Linear Electric Machine-Based Gravity Energy Storage for Wind Farm Integration

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***Abstract*—In this paper an above-ground, dry gravity energy storage system to help integrate wind energy sources into the energy mix, is described and developed. Using the principle of gravitational potential energy and a single piston example, multi-piston shafts and multi-shaft systems are proposed. From this analysis, some of the basic characteristics of the system, such as round trip efficiency and energy density, is derived. Using a generic wind farm and available literature, the paper discusses how the system can be constructed and used to help integrate wind farms with an electrical grid, while also demonstrating the comparatively small surface area that the storage system requires.**

***Index Terms*—Energy storage, wind farms, renewable energy sources, gravitational potential energy, linear electric machines**

I. Introduction

Renewable energy has grown tremendously since the start of the century, supplying 26 % of global electricity production in 2018 [1]. A total of 1246 GW of renewable energy (not including pumped hydroelectricity) was installed by the end of 2018, with wind power contributing 591 GW thereof [1]. Similarly, wind power represents 52 % of the renewable power supply of South Africa [2].

With wind power set to increase its share of power generation responsibilities further, integrating the additional wind power capacity presents many challenges due to the inherent variability of wind. This not only introduces uncertainty in the availability of wind, but also short term fluctuations [3].

This uncertainty and variability results in power quality problems, with ancillary services needed to provide frequency response, power smoothing and peak shaving, among others [4]. The need to ensure adequate grid flexibility and reliability with the growing participation of wind power has renewed the search for technologies that can assist with grid integration, such as new forecasting tools, demand-side control and energy storage [5].

Energy storage specifically has received renewed attention because of its wide range of applications [6], [7], from improving power quality, providing voltage and frequency support, long-term bulk storage and other grid support services such as upgrade deferral [5].

There are numerous energy storage technologies, making it useful to divide them into different categories. These technologies can be classified either by the service they provide or the method by which the energy is stored, i.e. the form in which the energy is stored. The from of energy storage can be divided as either mechanical, chemical, electrochemical, electrical or thermal energy storage, while the type of service they provide can be divided into three overarching categories, i.e. bulk storage, distributed storage and power quality services [8]. Storage systems can be further evaluated by comparing their technical characteristics, with some of the important characteristics being the system's energy and power rating, round-trip efficiency and cost, usually determined using a cost metric such as levelised cost of storage (LCOS).

The most commonly used utility-scale storage system is pumped hydroelectric energy storage (PHES), with batteries and flywheel storage systems being popular choices for storage systems installed alongside wind farms [3], [4], [9], [10]. Some other technologies include hydrogen storage, supercapacitors, superconducting magnetic energy storage, gravitational potential energy storage methods and compressed air schemes.

The focus of this paper is on a specific gravitational potential energy storage system, developing the energy storage concept proposed in [8] further. The paper is divided up into the following sections: Section II describes some of the existing and proposed gravity energy storage methods, with Section III further explaining and describing the specific storage method being considered in this paper. Section IV discusses how energy storage technologies are used to help integrate wind farms into the grid, with Section V detailing a design for the LEM-GES. Lastly, some conclusions and recommendations are given in Section VI.

II. Gravity Energy Storage Technologies

The use of gravitational potential energy as a method of energy storage is an old concept. PHES, which is currently the most used and mature energy storage method [11], is a form of gravitational energy storage. A number of variations on traditional PHES concepts have been proposed since its inception in the 1890s, including the use of old mineshafts for underground PHES (UPHES) and various piston-based

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pumped storage technologies [12]–[14]. PHES provides obvious advantages, e.g. scalability, commercial viability and high round trip efficiencies [15], but it also has some distinct disadvantages. Gravitational pull is relatively weak and the density of water is low, thus PHES requires either a large head or large volume of water with which to store a significant amount of energy. Site selection criteria is also very strict, as a potential site has to have sufficient water supply, the correct topography, economic feasibility and social acceptability [15].

It is only recently that waterless forms of gravity energy storage have also gained some traction, as can be seen by the proposed systems from ARES LLC [16] and Gravitricity [17].

Advanced rail energy storage (ARES) uses rail road shuttles to move large blocks of concrete, typically between 45–64 t each, uphill to charge the system and let the concrete blocks descend under gravity when discharging the system [16]. ARES has a round-trip efficiency of 80 %, a proposed lifetime of 40 years and no standby storage losses. ARES currently has their first commercial project underway in Nevada, a 50 MW, 12.5 MWh system. The aim is to build systems with a power rating ranging from 100 to 3000 MW and energy ratings up to 6 GWh.

Gravitricity proposes vertically raising and lowering a large mass down an abandoned mineshaft [17]. The system uses a piston (the large mass being hoisted) with a mass up to 3000 tonne over a distance of 1500 m, hoisted with a specialised system that is similar to those found in existing deep shaft mines. This system has a claimed round-trip efficiency between 80 - 90 % and a system lifetime of 50 years, with a rated power of up to 40 MW and an energy rating of a few MWh. Gravitricity has received funding to build a 250 kWh prototype [18].

The authors of [8] also use the idea of moving a piston vertically to store energy, however without the use of the more conventional mining hoist system. Instead, the piston forms part of a linear electric machine (LEM), which is used to move the piston. This enables the system to operate without the need for wire ropes, allowing for the use of multi-piston system, improving the storage system in numerous ways, not least of which is an increase in storage capacity. The authors also proposed that the LEM-based gravity energy storage (LEM-GES) system could be constructed in two different ways. One method would be to place the system in an old mineshaft, thereby ensuring that the system has a large height difference and can store a significant amount of energy. This does, however, restrict the system to suitable and available mineshafts. The other method is to build a shorter, above ground structure, allowing for optimal system placement, at the expense of system height. The second of the proposed the proposed systems is further developed in this paper, explaining the operation and how the system can be used in the integration of wind energy resources.

III. LEM-GES System Description

The LEM-GES system stores energy through the principle of gravitational potential energy, which can be stated as:

$$E = mgh, \tag{1}$$

with E being the potential energy in Joule, m the mass of the object in kilogram, h the height of the system in meters and g the gravitational constant (9.81 m/s^2). With 1 kWh being equal to 3.6 x 10^6 Joule, it is clear from (1) that a large mass or height is needed to be able to store even a few MWh of power, as can be seen by Gravitricity's proposed storage system being only a few MWh despite a piston mass of 3000 tonne and a height difference of 1500 m. This highlights two problems when designing any type of gravity energy storage system, namely how to achieve a sufficiently large object mass and system height so that enough energy can be stored for the intended energy storage application.

A. Piston Description

LEM technologies directly convert electrical energy to linear movement and vice versa, without the need for intermediary systems such as gearboxes or wire ropes. LEMs are commonly used in wave energy converter systems, magnetically levitated (MAGLEV) trains and ropeless elevator systems [19]–[21].

The LEM-GES system utilises the ropeless operation enabled by the use of LEM technology, by foregoing the use of a single, large piston in favour of multiple, smaller pistons. Each piston takes the form of a rectangular prism, with the LEM attached to the four sides of the prism, as shown in Fig. 1, with l_p being the piston length and w_p being the piston width.

LEMs can be obtained by 'cutting and rolling out' the corresponding rotary machine and can be classified according to topologies or the shape of the LEM, i.e. flat or tubular. [8], [19]. Similar to a rotary machine, it has one side with armature windings, which is referred to as the primary. The other side is called the secondary, or translator, and relates to the rotor of a rotary machine. LEMs can have any combination of permanent magnets and windings on the primary, secondary or both.

For an application such as the LEM-GES, where the secondary needs to cover the system height, it would be prohibitively expensive to have any active material (copper or permanent magnets) placed on it. Thus, any suitable LEM topology for the LEM-GES would require a passive secondary, as illustrated in Fig. 2.

Examples of topologies with passive translators are: flux switching, flux reversal, switched reluctance, vernier and vernier hybrid machines. Alongside the passive secondary requirement, three important characteristics need to be considered, namely the efficiency, power factor and shear force of the specific topology.

The efficiency of the chosen LEM is the main determining factor in the round-trip efficiency of the LEM-GES, while the power factor determines the rating of the power electronic converters. The shear force is directly related to the dimensions of the piston, as given by (2) [8].

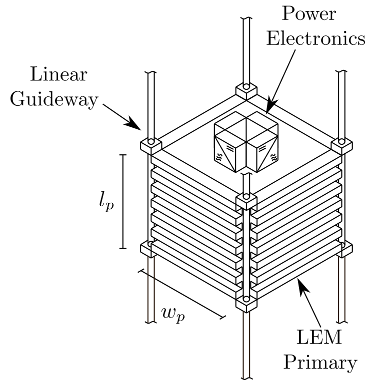


Fig. 1: Example piston in the LEM-GES system, excluding the armature winding.

TABLE I: The dimensions of a single piston.

Dimension	Value
l_p	3 m
w_p	1.5 m
Mass	50 tonne
Piston material	Iron
Material density	7850 kg/m^3
Shear force	30 kN/m^2

$$\sigma = \frac{1}{4}\rho w_p g. \tag{2}$$

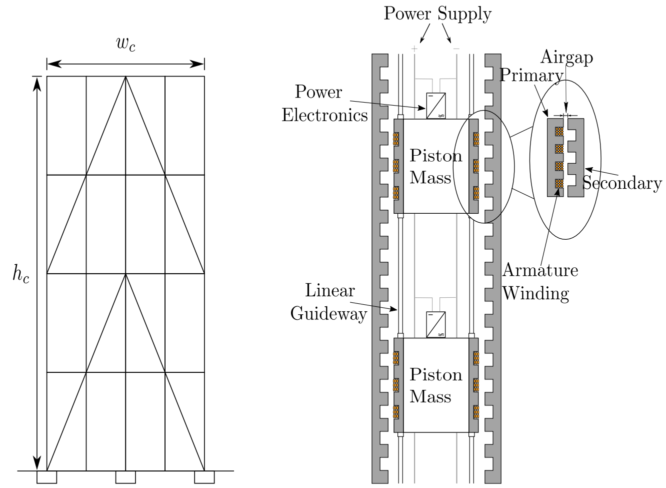
In (2), σ is the shear force in kN/m^2 and ρ is the piston mass material density in kg/m^3. The sizing of a piston and the choice of material is discussed in more detail by the authors of [8], with the piston specifications given in Table I.

B. Shaft Description

The multi-piston operation is illustrated in Fig. 2, with h_c being the shaft height and w_c the shaft width. Fig. 2 illustrates both how such a shaft would look when viewed from the outside and how the pistons are situated inside the shaft. The LEM-GES resembles a large ropeless elevator system, with multiple elevators in a single shaft.

The height of a single shaft as well as the stored energy is determined by the number of pistons that the shaft contains. There is an inherent trade-off between the height, and therefore cost, of the system and the energy storage capacity. For the purpose of this paper, an arbitrary travel distance of 100 m is chosen per piston.

Each additional piston extends the value of h_c by approximately four meters, three for the piston length and one for the necessary power electronic and other systems. To limit the total height, a maximum of 10 pistons per shaft is chosen. As a result, each shaft has dimensions of h_c = 140 m and w_c = 2.5 m. This width is to account for the piston as well as the secondary of the LEM and the supporting structure. Thus, according to (1), each piston has an energy capacity of 13.6 kWh, with each shaft having a stored capacity of 136 kWh. Each shaft has an energy density of 0.252 kWh/m^3. The round-trip efficiency, η, of each shaft is largely determined by the efficiency of the LEM being used. With some LEMs reaching an efficiency of up to 95 % [22], a conservative assumption of 90 % charge or discharge efficiency is assumed, to take into account the likely losses due to mechanical friction and power converter losses. A single shaft LEM-GES thus has a round-trip efficiency of 81 %. The specifications of a single shaft is given in Table II.



(a) Outside view of the LEM-GES.

(b) Cut through side view of the LEM-GES

Fig. 2: An outside view and a cut through side view of a single shaft of the proposed LEM-GES system.

TABLE II: The dimensions of a single shaft.

Specification	Value
h_c	140 m
w_c	2.5 m
Stored Energy	136 kWh
Energy Density	0.252 kWh/m^3
η	81 %

C. System Description

These shafts can be placed next to each other to form the complete LEM-GES system, as shown in Fig. 3, with h_s being the system height and equal to h_c, and w_s being the system width. This system has the same energy density and round-trip efficiency as a single shaft LEM-GES. The shaded areas visible in Fig. 3 indicate spaces without any shafts in. These serve as maintenance access points so that each individual shaft can be accessed.

The placement of multiple shafts next to each other in the beehive-like structure, each with multiple pistons, means that the system is highly modular, and can be adjusted to fit the specific application and situation, as is illustrated through examples in Section V.

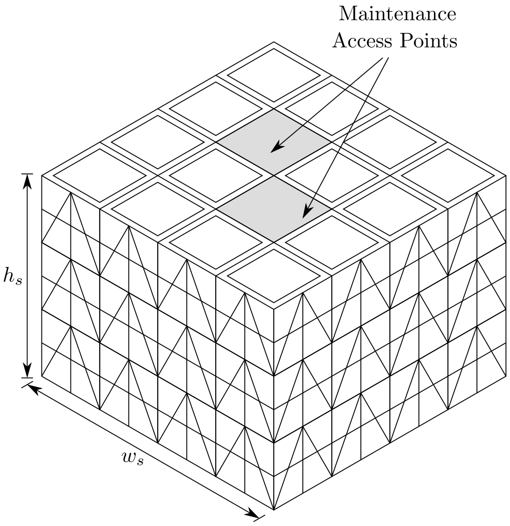


Fig. 3: An outside view of an example 14 shaft LEM-GES structure.

This system has numerous advantages. As it is an electromechanical conversion system, it can charge and discharge completely without damaging the system. It has a nearly unlimited cycling ability as well as a fast response time. The LEM-GES can be constructed anywhere, as it does not have any strict site restrictions, allowing for optimal placement. The system also has a long lifetime, which is almost entirely based on the maintenance. Owing to the system's highly modular nature, it can be adjusted throughout its lifetime, whether it be by adding extra shafts or replacing the LEM on the piston with a new design that is more efficient or allows for the use of more mass per piston. Similarly, the control of the system is highly customisable, as each piston could be controlled independently from the others. With the advance in machine design and control system strategies, it is possible to introduce variable speed operation of the LEM-based pistons. This not only enables the option to change the system discharge time within a certain range as needed, but opens up the possibility of faster charging than discharging times, thus increasing the cycling ability further.

Despite the numerous advantages of the system, it also has several disadvantages. The LEM-GES, as with other gravity-based storage systems, has a low energy density. The system will be physically large, regardless of the energy storage capacity. The LEM-GES requires a large capital investment due to the large amount of mass needed. As a result of this large upfront cost, for the system to be economically viable, it has to have a long lifetime and very high annual cycles [8], somewhat limiting the possible applications of the LEM-GES.

A comparison of the LEM-GES and other, selected energy storage systems is given in Table III [23], [24].

IV. Wind Farm Applications

Power output from a wind farm has a high variability, which can be hard to predict, thus negatively impacting the reliability and power quality of any system to which it is connected. These variations come at different time-scales, requiring multiple strategies to properly mitigate them [5]. The authors of [5] provide a frequency analysis of the power imbalance of a energy system with high renewable penetration to determine the required energy storage capacity. They decompose the power imbalance into four categories, namely slow cycling (12 hours or more), intra-day (3–12 hours), intra-hour (5 minutes to 3 hours) and real-time (2–5 minutes), that would require mitigating.

Similarly, [25] decomposes the output of a wind farm, using spectral analysis, into four categories. These are: outer-day (24 hours or more), intra-day (6–24 hours), short term (1–6 hours) and very short term (30 minutes to 1 hour).

These four categories can be used to determine the most effective allocation of an energy storage system, based on which category is being mitigated. The slow cycling and intra-day components can effectively be mitigated by sources such as PHES or conventional power generation plants. Energy storage systems can be employed to help alleviate the intra-hour and real-time components of the fluctuations [5], [25]. These shorter term fluctuations generally relate to several ancillary services, such as frequency support [9], [10], output smoothing [4], [5] and ensuring forecasted output power within a certain percentage error [3].

An optimal sizing, placement and control strategy for the LEM-GES system falls outside the scope of this paper. However, an acceptable size estimate can be found based on literature regarding this topic.

The authors of [4] investigate the control strategies for a battery energy storage system (BESS) and found that the BESS would have to be between 20–30 % of the rated wind farm power output capacity to provide appropriate output smoothing, assuming the use of a conventional lead-acid battery with an efficiency of 75 % and keeping the state of charge between 30 % and 70 %. The system has a discharge time of 5–20 minutes. The authors do mention that a higher efficiency and better depth of discharge can reduce the required energy storage capacity.

Similarly, [3] found the size of a battery energy storage system would need to be least 30 % of the rated wind farm watt capacity to ensure that the hour-ahead wind farm output is met within a 4 % error, 90 % of the time. The system uses a flow-battery based storage system, which can have efficiencies up to 85 % [24], with a discharge time of 70 minutes.

Considering flywheels, the authors of [9] suggests a storage system, similar to an earlier superconducting magnetic energy storage (SMES) system [26], for frequency support of offshore wind farms, rated at 25 % of the wind farm power output capacity. Both of these systems are meant to dampen the very short term fluctuations of the output power. These are both large for the intended purposes, with the authors of [10] finding a power rating of 5 % to be adequate. The proper sizing for this application comes down to a trade-off between the ability to suppress the very short term fluctuations and the cost of the system.

TABLE III: Comparison between the LEM-GES and selected energy storage technologies [23], [24].

Storage Technology	Energy Density (kWh/m^3)	Daily Self-discharge (%)	Lifetime (years)	Cycles	Round-trip efficiency (%)	Depth-of-discharge (%)
LEM-GES	0.252	0	50 +	Almost Infinite	81	100
PHES	0.13–0.5	Almost 0	40–60	10 000–30 000	65–85	95
Flywheel	0.25–424	55–100	20	20 000 +	85–95	100
Lead-acid	25–90	0.1–0.2	5–15	200–2000	75–90	80
Li-ion	94–500	0.03	5–15	3000–10 000	85–90	80
Flow Batteries						
VRB	10-33	Almost 0	5–10	12 000 +	85–90	100
ZnBr	5.2–70	Almost 0	5–10	2000–3500	70–80	100
PSB	10.8-60	Almost 0	10–15	800–2000	75	100

LEM-GES - Linear electric machine-based gravity energy storage; PHES - Pumped hydroelectricy storage; VRB - Vanadium redox battery; ZnBr - zinc bromine; PSB - polysulfide bromide;

V. LEM-GES SIZING AND DESIGN

The characteristics of the LEM-GES, e.g. fast response time, high cycling ability, high efficiency and a complete depth of discharge [8], make it suitable for use in applications similar to those just discussed. Two potential applications are considered in this section, with the LEM-GES being used to provide frequency support, output smoothing and forecast matching. The scalability of the LEM-GES is demonstrated by modifying the second of these systems to suit a longer discharge application.

According to the South African Wind Energy Association, the average wind power plant size in South Africa is 93.5 MW [2]. For frequency support, the size of the LEM-GES system is assumed to be 20 % of the rated power output of the wind farm, with a discharge time of 10 minutes, thus requiring a storage system of 18.7 MW and 3.12 MWh. Based on the capacity per shaft given in Table II, the LEM-GES would need 23 shafts to satisfy the storage requirement. A total of 230 pistons would be needed, each with a power rating of 82 kW. This can mean either one 82 kW inverter per piston, or four smaller converters for each side of the piston. The 10 minute discharge of the system constitutes the fastest discharge time, unless overrated power electronics are used. With 23 shafts, the LEM-GES system would require 6 maintenance access points, and would have a system width of roughly 15 m and a system heigh of 140 m.

To put in perspective the size of the LEM-GES, it is useful to compare it with a well-known entity. for this purpose, the system is compared to the size of a standard soccer field, which is on average 100 m by 60 m, with a surface footprint of 6000 m^2. This surface area is taken as one per unit (p.u.) for the comparison with the LEM-GES system designs. The frequency support system has a total surface area of 225 m^2, or 0.0375 p.u.

To provide output smoothing or forecast matching, it is assumed the energy storage requirement would be at least 30 % of the wind farm with a discharge time of at least an hour. Following the same method as for the frequency support scenario, the system would require 205 shafts, with a total of 2050 pistons. Each piston would have a power rating of 13.6 kW. The fastest possible discharge time is 60 minutes, unless overrated power electronic systems are used, as is the case for the previous example. The slowest discharge time, if each piston is controlled separately, is 2050 hours, or 34.17 days at a discharge power of 13.6 kW. If each shaft is controlled separately, the slowest discharge time is 3.42 days with a rated power of 136 kW. With 205 shafts, the system requires 52 maintenance access points, with the system having a per unit footprint of 0.26.

TABLE IV: Specifications of the LEM-GES systems for a 93.5 MW wind farm.

Specification	Frequency Support	Output Smoothing	Three Hour System
Power rating	18.77 MW	28 MW	28 MW
Discharge time	10 minutes	60 Minutes	3 hours
Stored energy	3.13 MWh	28 MWh	84 MWh
Number of shafts	23	205	615
Number of pistons	230	2050	6150
Total system mass	11 500 t	102 500 t	307 500 t
Inverter rating per piston	82 kW	13.6 kW	13.6 kW
h_s	140 m	140 m	140 m
w_s	15 m	$\approx$ 40 m	120 m x 40 m
Per unit storage footprint	0.0375 p.u.	0.26 p.u.	0.78 p.u.
Per unit wind farm footprint	5194 p.u.	5194 p.u.	5194 p.u.

The system specifications and dimensions for both applications are given in Table IV. The wind farm per unit footprint is calculated based on an average wind farm density of 3 MW/km^2 [27].

To illustrate the scalability of the LEM-GES system, the system for output smoothing is scaled up to provide the capacity factor output of the wind farm for 3 hours. This means that the LEM-GES would be able to cover either the morning or evening peak electricity usage. To simplify the comparison, the wind farm capacity factor is assumed to be 0.3. This LEM-

GES system would then need to be rated at 28 MW and 84 MWh.

While increasing the discharge time of the output smoothing system to three hours is a option, the extremely slow velocity of the LEMs would likely present large technical difficulties. A more reasonable option is to deploy three of the output smoothing systems and have them discharge consecutively. This system is shown in the last column of Table IV. Most notable of this system is that even at this large capacity, it has a relatively small footprint.

VI. Conclusion

In this paper the LEM-GES system is described and expanded, explaining the underlying storage principle, how the system addresses two constraining factors found in gravity-based storage systems and how the system can be used to further the integration of wind farms.

Three systems are discussed. One, a 18.77 MW, 3.13 MWh system designed to provide frequency support and the second a 28 MW, 28 MWh system intended to provide output smoothing. The third system consists of three units of the second system, discharged consecutively, and serves as an illustration of how the LEM-GES system can be expanded.

All three systems have a comparatively small footprint for a gravitational potential energy storage system. This is the result of using LEMs, which enables the use of multiple, smaller pistons, and allows for more mass to be hoisted per shaft than would be easily achievable through traditional methods. This ability enables systems with small height differences to be used, which allows the LEM-GES to be built above ground, and not be limited to areas, such as mineshafts, where a longer system height is feasible.

The developed LEM-GES systems are not optimised nor has an optimal control strategy been developed for them. Both of these factors have a large effect on the overall size of the storage system. As has been noted, the depth of discharge and high efficiency of the LEM-GES could potentially decrease the required system capacity, resulting in a smaller system than some of the battery systems mentioned.

The ability to be built above-ground, combined with the other characteristics of the LEM-GES, such as the high cyclability and small footprint, means the LEM-GES can be used to help with the integration of wind energy.

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