Chapter

Mechanical Energy Storage Systems and Their Applications in Power Systems

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Abstract

The negative environmental impacts of conventional power generation have resulted in increased interest in the use of renewable energy sources to produce electricity. However, the main problem associated with these non-conventional sources of energy generation (wind and solar photovoltaic) is that they are highly intermittent and thereby result in very high fluctuations in power generated. Hence, mechanical energy storage systems can be deployed as a solution to this problem by ensuring that electrical energy is stored during times of high generation and supplied in time of high demand. This work presents a thorough study of mechanical energy storage systems. It examines the classification, development of output power equations, performance metrics, advantages and drawbacks of each of the mechanical energy storage types and their various applications in the grid networks. The key findings in this work are the strategies for the management of the high costs of these mechanical storage devices. These include deployment of hybrid energy storage technologies, multi-functional applications of mechanical energy storage systems through appropriate control methodologies and proper sizing strategies for cost effectiveness and increased penetrations of renewable energy sources in the power grid.

Keywords: mechanical energy storage, renewable energy, intermittent, performance measures, power systems

1. Introduction

Until now, the entire energy sector depends on fossil fuels for the generation of electricity, but more environmentally friendly options are advancing in the form of renewable energy sources. The transition from conventional (traditional) power plants to more environmentally friendly options will necessitate a need for more flexibility in the generation, transmission, and consumption of electricity. Energy storage systems (ESSs) can provide the flexibility that is needed for a robust high quality stable electrical system when technically integrated into the grid network. The following are some of the features of energy storage:

- Being able to store energy at the time of excess electricity production and making it available for use within a very short time window when the need arises.

- With the help of energy storage technologies, energy can be stored and made available at the very point where it is needed whether at the transmission, distribution, or consumption levels. This flexibility ensures the postponement of infrastructural upgrades in generation, transmission, and distribution networks.

- The consumption of energy varies with time. Sometimes the demand is high while at other times the demand is low. Energy storage devices can be deployed to meet the varying energy demands per time.

- Energy storage technologies such as pumped-hydroelectric storage (PHS), battery energy storage system (BESS), supercapacitors, etc. are flexible in providing multiple services to the grid. They can serve as loads during their charging process and therefore offer a service to the grid like voltage rise mitigation, while in their discharging mode, they can be controlled to provide peak-shaving service, frequency support or inertia support.

- Finally, energy storage technologies have the flexibility of participating in some special services to the grid for example the black start service. The system offering the black start service must possess the capacity to move from shutdown into operation without the aid from the grid. This type of service is required during periods of persistent blackouts. Energy storage technologies with high energy capacity like PHS, compressed air energy storage (CAES), and gravity energy storage (GES) can provide excellently the black start service to the.grid.

There are six different categories of ESS, and these are: mechanical, thermal, chemical, electrochemical, electrical and hybrid system. Each category has unique characteristics in terms of life cycle, discharge time, discharge loss, energy density and power rating. All these characteristics account for their suitability for specific applications in the power system.

In mechanical energy storage system (MESS), there is a conversion of energy from mechanical to electrical form [1]. In times of low energy demands, electrical energy is taken from the grid and stored until the time of high demand when it is then converted back to electrical energy and transmitted back to the grid [2]. The flexibility in the conversion processes of MESSs accounts for their global applications [3]. MESSs are classified as pumped hydro storage (PHS), flywheel energy storage (FES), compressed air energy storage (CAES) and gravity energy storage systems (GES) according to [1, 4]. Some of the works already done on the applications of energy storage technologies on the grid power networks are summarized on **Table 1**.

Considering the works summarized in **Table 1**, the authors have done extensive research on energy storage integration to the grid network taking into accounts several aspects such as energy storage technology types, applications (both single and combined), limitations and challenges of energy storage systems, power electronic converters for energy storage interface. Simulation tools (software) for energy storage systems and storage system placement and sizing. However, to the best of our knowledge, nothing has been done on how to manage the high cost of energy storage system which according to [22] is the main reason hindering the massive deployment of energy storage system in the grid.

References	Contributions	Years of publication
[1, 3, 5–7]	The works present an in-depth review of energy storage technology types and their applications in the grid power networks.	2019, 2014, 2011, 2009, 2013
[8, 9]	The papers present the economic and reliability impacts of energy storage systems in power system networks.	2018, 2021
[10, 11]	The works discuss the application of energy storage systems in different levels of grid voltage. Besides, the conditions for integration of energy storage into the grid for proper compatibility with the operational codes and standards were emphasized.	2016, 2017
[12–14]	The authors explore the possible approaches of combining applications of energy storage systems. The technical requirements for the combination of applications were also discussed.	2004, 2003, 2019
[15, 16]	The works evaluate the challenges militating against the massive deployment of large-scale energy storage technologies for grid applications considering the various economic, legislative, and technical aspects.	2016, 2020
[17]	The work provides an in-depth review of the methodologies of storage sizing and placement on the grid networks. It covers several areas such as analytical approach, mathematical programming, exhaustive search, and heuristic methods.	2016
[18–20]	The papers perform a detailed analysis of power electronics converters used in interfacing energy storage systems with the grid network.	2016, 2017, 2020
[21]	The work discusses some of the software used in the simulation and analysis of energy storage systems and specific energy storage applications they are designed to implement.	2017
[22]	The work evaluates the impact of energy storage systems on the economic operation of distribution systems	2020

Table 1.
Summary of the works done on the applications of energy storage in the grid networks.

Therefore, the principal contribution of this work is bringing to light certain key approaches that should be addressed to manage the high costs of energy storage systems, thereby promoting their massive deployment into the grid networks.

The block diagram showing a simple classification of mechanical energy storage systems according to [23, 24] is given in **Figure 1**.

2. Pumped hydro-electric storage (PHS)

The PHS is a utility-scale energy storage technology that has been in implementation since 1890s [25]. It has a high commercial acceptance, and it is well-established. In PHS, large amount of water is delivered to an upper reservoir, during period of excess generation of electricity and it is converted back to electricity through the use generator and turbine during period of shortage of electricity. An illustration of pumped hydro-electric storage is shown in **Figure 2** while **Table 2** shows the performance measures.

It was reported in [26] that one of the earliest technologies for the storage of energy is PHS. The operating cost for energy units for PHS as compared to other energy storage systems has been reported to be the cheapest according to [18].

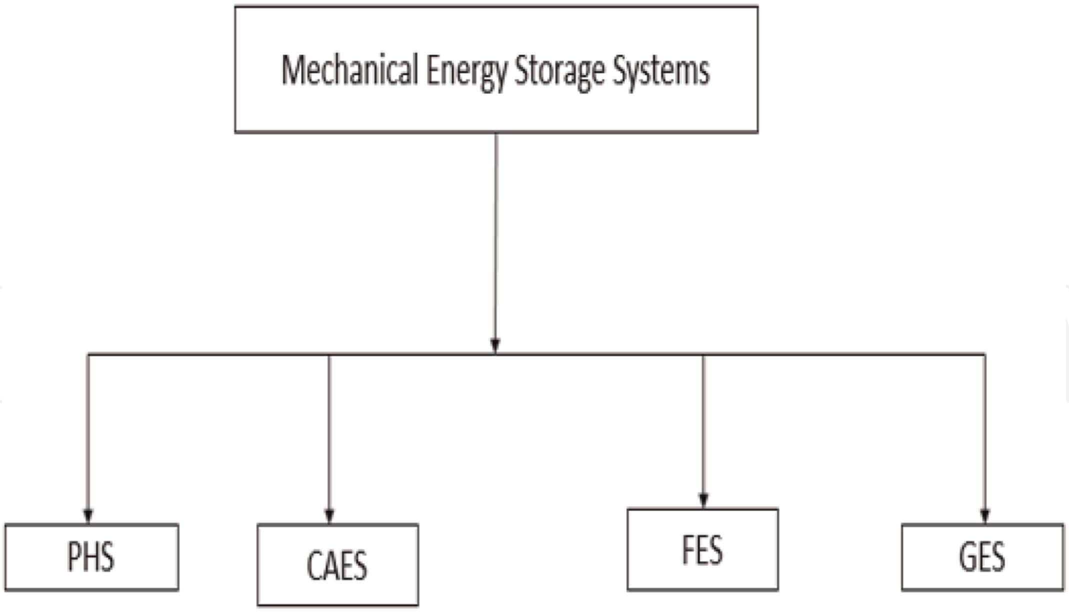

Figure 1.
Block diagram of mechanical energy storage systems.

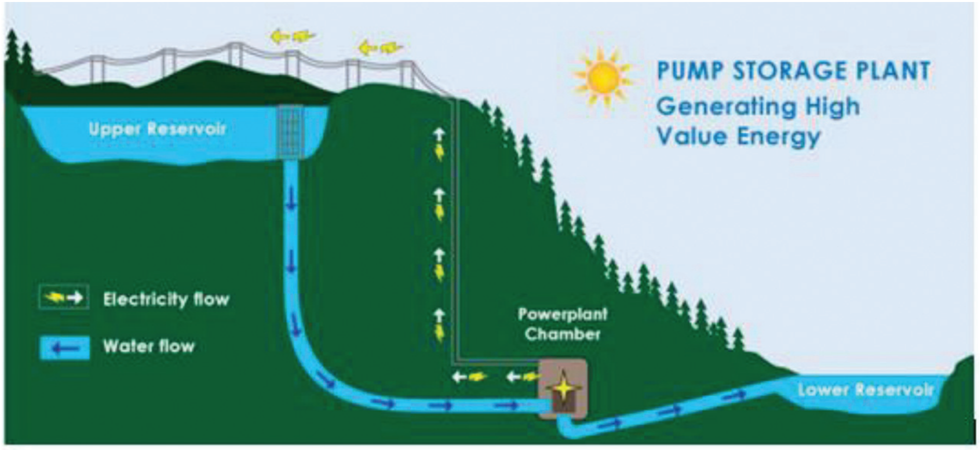

Figure 2.
An illustration of pumped hydroelectric storage [8].

In 2017, there were about 270 PHS stations globally producing 127 GW of electricity [27]. The United States and the European Union (EU) have 40 and 160 PHS stations respectively while the rest of the world has 70 PHS units [27].

2.1 Output energy equation of a PHS

Pumped-hydro-electric storage is generally used for energy-based applications because of its ability to deliver power for very long period in several hours [28]. It functions by utilizing the potential energy of water due to the force of gravity. When using the power from the grid during a period of low demand, water is pumped from lower reservoir to the upper reservoir. In the time of high demand of power, the water stored in the upper reservoir is released into the lower reservoir for the operation of the turbine and generator in order to inject power into the grid [24].

Efficiency (%)	70–85
Number of cycles (in cycles)	10,000–35,000
Expected life(years)	30–60
Specific energy (Wh/kg)	0.5–1.5
Specific power (W/kg)	N/A
Power capacity cost ($/kW)	600–2000
Energy capacity cost ($/kWh)	0–23
*BOP ($/kWh)	270–580
Power conversion system (PCS) ($/kW)	0–4.8
**O&M ($/kW-yr)	3–4.4
Maturity of the technology	Mature/ Implemented.

Adapted from [13]
**BOP: Balance of payment. **O&M: Operation and maintenance.*

Table 2.
Performance measures of PHS.

The energy stored, according to [29], depends on the volume of the water and the height of the waterfalls. This is described in Eq. (1).

$$E(phs) = \ell g h V \tag{1}$$

where $E(phs)$ is the stored energy in joules, ℓ is the density of water equivalent to $1000\ kg/m^3$, g is the acceleration due to gravity equivalent to $9.8\ m/s^2$, h is the height of the waterfalls (in meters) and V the volume of water stored in the upper reservoir in m^3.

2.2 Advantages and drawbacks of PHS

PHS has a high-power capacity ranging from some MW to about 3GW with a cycle efficiency of approximately 70–85 cycles and over 40 years lifetime [4, 6]. However, the drawbacks of a PHS lie in getting available sites to accommodate two large reservoirs and dams, the long-time involve in the preparation of the site, a high capital cost (in hundreds to thousands of millions of dollars) for construction, and environmental issues (removing trees and vegetation from a large amount of land) prior to the reservoir being flooded [30, 31]. The United States has an existing 23GW of PHS capacity installed [32].

3. Compressed air energy storage (CAES)

In this storage system, power from the grid (during period of low demand) is used to pump air into underground geological formation until the air is at high pressure [33]. During discharge, air at high pressure is drawn from the storage cavern and undergoes a heating and expansion process inside high- and low-pressure turbines, for conversion into kinetic energy and thereafter, transformed into electrical energy in a generator [29, 34]. One innovative system in the application of CAES is by combining it with a wave energy system according to [6]. The well turbine being an integral component of the wave energy system [35] uses the excess power produced by the renewable energy sources during the period of peak production. Through these methods, most of the renewable energy generated during the period of peak production would be used if not immediately. The excess power generated during peak production is used in storing fresh air in salt caverns [36]. The CAES turbine, using this fresh air can generate 3 times the output power for the same natural gas input [37]. With this innovation, a higher efficiency of the system is achieved.

An illustrative topology of a CAES is shown in **Figure 3** while the performance metrics are given in **Table 3**.

The current technological advancement on the improvement of the efficiency of CAES is focused on developing an advanced adiabatic CAES (AA-CAES) through which air is adiabatically compressed and pumped into an underground cavern. The success of this depends on the compressor and the expanded trains of the CAES [33].

In natural gas power plants with attached CAES, the air at a high pressure is mixed with natural gas for combustion [38]. The integration of CAES systems to an existing grid is relatively easy due to its similarity to a conventional gas combustion system [39].

CAES can be effectively utilized through the implementation of a hybrid energy storage system. A hybrid energy storage system involves the integration of different energy storage technologies for the implementation of several functions in the grid network [40]. To achieve this, the technical characteristics of the different storage technologies such as the power and energy capacities, response time and discharge time should be known. Besides, the application technical features should be analyzed for proper hybridization of different technologies. Examples of such hybridization include, CAES with flywheel examined in [40], CAES and supercapacitor energy storage and pumped hydro energy storage with CAES in [7]. CAES creates a potent energy reserve [41] and has three main components namely compressors, air storage reservoir and expanders [42].

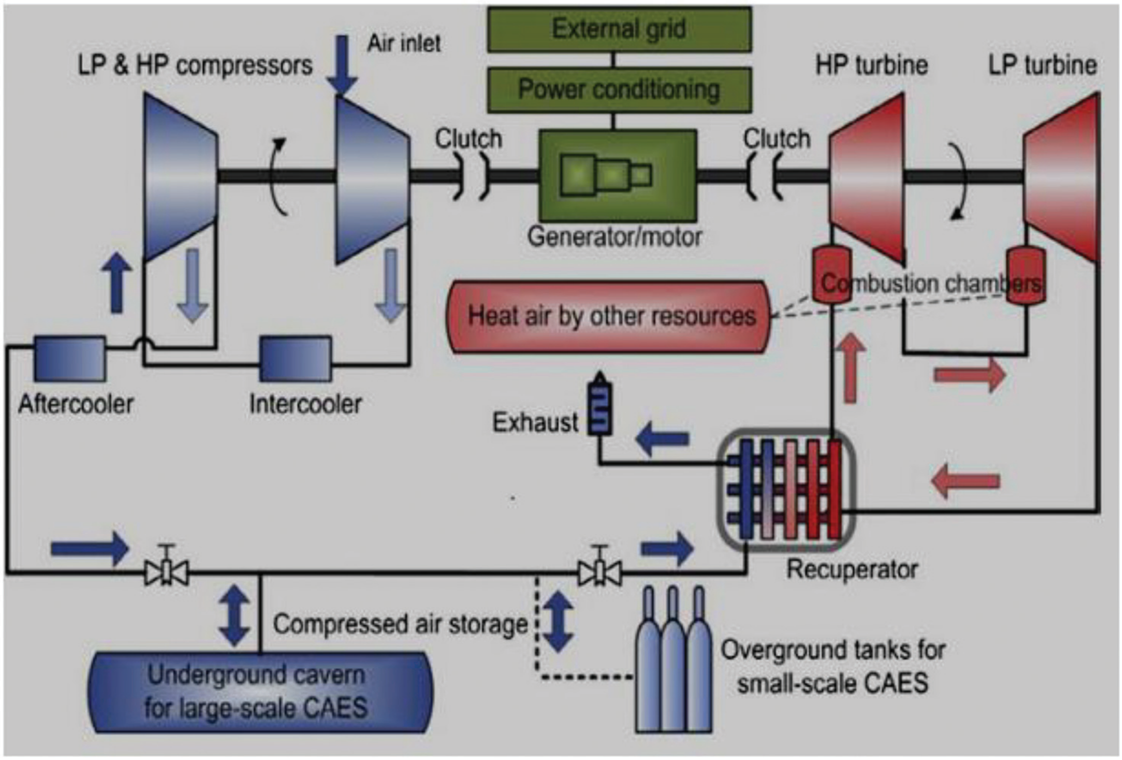

Figure 3.
An illustrative topology of a CAES [8].

Efficiency (%)	57–85
Cycle lifetime (cycles)	N/A
Expected lifetime (years)	20–40
Specific energy (Wh/kg)	6–30
Specific power (W/kg)	N/A
Power capacity cost ($/kW)	400–800
Energy capacity cost ($/kWh)	2–140
BOP ($/kWh)	270–580
*PCS ($/kW)	46–190
O&M ($/kW-yr)	1.6–29
Maturity	Commercial

Adapted from [13]
**PCS: Power conversion system.*

Table 3.
Performance measures of CAES.

3.1 Advantages and drawbacks of CAES

CAES has a large energy capacity, little geographical dependency, long lifespan, and low cost per kW [43]. The CAES system has a lifetime of about 40 years with an energy efficiency of 71% [29]. CAES owing to its installed capacity which is from 35 to 300 MW is deployed in the grid to support load leveling, voltage, and frequency control, etc., [44].

However, CAES suffers the same limitations as PHS, that is difficulty in locating a specific geographic place for installations. To overcome this limitation, high-pressure carbon fiber tank air storage is proposed for the implementation of distributed CAES system [12, 45, 46].

Also, CAES installations have relatively low efficiency [33]. The recent developments of hybrid CAES plants with offshore and onshore wind plants shows increased overall efficiency with reduced fluctuations in the power output.

3.2 Output energy equation of a CAES

CAES is an energy-based storage system that utilizes the principle of the gas turbine to produce electricity. Excess electricity (during periods of peak production) is used to compress and store air at very high pressure. When electricity is needed, the stored air at high pressure is deployed to drive a turbine to generate electricity [47, 48].

The power taken by each compressor (P_C) is given in Eq. (2) according to [49].

$$P_C = \left(\frac{K}{K-1}\right)\left(\frac{QRT_{in}}{\eta_c}\right)\left[\left(\beta^{(K-1)/K} - 1\right)\right] \tag{2}$$

where K is the adiabatic exponent, Q, the mass flow rate of air, R is the gas constant, T_{in} is the temperature inlet of the compressor, η_c is the efficiency of the compressor and β is the compressor ratio. The air temperature of the outlet (T_{out}) of each compressor stage could be expressed as in Eq. (3) according to [49].

$$\mathrm{T_{out}} = \mathrm{T_{in}}\left[\frac{\beta^{(t-1)/k} - 1}{\eta_c} + 1\right] \tag{3}$$

Considering a compressor with many stages, n and charging time (t_c), the total energy taken by the compressor (W_c) can be evaluated using Eq. (4).

$$\mathrm{W_c} = \sum_{i=1}^{n} P_c t_c \eta_c \tag{4}$$

where η_c is the efficiency of the air compressor. Applying the adiabatic efficiency to compute the actual shaft power of the turbine, the power of each turbine (P_e) is given in Eq. (5) according Ref. [49].

$$\mathrm{P_e} = \frac{K}{K-1}(\mathrm{QRT}\eta_e)\left[1 - \left(EXR^{(K-1)/K}\right)\right. \tag{5}$$

where, Q is the mass flow rate of the turbine, η_e is the turbine efficiency, EXR is the expansion ratio of the turbine and T is the temperature of the turbine.

For a multi-stage turbine of m-number of stages, having a discharging time of t_e, the total electrical power output (W_e) is calculated using Eq. (6).

$$\mathrm{W_e} = {}_{\mathrm{g}}\sum_{t=1}^{m} P_e t_e \tag{6}$$

where, η_g is the efficiency of the generator.

3.3 Improving the efficiency of a CAES system

Energy storage efficiency is the principal factor militating against the development of CAES [49]. The energy efficiency of CAES depends on the energy efficiencies of all the units making up the CAES. These include the compression unit, air storage unit, heat regeneration unit and turbine generation unit. Thus, improving the performance of each of these units enhances the efficiency of CAES.

3.3.1 Compression subsystem

In order to have a compression subsystem with a high efficiency the exhaust temperature of the compression should be increased. This will result in an improvement in the heat storage temperature of the system and its storage efficiency.

3.3.2 Air storage subsystem

Underground salt cavern can be used to store large amount of air, and this will reduce the pressure fluctuations and consequently improves efficiency [49].

3.3.3 Regeneration subsystem

The efficiency of CAES is directly proportional to the temperature of the heat regeneration subsystem. As the temperature of the regeneration unit increases, the system efficiency also increases. In places where there is abundant supply of wind and solar energy, they can be adequately harnessed to provide heat for the regeneration subsystem, thereby increasing its temperature.

3.3.4 Turbine generator subsystem

The turbine generator unit is one of the major component parts of a CAES. It participates in the thermoelectric conversion in the energy-discharging process. The development of new and efficient air turbine will help in increasing the efficiency of CAES in general.

4. Flywheel energy storage (FES)

A flywheel energy storage (FES) is a rotating disk that can store or dissipate mechanical kinetic energy utilizing rotatory inertia [16]. An illustrative topology of an FES is shown in **Figure 4** and its performance metrics is given in **Table 4**.

In FES energy is stored in the angular momentum in a rotating mass [46]. Unlike PHS and CAES, FES is a power-based energy storage system [50]. It is deployed in applications that require short duration with short discharge time in the range of 1–100 s [37]. FES is used for voltage support [28], frequency support [37], fluctuation suppression, and provision of short-duration power quality. Globally, several FES systems are in use with an installed capacity of more than 940 MW [36].

4.1 Energy output and shaft factor equations of a flywheel

The rotating mass(disk) is mechanically connected to the shafts of the machines [29]. The energy stored by flywheels is given in Eq. (7) according to [48].

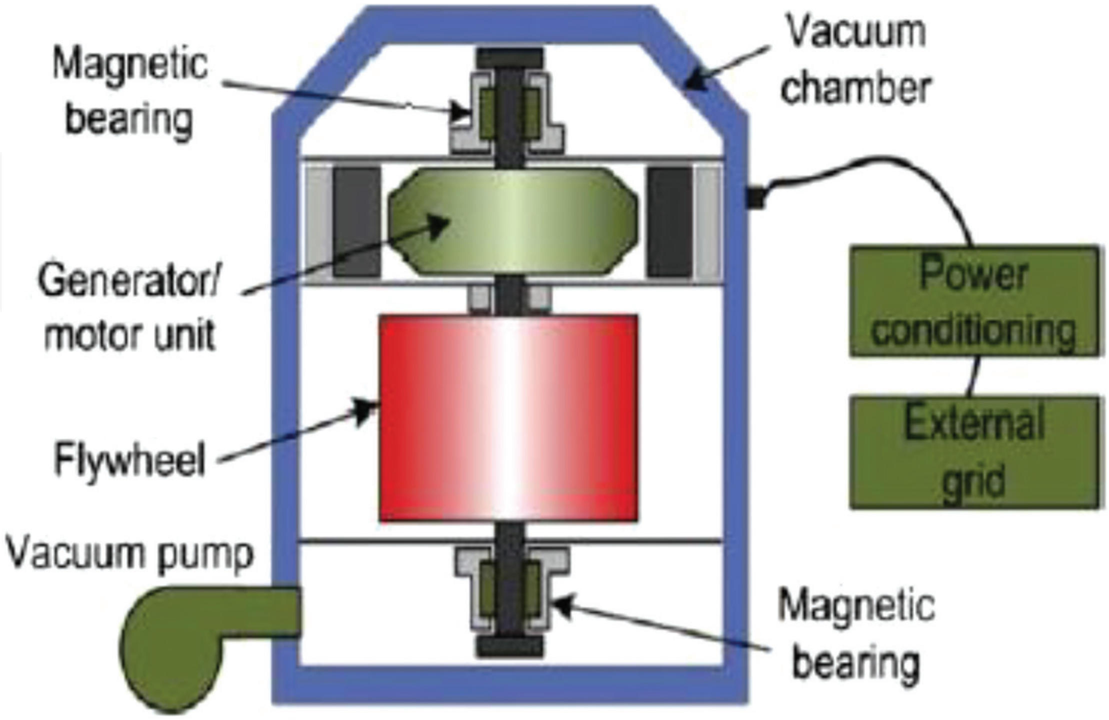

Figure 4.
An illustrative topology of a FES [8].

	Flywheel (low speed)	Flywheel (high speed)
Efficiency (%)	70–95	70–95
Cycle lifetime (cycles)	20,000–100,000	20,000–100,000
Expected lifetime (years)	15–20	15–20
Specific energy (Wh/kg)	10–30	10–30
Specific power (W/kg)	400–1500	400–1500
Power capacity cost ($/kW)	250–360	250–400
Energy capacity cost ($/kWh)	230–60,000	580–150,000
BOP ($/kWh)	110–600	110–600
PCS ($/kW)	0–120	0–1200
O&M ($/kW-yr)	6–22	6–22
Maturity	Developed	Developed

Adapted from [13].

Table 4.
Peformance measure of Flywheel energy storage.

$$E_{fes} = \frac{1}{2} J W^2 \tag{7}$$

where E_{fes}, (joules) is the energy stored by flywheel, J (in kgm^2) is the inertia of the rotating parts, W is the rotational speed in rad/s. The moment of inertia J is defined according to Eq. (8)

$$J = \int X^2 dM_x \tag{8}$$

where X is the distance from the axis of rotation, differential mass = dM_x. Considering a flywheel with radius r, having a mass M concentrated in the rim, the solution of the integral equation becomes Eq. (9).

$$J = \int X^2 dM_x = Mr^2 \tag{9}$$

The energy stored by the flywheel becomes $E_{fes} = \frac{1}{2}JW^2$, where W is the angular velocity. Thus Eq. (9) is transformed into Eq. (10).

$$E_{fes} = \frac{1}{2}\, Mr^2 W^2 \tag{10}$$

The energy density (E_{mass}) is given in Eq. (11).

$$E_{mass} = \frac{1}{2} r^2 W^2 \tag{11}$$

To obtain the volume energy density, (E_{volume}), we divide Eq. (10) by the volume V, therefore we have the volume density given as in Eq. (12)

$$\mathrm{E}_{\mathrm{volume}} = \frac{E_{fes}}{V} = \frac{1}{2}\frac{M}{V}r^2W^2 \tag{12}$$

$$\text{But density } (\rho) = \frac{mass}{volume} \tag{13}$$

The density is given by Eq. (13)

Therefore, the volume energy density is now expressed as shown in Eq. (14).

$$\mathrm{E}_{\mathrm{volume}} = \frac{1}{2}\rho r^2 w^2 \tag{14}$$

For the flywheel's rim, the tensile stress is given by σ, which is defined in Eq. (15) according to Ref. [36].

$$\sigma = \rho W^2 r^2 \tag{15}$$

Thus, from Eq. (15),

$$\mathrm{E}_{\mathrm{volumemax}} = \frac{1}{2}\sigma_{max} \tag{16}$$

where σ_{max} is the maximum tensile strength of the material (rim). For maximum kinetic energy per volume of the flywheel will depends on high tensile strength. Therefore, the choice of the maximum value of $\mathrm{E}_{\mathrm{volume}}$ or $\mathrm{E}_{\mathrm{mass}}$ will depend on the area of application. The maximum energy density ($\mathrm{E}_{\mathrm{mass(max)}}$) with respect to mass is given by Eq. (17).

$$\mathrm{E}_{\mathrm{mass(max\,)}} = \frac{1}{2}\frac{\sigma_{max}}{\rho} \tag{17}$$

The general expression for the maximum energy density ($\mathrm{E}_{\mathrm{mass(maxg)}}$) of a flywheel with respect to mass is given in Eq. (18).

$$\mathrm{E}_{\mathrm{mass(maxg)}} = \frac{K\sigma_{max}}{\rho} \tag{18}$$

where K is the shape factor. The values of K for several flywheel shapes are provided in **Table 5**.

4.2 Components of a flywheel energy storage

FES is made up of several parts namely motor-generator system, a motor control system, bearings, a flywheel, and a flywheel housing [35]. The type of bearings used in

Flywheel shape	Shape factor (K)
Constant stress disc	0.931
Flat unpierced	0.606
Thin rim	0.500
Rod or circular brush	0.333
Flat pierced disc	0.305

Table 5.
Flywheel shape factors [51, 52].

a flywheel is very important because of mechanical friction which is responsible for loss of energy in flywheel energy storage. Mechanical bearings are not ideal for FES because of the constant need for lubrication and maintenance. In modern FES, mechanical bearings are replaced with magnetic bearings. These can levitate the shaft thereby reducing the impacts of friction and the need to lubricate [35]. The motor-generator unit of a FES has a dual function. It can operate as a motor during the time of excess production of electricity in order to gain kinetic energy. When there is a need for electricity, it acts as a generator and converts the kinetic energy stored in the flywheel to electrical energy [51, 53]. FES housing provides a vacuum for the placement of FES. The housing guarantees that there is no loss of energy through air friction.

4.3 Advantages and drawbacks of FES

The merits of FES over other mechanical energy storage technologies include low costs of maintenance, very high efficiency, high power density, and long lifetime [38]. Its disadvantages are low energy densities and very high losses due to friction [54].

4.4 New advances in FES technology

There are several advances in FES technology geared towards reducing energy losses, improving efficiency, and widening the scope of applications.

Among these innovations is the use of high-temperature superconducting (HTS) bearings. This has the capacity of improving the overall round-trip efficiency of FES technology to over 90% according to [39].

In the area of applications, FES could be deployed in hybrid systems comprising of fuel cells, flow cells, ultra-capacitors, lithium-ion batteries, and small co-generation systems with low temperatures according to [43]. Besides, other new areas of applications of FES systems are in Kinetic Energy Recovery System [45], and in electric vehicle propulsion system [46], KERS/ERS.

5. Gravity energy storage (GES)

In GES electric pumps are used to pump water under a movable rock piston and through that, the rock mass is lifted. In the time of low production of electricity, the water which is already under high pressure from the rock mass is released to a turbine for the generation of electricity via a generator. Through this method, large quantities of water can be stored for several hours between 6 and 14 hours and can be made available to produce electricity when the needs arise. The size of the storage could be chosen between 1 to 10GWh and the rock piston diameter should be at least 100 meters.

6. Applications of mechanical energy storage systems in power system grid

With the increasing penetration of renewable energy sources in the grid network and the variability of these energy sources, it becomes necessary to bring a balance between power generation and demand. Therefore, energy storage systems integration into the grid becomes absolutely necessary [29]. The applications of mechanical energy storage systems in smart grid could be divided into energy-based and power-based applications.

6.1 Energy-based applications

Sufficient storage capacity is a requirement for energy-based applications to participate in very long discharges in a time window of one or more hours. PHS, CAES, and GES are used for energy-based applications discussed in the subsequent sub-sections.

6.1.1 Load following

Load following is a service in which the energy storage technology e.g., CAES, provides power for a long-time range (one or more hours) [16]. The intermittency of renewable energy sources accounts for the imbalance between generation and loads leading to variations in voltage and frequency. Mechanical energy storage systems such as PHS, CAES, and FES can provide the needed power to compensate for imbalance and stabilize the system frequency and voltage.

6.1.2 Peak-shaving

In this service, mechanical energy storage technologies, such as PHS, CAES, and GES are used to store energy during the time of excess production of power and to inject back energy into the grid during limited generation of power. In this service, power is delivered by the storage technology for several hours.

6.1.3 Transmission line curtailment

The capacity of a transmission line determines the optimal flow of power through it. When this exceeds the line capacity, the generation must be curtailed. In transmission line curtailment, CAES/PHS technology is used to inject power into power into the networks in a time window of 5–12 hours in line with the transmission line capacity. The applications of CAES for transmission curtailment are examined in [55–57].

6.1.4 Unit commitment

Owing to the uncertainties concerning variations in wind and of solar irradiation, managing the commitment of wind turbines and solar panels to meet the estimated demand always is difficult. Therefore, the use of energy-based storage system such as PHS in the networks may be useful to combat the effects of uncertainties in wind forecasting and to reduce the energy reserves if the system during its normal operation. In [58], the unit commitment problem was formulated in a power system with wind generation and CAES.

6.1.5 Spinning reserve

Mechanical energy storage systems such as PHS, CAES and GES can be used to compensate for unexpected contingencies for example the failure of a generating unit.

6.2 Power-based applications

In this application premium is placed on mechanical energy storage being able to charge or discharge within a very short interval of time (in milliseconds of time). FES is the best type of mechanical energy storage system for power-based applications because of its very short response time. Other energy storage systems that can be used for power-based applications include battery energy storage systems, [BESS], super-capacitors, and superconducting magnetic energy storage system (SMESS) [50]. The following subsections discusses some of the power-based applications where FES and other non-mechanical energy storage systems (such as BESS, super-capacitors and SMESS) could effectively be deployed.

6.2.1 Voltage control support

For the maintenance of proper voltage levels in the power system grid, the regulation of the flow of reactive power into power system network is very important. FES can effectively be used for both active and reactive power control thereby providing an excellent voltage control in the grid network.

6.2.2 Provision of inertia support

With the replacement of the fossil-fuel based power plants with the non-synchronized renewal energy power plants in the modern power grid, the total synchronized inertia of the system is getting diminished. This, if not checked, could result in frequency instability of the power system during contingency events. Mechanical energy storage systems especially FES (due to their short response time) can be used to emulate the provision of inertia of synchronous -based generators.

6.2.3 Fluctuation suppression

Certain loads in power systems (like electronic devices) are highly sensitive to non-sinusoidal voltage and current characteristics. FES may be used to inject power of high quality by quickly charging and discharging thereby smoothing out very short-term fluctuations.

6.2.4 Provision of a short duration power quality

Mechanical energy storage system especially FES can be deployed for the provision of short-duration power quality by supplying active power for very short duration in the range of 1–10 seconds.

7. Managing the high cost of mechanical energy storage systems

Energy storage systems especially PHS, CAES, and FES have been identified as a key device for realizing the goal of having high renewable penetration (wind and solar photovoltaic) in the modern grid. However, the extremely high cost of energy storage systems can constitute a barrier to achieving the above-mentioned goal. One way towards overcoming the challenge of high cost of energy storage systems is by the implementation of hybrid energy storage system. This involves the integration of different energy storage technologies for the implementation of several functions in the network. To achieve this, the technical characteristics of the different technologies such as the power and energy capacities, response time, and discharge time should be known. Besides, the application technical features should be analyzed for the proper hybridization of different technologies. **Table 6** shows the summary of application technical characteristics. Considering the various possible combine applications listed in section four of this work and referring to **Table 5** of applications technical characteristics, PHS and FES can be integrated together to provide for both power and energy-based applications. PHS can manage the energy-based applications such as peak shaving, and capacity firming while the FES can provide frequency excursion suppression, grid angular stability and grid voltage stability. Also, a black start application, frequency stability, regulation control and fluctuation suppression can be implemented by combining PHS and FES.

A second approach towards managing the extreme high cost of energy storage systems is by implementing the multi-functional utilization of the storage systems. In this approach, a single energy storage system is controlled in such a way to execute several functions. This will improve the cost effectiveness of energy storage system and will reduce the significant slack period of the storage system. However, the implementation of energy storage for multi-functional utilization will require the development of appropriate control methodologies. Without these, it will be impossible to utilize energy storage for multi-purpose applications.

Besides, the choice of suitable storage technology is very crucial for the multi-functional operation of an energy storage system. Some storage technologies are

Applications	Required time response	Reference duty cycle	ESS power (MW)	ESS AC voltage (kV)	Full power discharge duration
3-hour load shift	10 minutes	scheduled 3 hours of discharge	1–200	4.2–115	3 hours
10-hour load shift	10 minutes	Scheduled 10-hour discharge	1–200	4.2–115	10 hours
Renewable time shift	1 minute	Optimized by technology	2–200	4.2–34.5	5–12 hours
Fluctuation suppression	20 milliseconds	Continuous cycling	2–50	4.2–34.5	10 seconds
Short duration power quality	20 milliseconds	Hot standby	1–50	4.2–34.5	5 seconds
Long duration power quality	20 milliseconds	Hot standby	1–50	4.2–34.5	4 hours
Frequency excursion suppression	20 milliseconds	Hot standby	10–500	4.2–750	15 minutes
Grid frequency support	20 milliseconds	Hot standby	2–200	4.2–34.5	10–30 minutes
Angular stability	20 milliseconds	Hot standby	10–500	4.2–750	1 second
Voltage stability	20 milliseconds	Hot standby	10–500	4.2–750	1 seconds
Transmission curtailment	1 minute	Optimized by technology	2–200	4.5–34.5	5–12 hours

Table 6.
Application technical characteristics [23].

energy based, capable of delivering power over a prolonged period (e.g., PHS, CAES, etc) while others are power based (i.e., FES, SMESS), only being able of delivering high impulse power for few seconds. Therefore, it is necessary to evaluate the technical features of the various storage technologies to make appropriate choice of the required storage system.

Finally, good sizing methodology must be developed, bearing in mind that when energy storage systems are undersized, the reliability of the system becomes impaired while over sizing of the energy storage systems may results in less cost effectiveness.

8. Conclusion

In this work, a study on mechanical energy storage technologies and their various applications in the grid networks are presented. Their operating principles, topologies, various subsystems, performance measures, advantages and drawbacks were discussed.

In addition, the work also presents the development of output power equations for each mechanical energy storage type based on the fundamental principles of potential energy due to gravity, air compression atvery high pressure, and kinetic energy of rotating masses.

Moreover, the capacity of energy storage systems in providing flexibility that is essential for robust, high quality stable electrical systems, in a grid network with a high penetrations of renewable energy sources were examined in detail.

Further highlights in the work include key approaches to improving the efficiency of mechanical energy storage systems especially compressed air energy storage system and flywheel energy storage system. Such strategies take in cognisance the need of improving the performance of every subsystem and the deployment of new advances in technology such as the use of high temperature superconducting bearings for FES.

Lastly, the management of the high cost of energy storage systems through the implementation of hybrid energy storage systems, multi-functional applications of energy storage technologies and appropriate sizing methodologies were discussed. The diligent pursuit of these strategies will surely reduce the costs factor in energy storage systems and consequently result in more of their deployment into the grid networks.

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