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Application of Flywheel for Active Distribution system

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***Abstract*—As a Result for the continuously growing market of renewable resources and distributed generation (DG), the need for efficient energy storage systems is becoming more essential. Where, adding efficient storage units in conjunction with the existing DGs to construct a self-adequate microgrid will become the keystone in building the future active distribution networks. Integration of proper and efficient storage should improve the system performance by achieving self-adequacy for the distribution network, minimizing the average electricity cost, reducing fuel consumption and hence reducing green house gases (GHG) emissions and smoothing the intermittent renewable resources (i.e. solar and wind) output power. However, to achieve these benefits many constraints should be satisfied such as selecting suitable storage technology, proper sizing of storage units, efficient operating strategy and applying fast and reliable control algorithm. In this paper, a comparative study between different available storage techniques such as electrochemical, electric field, magnetic field and kinetic energy is carried out to justify a selection criterion in terms of specific power, specific energy, lifetime, maintenance/operation cost, capital cost, burst power and efficiency. Then based on the study, flywheel storage is selected as a promising storage technique for those systems need high power and short to long term power transfer capabilities with seconds to minutes complete discharge time that helps for the stabilization of the system frequency and at the same time supplying sudden load which improves load following capabilities of DGs.**

***Index Terms*—Active distribution, Energy storage, Flywheel, Renewable energy**

I. INTRODUCTION

This era can be considered as the era of renewable resources. This fact results from the increasing depletion rate of conventional energy resources such as fossil fuel and the great concern about the environment. Renewable resources used for electricity generation is emerging rapidly [1],[2] all over the world for residential, commercial and even industrial loads.

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However, as the penetration level of these renewable resources increases on the distribution network as the design, protection and operation of the distribution network becomes a complex issue [3]. In addition, the renewable resources with intermittent output power such as wind and solar energy resources are more common. This intermittent power causes unwanted oscillations and frequency variations [4],[5],[6] in the distribution network and can affect the stability of the network and the operation of protection and regulation devices (e.g. operation of voltage regulators can be affected by power variability). These problems can be solved by installing energy storage devices in conjunction with renewable resources to reduce their power variability and to allow customers and utilities to gain maximum profit from the renewable resources.

In this paper, a general overview on different storage technologies available is presented and comparison of their characteristics is carried out in order to validate a selection criterion based on the application and the suitable performance of the storage technology for this application. Moreover, detailed discussion is presented for the flywheel energy storage as a promising storage technology for power related applications and short term energy applications. Finally, general control strategy for the operation of the flywheel energy storage units and availableresearch areas areproposed.

This paper is divided intofive sections. Where, section I describes the current applications of energy storage categorized by the place of implementation and general topologies for applying the energy storage. then, section II presents different storage techniques available and justifies the performance parameters used to judge the operation of the storage technique with comparison between common storage technologies used, section III focuses on the flywheel energy storage with explanation of general layout and components of flywheel energy storage system and its main components and block diagrams then the general operation strategy of the system is presented and the control flowchart is concluded and section IV draws the comments and conclusions for this work.

II. ENERGY STORAGE CURRENT APPLICATIONS

Energy storagesystems (ESS) are emerging among all power system sections from generation to distribution with wide applications. The current applications for energy storage categorized by the location of implementation are [7],[8],[9],[10]:

A. With Generation Units

- Using ESS as frequency regulation reserve[11]:
  ESS is usually interfaced through power electronics which have fast response. As a result, ESS can be used to mitigate load-generation imbalance to achieve both primary and secondary frequency control.
- Using ESS to Improve load factor:
  Storing energy during off-peak periods (i.e. at night) and use it during peak periods which result in almost uniform load factor. Better utilization of installed generation assets and deferment of the installation of new generation units are achieved by improving the load factor.
- Using ESS as a contingency reserve[12], [13]:
  To supply loads when the power supply falls during contingences where the reserve is available instantaneously. This situation can last from seconds to minutes until maneuvering takes place and loads are transferred to another source or the contingency is cleared.
- Using ESS for area Control to avoid unscheduled power transfer between utilities.
- Using ESS for black start[14]:
  Energy storage systems can start without assistance and hence used to energize the transmission system in order to assist other facilities to start up and synchronize to the grid.

B. With Transmission and Distribution

- Using ESS for transmission expansion deferral[15]:
  To collect and store produced power during the periods where the transmission capacity is insufficient then release it again when the transmission grid is not loaded too much which defers the transmission capacity expansion or upgrade for a period and avoid ttransmission curtailment.
- Using ESS for ancillary voltage support[16]:
  Storage can provide real power at unity power factor and reactive power which could be used for voltage support of transmission or distribution system during heavy loading periods.
- Using ESS to improve power quality and reliability[17], [18]:
  Energy storage can inject power to mitigate voltage sag and harmonics as well as to serve as a backup source in case of contingencies.
- Using ESS to ensure system stability:
  To keep all components connected to transmission system synchronized in order to avoid system collapse by balancing load and generation.

C. With End Users

- Using ESS to improve power system reliability:
  ESS acts as UPS by supplying the load power for short duration during supply interruptions (especially for critical loads).
- Using ESS to avoid high electricity prices during peak periods:
  Store energy during low-priced periods (off-peak periods) and release it during high-priced periods (peak periods) to reduce the average electricity price.

D. With Renewable Resources[19]

- Forecast hedge:
  Supply the difference (shortfalls) between the forecasted wind energy and the actual delivered energy and hence reduce any shortfalls penalties[20], [21].
- Time shifting:
  Renewable energy resources are usually controlled using maximum power point tracker (MPPT) to maximize the gained profit from these resources. However, it is required to store excess energy during off-peak periods and discharge this energy during peak periods to achieve optimum utilization of the renewable resources.
- Grid frequency support:
  Energy storage could be used to stabilize grid frequency during large decrease in the supplied energy from renewable resources for short intervals[16].
- Fluctuation damping:
  Energy storage could be used to damp the fluctuating nature of intermittent renewable resources and hence helps to smooth the supplied power[22], [23].

III. IMPLEMENTATIONSTRATEGIES FOR ENERGY STORGAE

Energy storage could be implemented using two strategies[24],[7]:

A. Massive Energy Storage

Bulk energy storage units used near main generation stations or at the transmission level using Pumped Hydroelectric (PH) Or Compressed Air Energy Storage (CAES) technologies.

B. Distributed Modular Energy Storage

Small storage units used near load centers, substations or renewable generation stations using batteries, capacitors, super conductors or flywheel storage units.

However, the distributed modular energy storage strategy is being more adopted due to the advantages of increased service reliability, improved supply security,

, Improved electrical performance due to the fact that they are erected close to load centers. Moreover, distributed energy storage has competitive prices compared with other alternatives.

IV. DIFFERENT STORGAE TECHNOLOGIES

Energy storage technologies suitable for distributed strategy can be classified according to the storage medium[7],[25] as shown in Fig. 1 (energy storage techniques suitable for distributed modular storage are considered).

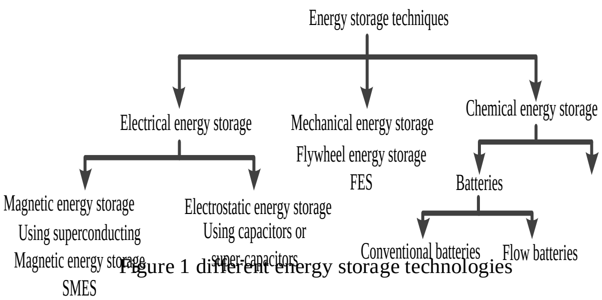

Figure 1 different energy storage technologies

The criterion utilized to select the suitable storage technology is based on justifying the following parameters[7]:

- Initial cost and running costs (operation and maintenance (O&M) cost).
- Power density (W/Kg) and energy capacity.
- Round trip efficiency.
- Life cycles and life time.
- Charge and discharge times.
- Environmental effects.
- Emissions.

Table I presents a comparison between the more common storage technologies for different performance parameters such as round trip efficiency, discharge time, capital cost, O&M cost and environmental effect[7],[8].

One of the main critical factors in achieving proper selection of the suitable energy storage technology is to determine the category of storage capacity required for a certain application. In addition, the required discharge duration. Where, storage applications are generally divided into two main categories: energy related applications and power related application as shown in Fig. 2.

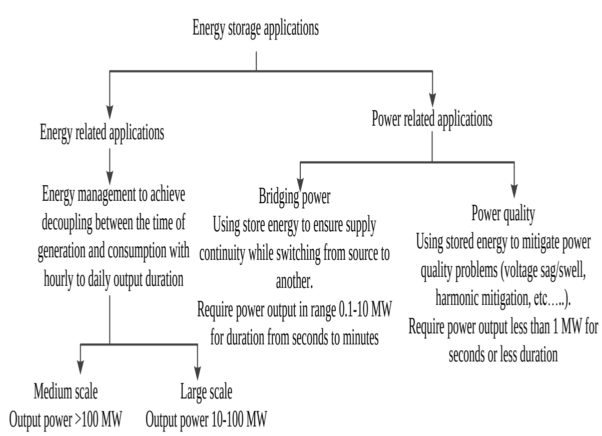

Figure 2 categories of energy storage applications

Based on these categories of applications, a comparison between different storage technologies considering specific power and energy capacity [26] is shown in Fig. 3.

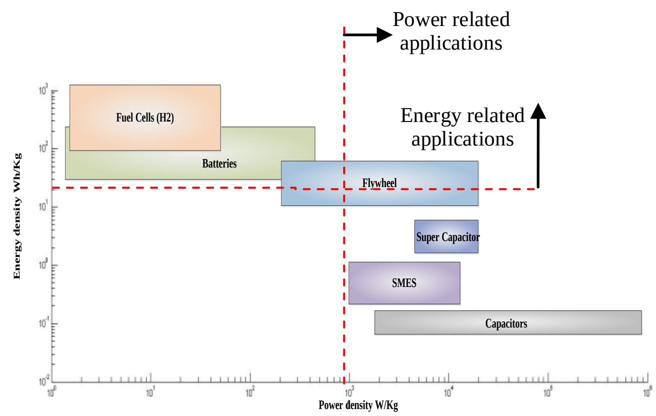

Figure 3 specific power and specific energy for different storage technologies[27]

Fig. 3 reveals that, capacitors, SMES and flywheels are superior for power related applications. Conversely, fuel cells, batteries and flywheels are more suitable for energy related applications. So that, flywheel represents a promising storage technique that covers wide range of applications and provides numerous advantages such as low initial cost, moderate maintenance cost, long life time, high power density, medium energy capacity, high round trip efficiency and environmental friendly operation and end of life disposals [28].

Batteries are the most common storage technology used among various applications. However, batteries have many drawbacks that retard their implementation rate. One of the critical drawbacks of batteries is their limited life time. In addition, the life time is greatly affected by the depth of discharge (DOD) as shown in Fig. 4. Also, the complexity of determination the state of charge (SOC) of batteries that shows the stored energy in batteries is a challenging disadvantage.

Consequently, batteries are suitable for energy related applications with non-frequent charge/ discharge cycles and no shallow or deep discharge not to deteriorate the batteries life time rapidly.

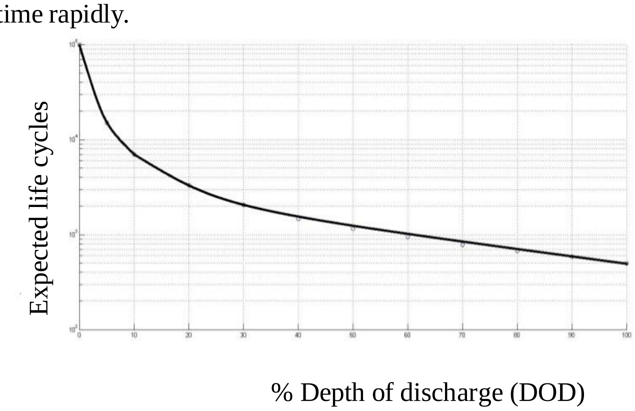

Figure 4 Relation between the life cycles of batteries and the depth of discharge[45]

TABLE I COMPARISON BETWEEN COMMON STORAGE TECHNOLOGIES FOR DIFFERENT PERFORMANCE PARAMETERS

Performance parameters	**Different Energy Storage Technologies**						
	SMES	***Capacitors***	***Super capacitors***	***FES***	***Conventional batteries***	***Flow batteries***	***Fuel cell***
Round trip efficiency %	80-90	60-75	90-100	90-95	60-80	70	20-50
Life time (years)	20-30	5	10-20	15-20	5-15	5-15	5-15
Cycle life (cycles)	30000-100000	50000	50000-500000	10000-10000000	1000-3000	1500-14000	1000
Discharge time	milliseconds to 8 Seconds	milliseconds to 60 minutes	milliseconds to 60 minutes	milliseconds to 40 minutes	Seconds to hours	Seconds to 10 hours	Seconds to 24 hours
Capital cost ($/KW)	200-500	200-500	100-500	250-450	100-4000	600-2500	10000-15000
O&M cost ($/KW/year)	10-25		10-15	20-30	10-60	10-80	
Environmental effect	Negative due to strong magnetic field	Small	Small	Almost none	Negative	Negative	Negative

Conversely, flywheel storage performance is independent on the DOD and can operate efficiently during both shallow and deep discharge without affecting the life time of the storgae units[29]. In addition, the determination of the SOC is very simple and achieved by measuring the speed of the flywheel. Hence,flywheel storage is suitable for power related application and short time energy related applications and their fast response facilitate their implementation to mitigate voltage sag/swells, improve load following capabilities and help with black start of generators.
Hence, FES can be considered as a promising storage technology to overcome drwabacks of batteries. However, the energy capacity of FES still need more enhancement and improvement.

V. FLYWHEEL ENERGY STORAGE TECHNOLOGY

Flywheel energy storage (FES) is coming around again after achieving a round of improvements in rotor materials, magnetic bearing control, power electronics devices and electrical machines control[30]. The main components of flywheel energy storage system (FESS) [31],[32] are motor/generator, rotating inertia, vacuum vessel and magnetic bearings as shown in Fig. 5.

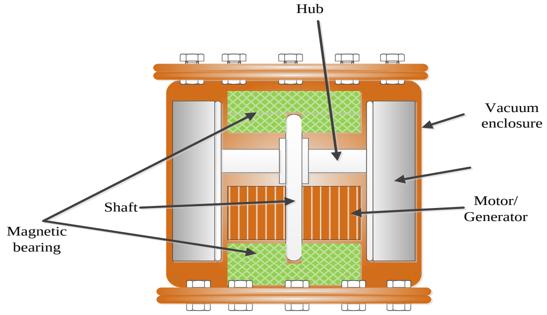

Figure 5 main components of flywheel storage unit[33]

Generally, the kinetic energy stored in the flywheel is calculated using $E = \frac{1}{2} J \omega^2$, where$J$ is the moment of Inertia and ω is the rotating speed.

A. *Different Types of FES*

There are two strategies to increase the stored energy capacity in the FES[34],[35]:

- Low speed FES*:*
  This strategy is based on increasing the rotor inertia by using a steel mass with a large radius with rotational speed up to 10000 rpm. in this type of FESS a standard motor, standard power electronic conversion interface and conventional bearing can be used which give the advantages of low cost and the use of proven technologies when compared to a high speed FESS. The main disadvantages are less stored energy per volume, higher losses, increased volume and mass and the rotational losses will limit the long-term storage ability.

- High speed FES:
  This strategy is based on using flywheel with light weight rotor running at very high rotational speed up to 100000 rpm where the rotor is made from composite materials, with ultralow friction bearing (magnetic bearing) and operated in vacuum vessels to eliminate air resistance and hence reduce the drag and friction losses. This high speed FES has the advantages of high energy and power density, compact and light weight.

B. *Block Diagram for FESS Combined with a Renewable Energy Source :*

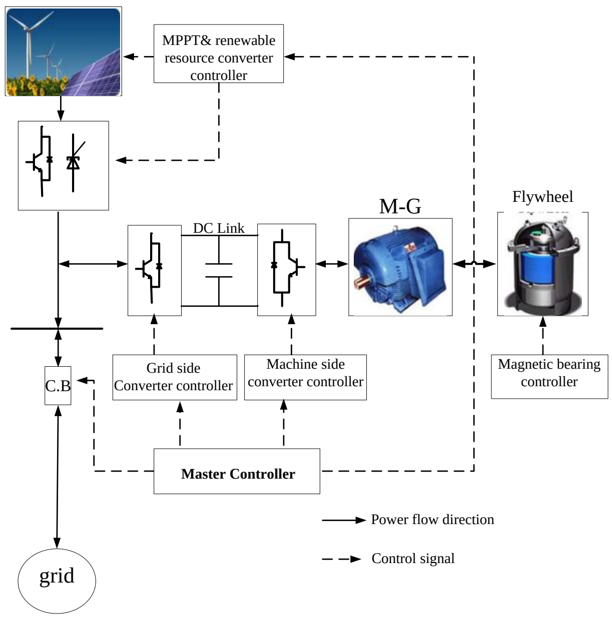

Figure 6block diagram of flywheel energy storage system and renewable energy source with main controllers

Figure 6 presents the general layout of FESS coupled to a renewable energy source (RES) as an application for FES. Hence, the FES can be used to smooth the output power of RES. Moreover, Fig. 6 shows the main controllers needed for controlling independent components as well as the master controller that controls the storage system converters, MPPT of RES and the circuit breaker connects the RES and the FESS to a grid.

Research efforts are being directed towards many components of the FESS shown in Fig. 6 such as:

- Selecting the most suitable electrical machine to be coupled with the flywheel (e.g. permanent magnet synchronous, doubly fed induction machine, squirrel cage induction machine or synchronous reluctance machine)[36].
- Selecting the appropriate control algorithm for the grid side converter and the machine side converter and selecting suitable converters topology[2], [37–42].
- Designing suitable protocol for the master controller that masters all controllers by setting the reference values.
- Designing the controller for the renewable resource and integrate it with the storage controllers in order to maximize the gained profit from renewable resource and improve the performance of the power system.
- Optimum sizing of storage system to minimize average energy cost and maximize the gained profit[43].
- Modeling of renewable energy resources in conjunction with the storage elements and then study the effect of FESS on smoothing the output power by reducing its variability through charging and discharging of the FESS.
- Study the dynamics of the system and the ability of energy storage in conjunction with the renewable resources to provide ancillary services to the grid.

C. General Operating Modes of FESS and Control algorithm:

Generally, the operating mode of energy storage system depends on the power imbalance between generation and load and the SOC of the energy storage.

FESS has the following operating modes:

- Idling mode: during this mode the control system keeps the flywheel speed constant at optimum operating speed $\omega_{optimum}$ by controlling the input power to the flywheel to overcome the losses and hence keeping enough spinning energy stored in the flywheel. (This mode is called sometimes stand-by mode). In addition, the idling mode may be used when the flywheel speed reaches its maximum value (at maximum stored energy).
- Flying mode: during this mode the control system accelerate/decelerate the flywheel to store/supply energy to the system in order to achieve the target of storage system (e.g. to mitigate swell/sag problem or to smooth the output power of renewable resources). The flying mode can be divided into two cases as follows:

  - Generator mode: when $P_{load} > P_{generated}$ and ($\omega > \omega_{min}$ for normal operation or $\omega > 0$ for contingencies).

  - Storage mode: when $P_{load} < P_{generated}$ and $\omega < \omega_{max}$

  Where, P_{load} is the load power required by the grid.
- Starting mode: during this mode the flywheel is started from rest to the minimum operating speed ω_{min} when$P_{load} < P_{gen erated}$. Then the controller moves to the flying mode or the idling mode.

FESS controller changes the mode of operation depending on the operating condition. Table II shows main logic to determine the operating mode for FESS.

The flow chart of the main controlling algorithm for FESS based on the logic described in table II is shown in Fig. 7.

This flow chart represents the basic control strategy used for the determination of operation mode for flywheel energy storage system.

TABLE II LOGIC FOR DETERMINATION OF THE MODE OF OPERATION OF THE FLYWHEEL STORAGE SYSTEM

$P_{load} < P_{generated}$	$\omega_{min} \leq \omega$	$\omega \leq \omega_{max}$	$\omega = 0$	$P_{generated} - P_{load} \leq \Delta P$	*Mode*
True	True	True	False	True	Idling
True	True	True	False	False	Flying /Storage
True	False	False	True	False	Starting
False	True	True	False	False	Flying /Generator
False	False	True	False	False	Flying /Generator

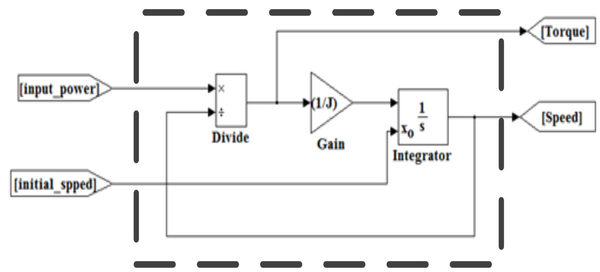

Figure 8 flywheel dynamic simulation model

After the determination of the input power to the FESS, the system dynamics can be studied by implementing the mechanical equation of the flywheel [44] as shown in Fig. 8.

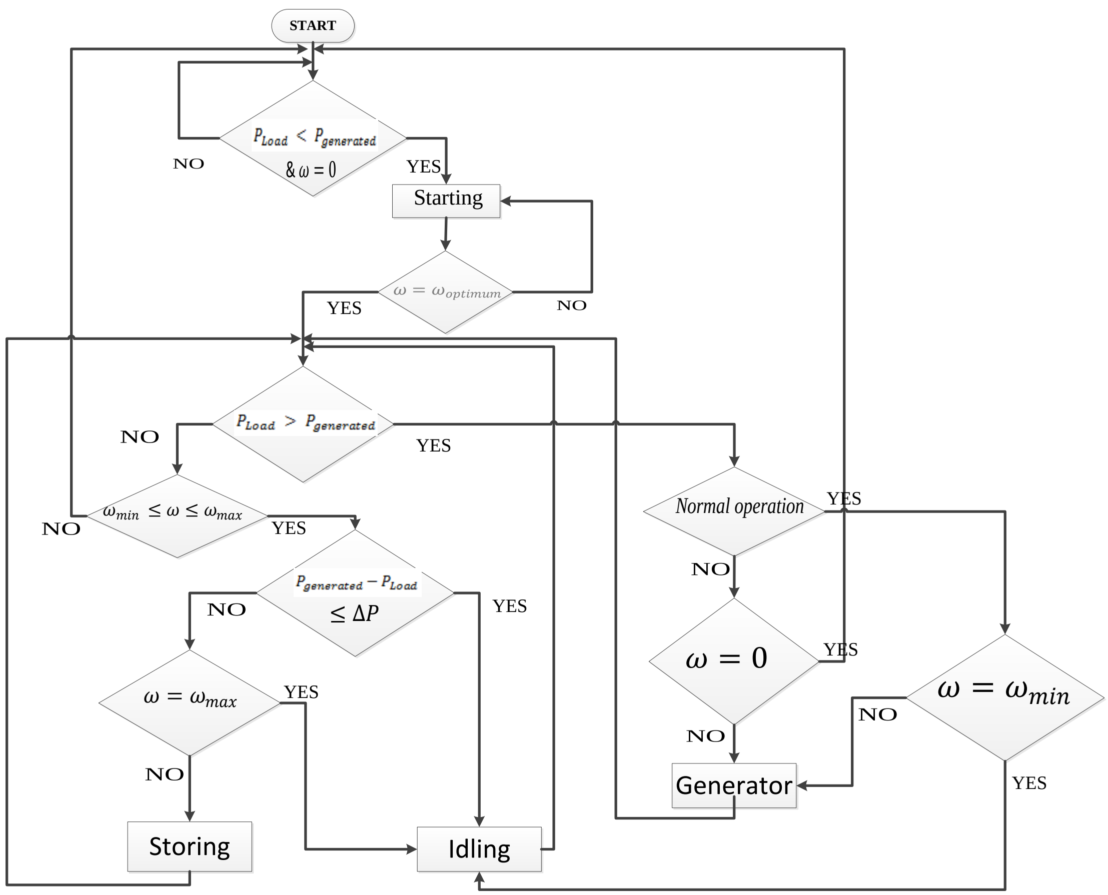

Figure 7 flow chart of the main control algorithm to determine the flywheel storage mode of operation

VI. Comments and Conclusions

The study in this article shows the increasing importance of energy storage systems in the future distribution networks to achieve self-adequacy and to provide ancillary service. Also, the distributed modular energy storage topology is found to be more advantageous than the massive storage topology in terms of reliability and low cost.

Then flywheel storage systems have been selected as a solution for the disadvantages of using batteries (the most common energy storage) especially the limited life time, hazardous disposal and SOC of batteries determination. In addition, the fast response of flywheel energy storage facilitates its use for increasing load following capabilities of slow generation units. Moreover, the life time of flywheel storage is independent of the DOD and hence it is suitable for applications require frequent charge/discharge cycles such as smoothing the output power of intermittent renewable resources [24],[28],[37]. However, for long term energy related application batteries are the most suitable energy storage unless more improvement for the energy capacity of flywheel storage takes place.

In addition, the block diagram for flywheel energy storage system has been presented with controllers required for each component of the flywheel storage system as well as the master controller that sets the reference values for distributed controllers, controls the MPPT to achieve maximum profit and controls the circuit breaker connects the storage system to the grid. Then, a flowchart for the determination of the mode of operation of flywheel storage has been presented based on the comparison between generated power and load power with the knowledge of the flywheel rotating speed (this speed reflects the SOC). Moreover, a simple dynamic model for the flywheel is presented to simulate the system dynamics based on the stored energy equation and using the input power for the flywheel system calculated after the determination of the mode of operation of flywheel system.

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