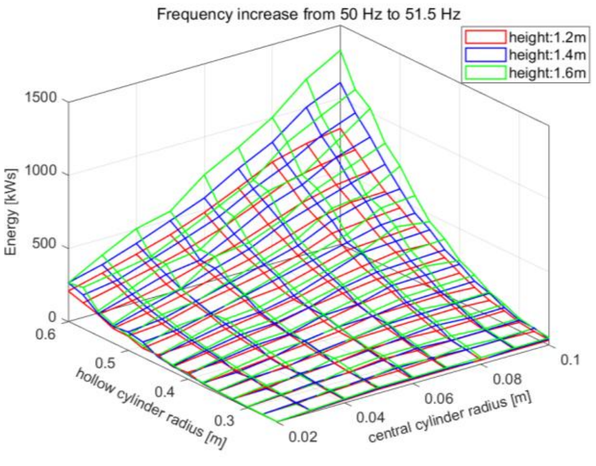

Figure 2: Energy stored during a frequency increase from 50 to 51.5 Hz for different radii and heights

As already mentioned, the ratio of the moment of inertia is important to evaluate the demonstrator for the purpose of inertia provision. Therefore, it is shown in Figure 3, as an example only for the frequency drop.

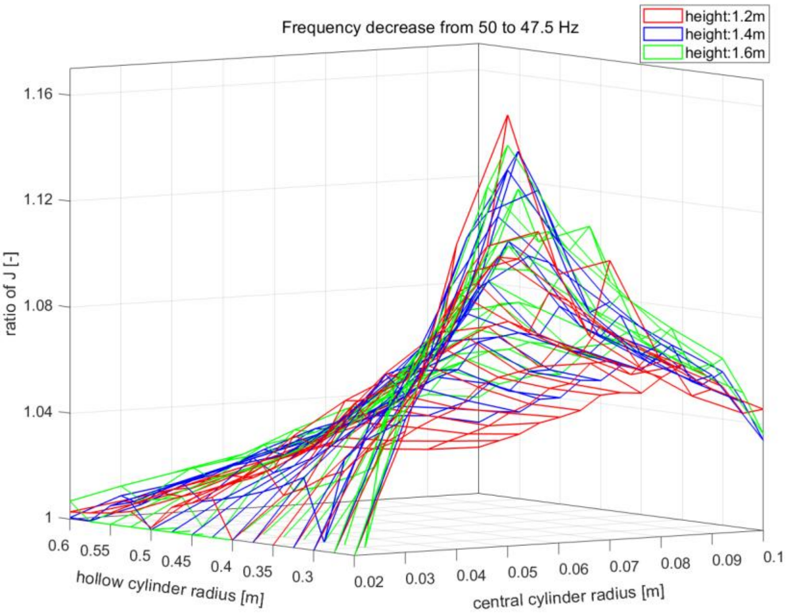

Figure 3: Ratio of moment of inertia of the HVI-FW for a frequency drop from 50 to 47.5 Hz for different radii and heights

The highest ratio of the moment of inertia is not reached by increasing the radii and heights, but by the optimum ratio between those. The height has a minor influence, which is why the curves for all three heights are similar. In principle, it can be seen that the smaller the hollow cylinder radius is in relation to the central cylinder radius, the better the moment of inertia ratio. However, after reaching an optimum, the inertia ratio decreases again as the central cylinder radius increases further because less fluid can be displaced due to the smaller radius difference. The highest moment of inertia ratio of 1.16 is achieved at a height of 1.2 m, a central cylinder radius of 0.05 m and a hollow cylinder radius of 0.25 m.

This results in a conflict of objectives for the flywheel design. It cannot be designed for both maximum energy storage and maximum moment of inertia ratio at the same time. Since the provision of inertia is the primary focus, but the moment of inertia ratio must also be taken into account, the criterion was set that the inertia ratio must be greater than 1, see chapter 4. Using the criteria, which are explained in chapter 4, the possible geometry combinations can be filtered according to suitability.

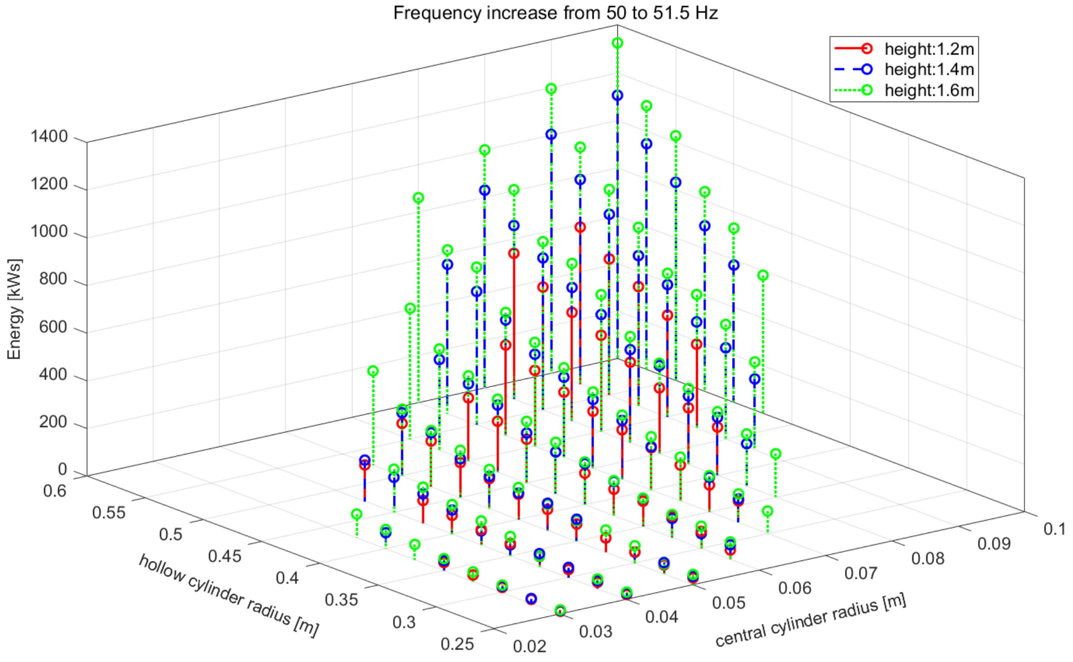

Figure 4: Stored energy by suitable geometries during frequency increase from 50 to 51.5 Hz

As expected, Figure 4 shows an increase in stored energy towards larger radii and heights. However, it is noticeable that combinations of large hollow cylinder radii with small central cylinder radii (left corner) are not suitable. This is due to the fourth criterion 'The specific energy of HVI-FW is greater than that of a conventional flywheel'. Large hollow cylinder radii combined with low fluid volume result in low specific energy density due to high passive masses, meaning that the use of HVI-FW offers no advantages over conventional flywheels. Furthermore, the combination of small hollow cylinder radii with large central cylinder radii (right corner) is also unsuitable, as not enough fluid can be displaced with regard to the first criterion that at least 80% must be displaceable.

Figure 4 suggests that even larger geometries should be tested to achieve optimum results. However, if we consider the frequency drop from 50 to 47.5 Hz, a limit value can already be identified, at least under the selected criteria and assumptions (see Figure 5).

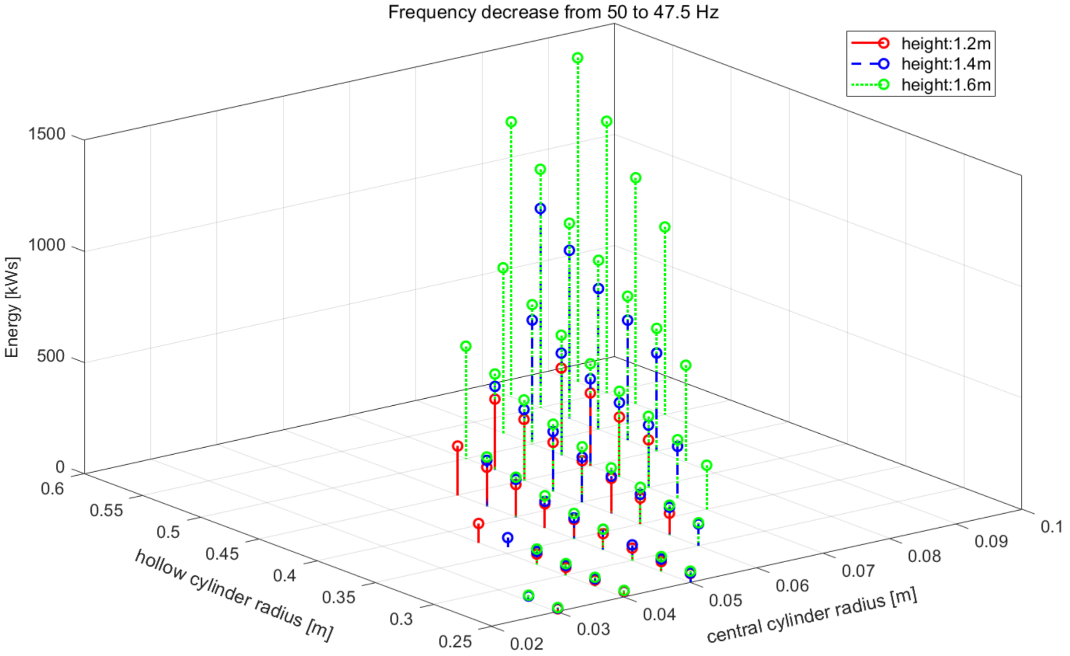

Figure 5: Energy provision by suitable geometries during a frequency decrease from 50 to 47.5 Hz

Considering the case of frequency drop, significantly fewer geometric combinations are suitable. The lower speed amplifies the phenomena of the left and right corners which is already observed in Figure 4. Although the speed difference is greater, a larger fluid volume must be displaced. Therefore, the first criterion, that at least 80% of the fluid volume must be displaced, has a particularly strong effect here.

Since the HVI-FW should be able to provide inertia in both positive and negative direction, only the suitable geometries from Figure 5 are considered. The geometry combination with the lowest energy and consequently lowest power output is a hollow cylinder radius of 0.25 m, a central cylinder radius of 0.03 m and a height of 1.2 m. It provides 13.22 kWs during a frequency drop. 1,458.29 kWs are provided by the largest combination of a hollow cylinder radius of 0.575 m, a central cylinder radius of 0.09 m and a height of 1.6 m. Assuming that the power is supplied over a period of 10 seconds [10], this results in a power range of around 1 to 145 kW. The difference in size between the flywheel for 1 and 145 kW is shown in Figure 6. The geometries and wall thicknesses calculated using the design tool are taken into account.

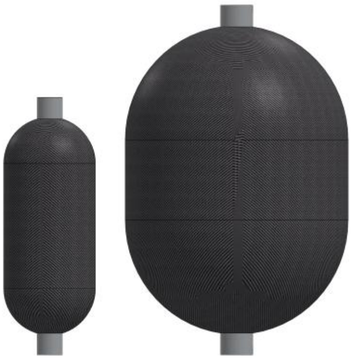

Figure 6: Comparison of the dimension of HVI-FW for 1 kW (left) and for 145 kW (right)

In order to determine the total potential inertia provision of HVI-FW in Germany, it is assumed that the flywheel is connected to all existing electric power generators in Germany. It is also assumed that these are all connected synchronously to the grid. Due to the German core energy market data register, there are 13,993 conventional power plants in use which have a rated power between 1 kW and 145 kW [11]. Figure 7 shows an overview about the amount of power generators in Germany and their cumulated rated power. In the selected range between 1 and 145 kW, it can be seen that most generators have a lower rated power. In total, they offer an installed capacity of 512 MW. It is assumed that these are all connected synchronously to the grid. The chosen inertia constant of 10 s [10] and the installed power can then be used to determine the inertia provided by HVI-FW, when connected to these electrical machines.

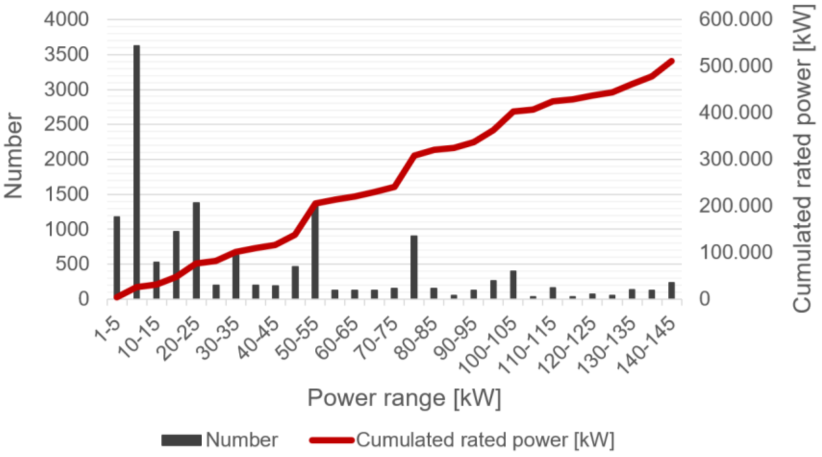

Figure 7: Overview of the amount and rated power of generators in Germany between 1 and 145 kW based on [11]

By installing the HVI-FW as an additional rotating mass on these power generators, the discharge of the HVI-FWs over a time period of 10 s at the rated power amounts to around 5.12 GWs during a frequency decrease from 50 to 47.5 Hz. This inertia provision is additional to the inertia provided by the electric machine the flywheel is attached to. Making a conservative approach by assuming an average inertia constant of 4 s [12], the energy discharged amounts to around 0.2 GWs during the frequency drop decrease from 50 to 47.5 Hz. By attaching HVI-FW to those generators, their provided energy is 26 times higher than without during that frequency decrease.

6 Discussion and conclusion

Assuming that the HVI-FW is connected to all existing rotating electric machines in the power range of 1 – 145 kW in Germany and that these are connected synchronously to the grid, the energy inherently provided by the HVI-FW in the event of a frequency drop from 50 to 47.5 Hz is approximately 5 GWs. This multiplies the energy provided by the electric machines themselves, which is 0.2 GWs, by a factor of 26. Due to its variable moment of inertia, the HVI-FW provides a significant amount of energy in this limited frequency band.

It should be emphasised that this result is based solely on the use of low-scale existing generation-side infrastructure. Additional potential exists in the use of load-side machines. Furthermore, electrical machines can of course also be procured and HVI-FW connected directly to the grid in order to further increase capacity which can then also be used for other purposes. For example, HVI-FW can also be used for inherent uninterruptible power supply and could then simultaneously provide inertia for frequency stabilisation, thus having a dual-use effect [13]. It can be concluded that the inertia potential of HVI-FW is significantly greater than determined in this article, but it will still not cover the major share of the inertia demand. Battery storage capacities in Germany are growing steadily, as they are essential for the energy transition by compensating fluctuations in renewable energies and bridging the gap between generation and consumption [1]. It therefore makes sense that they are also used as existing infrastructure for providing inertia. The aim of the HVI-FW is thus to provide a sensible and sustainable complementary solution to grid-forming frequency converters by continuing to exploit the grid-forming advantages of synchronously rotating machines.

7 References

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