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Improving system frequency in smart grids in presence of wind and PV generation units using flywheel energy storage system

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ABSTRACT
To have rigid frequency in power system it is necessary to have instantaneous balance between generation and loads.Inevitable frequency oscillations caused by renewable energy resources Produce variations in power system frequency. The advantages and positive effects of Flywheel Energy Storage System (FESS) under normal conditions of system and during loss of generation and loss of load occurrence has been studies in this paper. FESSwith a novel control schemeis usedin order to balance load and generation, and as a result to smooth grid frequency. Under study system is a smart grid with wind and PV generation units. Simulation results show that frequency response of grid in presence of perturbation has been improved significantly. The validity of the proposed method is evaluated by computer simulation analyses using MATLAB Simulink.
Keywords: Frequency control, Voltage control, Flywheel energy storage system, Flywheel, Smart grid.

INTRODUCTION

Increase of fossil-based fuel costs and growing concerns about global climate changes face us with challenge of finding better and cleaner sources of energy. In this situation, there is an important rule for Renewable generation in power system, that is why energy market is directed strongly towards renewable energies.

Although renewable energies are vital for modern grids, but they also could be a source of instability in power system. Sunshine and wind speed are two unpredictable factors with random changes. if system experiences extreme drop in wind speed, it will be a great challenge and system needs proper backup to win through it.

Power system Investors always seeking for renewable energies with cheapest and easiest installations properties and with simple control and operation methods. Power systems of today, experiencing Islanding modes due to increasing worldwide demand for electricity [1]. A micro grid includes a wide variety of distributed energy resources. wind farms and photovoltaic cells are two main energy resources with these conditions. Many studies have been done about this issue. For example, the availability of a large solar power plants and the impact of weather on its production has been discussed in [2] and Effects of grid-connected solar power plant on power quality and reliability of the network has been reviewed in [3].

Microgrids include a huge range of distributed energy sources. In islanded operational, The most important factor of control issues are load-sharing control and voltage and frequency control (In other words: active and reactive power control)[4, 5]. On the other hand, wind speed is a highly stochastic parameter that can diverge quickly and generated output power of wind turbine is proportional to the cube of wind speed. So that any deviation in wind velocity will cause a high fluctuation in the generated wind power[6]. This oscillation of power may cause frequency Variations or flicker phenomena or in some cases voltage instability problems[7].Due to these kinds of problems in the presence of a cluster of Distributed Generation units, the power system has Urgent need for energy storage system to save energy during times with a surplus of energy and return it to the power grid when system experience shortage of energy. With regard to random variation of DERs, it would be vital to install energy storage systems in distribution system, close to or far from generation units, depend on the need of system.A comparison between Response times of generating units and energy storage systems has been brought in table 1.This time intervals can explain the whole idea, briefly.

Table 1 - Comparison Response times of generation units and energy storage systems

	Response time	Amount of energy	Control loop
Ordinary generation units (thermal)	5 Min	>1 Hr	AGC
Energy storage systems	4-6 Sec	15-25 Min	AGC

Different solutions proposed to regulate power fluctuations in the networks with renewable power plants. In many cases, such as [8-10]FESS has been introduced as a proper energy storage system and effective frequency regulator.In some references such as [11]superconducting magnetic storage systems have been used to minimize oscillation frequency and in a couple of studies battery energy storage system (BESS)have been recommended to regulate frequency [12, 13].Also, In some studies such as [14] hybrid storage systems have been applied to power system.

FESS is not a new idea, although it has been a very popular system in recent years, which is because of recent advances in the field of bearings and power electronics. FESS has many advantages including high efficiency, long life, inexpensively maintained, large energy capacity and no pollution to the environment, Also it is very fast in reaction and effective due to its moment inertia [1]. Flywheel also has great capability of integrating with power electronic switches and converters. As a result, novel control methods of power electronic devices could be used for controlling power flow of FESS.

Integration of FESS with renewable energy resources is a brilliant idea, which maximize beneficial aspects of existing networks by improving power quality of the system. On the other hand, FESS is a dc system and it needs a proper dc/ac conversion system using suitable means of power electronics commutations[15].

Flywheel Energy Storage System (FESS)

Flywheel invention belongs to industrial revolution era, but the other sides of technology where not mature enough to use flywheel as a storage system at the time. High rate of losses and lack of appropriate converter were two main factors of that failure. After a major improvement in bearing technology and power electronics, FESS has come around again to be a promising alternative to traditional battery systems [16]. FESS is a physical device storing kinetic energy in a spinning rotor. This energy could be transferred into electrical energy via an electrical generator, thus FESS is an electrical storage system. The amount of electrical (kinetic) energy stored in FESS depends on themes of rotor and its shape. Numeral rotational speed is one of important factors.

FESS, also called electromechanical battery, consists of different mechanical and electrical parts. The most important parts in a typical FESS comprised of the rotor, motor-generator, power electronic converter, controller and semiconductor bearings. When energy of power grid is plentiful and inexpensive, FESS would work in motoring mode and rotor of flywheel would be speeded up. In this way, rotational energy will be stored in FESS. On the other hand, during times that system experiences lack of energy, FESS returns energy to the grid and the rotor would be slowed down to release enough electrical energy. In this mode, electrical machine would work in generating mode.

The kinetic energy stored in spinning mass of rotor would be as:

$$E_k=½J\omega^2 \quad (1)$$

Where J is Moment of Inertia of the rotor and ω is Rotational speed.It is important that the moment of inertia is a function of the mass and shape of the rotor. This relation expresses as follows:

$$J=\int x^2 dm_x \quad (2)$$

Where x is the distance of the differential mass dm_x from the axis of rotation. There is a fact that in order to achieve higher capacity for energy storage, angular velocity is more important than mass. This point proves that FESS with lighter mass but higher speed is prior to any other structure [16].

An important question is why FESS is prior to BESS? Main advantages of Flywheel over ordinary batteries are fast reaction and great effectiveness of flywheel due to its moment inertia while battery does not. BESS is not suitable for power regulation under deep and sudden variations or extreme changes of power flow. BESS has low reliability and short life under stressful conditions. Rate of charging or discharging for BESS

is limited due to its inevitable chemical process, while there is no limitation in FESS.It should be noted that in frequency regulation rapid response is very necessary in order to track power variations in short time-intervals.
In addition, FESS has smaller size and longer life compared to BESS. The state of available charge for FESS is obvious at any moment, but in BESS it is more difficult to determine the exact state of charge. However,FESS has some disadvantages; it needs a motor-generator, bidirectional power converter, control system and some other parts. This increases the costs of storage system. That is why FESS is more expensive than BESS. However, countless benefits of FESS make it a proper choice for power regulation.

System model
FESS structure
General structure of a FESS system has been illustrated in Figure 1.This model includes a flywheel rotor, Permanent Magnet Synchronous Machine (PMSM), power electronic converter and a control system.

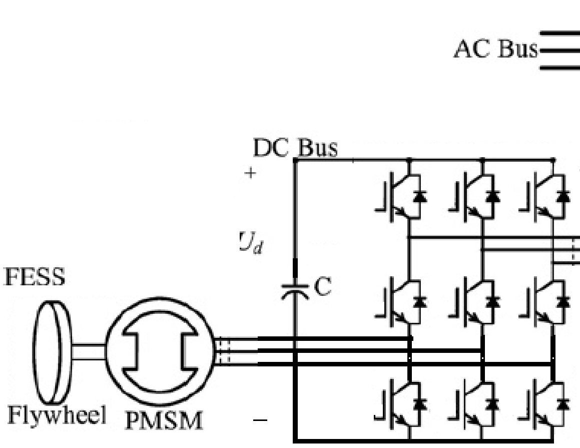

Fig 1. General structure of a FESS system

Power interface
The power electronic interface transfers AC power from grid to a DC-link and vise verso. This part consist of a PMSM and a bidirectional converter. Electrical machine is a high-speed PMSMusually known as an integrated synchronous generator (ISG)[17]and power converter usually is a three-phase full bridge[18].
The main reason that PMSM is best choice for FESS is be due toits high efficiency because PMSM rotor has no losses. In addition, PMSM is very light and small size in compare with any other types of machine. Rotor environment is in vacuum in order to minimize rotational losses.
In order to achieve high power levels these designs typically use magnates with high-energy products, such as neodymium–iron-boron. The so-called Hallbach array for the permanent magnets allows eliminating all the iron losses at expense of lower magnetic flux and thus lower power[19].

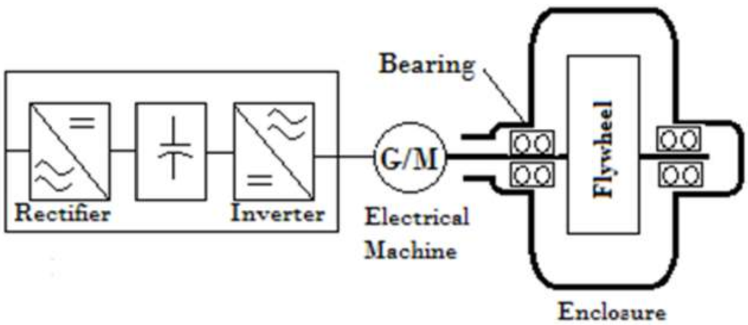

Fig 2. Different parts of a conventional FESS

Control system
In general, there is two most important tasks for control system:
1. Switching power electronic devices
2. Control of bearings and keep the balance of rotor.

Pulse width modulation techniques are very popular for conventional FESS power converters. Today, bidirectional converters are best choice for FESS in order to have one converter either for charge or discharge modes. This kind of converters usually equipped with IGBT switches which can achieve a full-load efficiency of greater than 90%, however this efficiency falls off at low loads[1]. In this study, a three-phase full bridge VSI converter with PWM control scheme has been used. To connect power converter and electrical machine, LC filter might be necessary. This filter helps machine, supplying it with a full sine wave with low ripples and notching. As a result,PMSM losses will be reduced and the coil will prevent electromagnetic interference (EMI).

In this scheme, only the rotor-side converter will be controlled in order to control PMSM. Higher switching frequency results low torque ripple and an increase in bandwidth control, although the switching losses will increase too.

Connecting FESS to power system requires a bidirectional converter. Figure 2 shows the topology of this converter. A typical FESS inverter consists of a rectifier and an inverter that connect to each other viadc-link. This converter allows FESS system to transfer active and reactive power to the grid.

As discussed before, proper switching frequency results reduction of ripples. In this case, LC filter could be smaller. This is a dramatic reduction in cost and size of FESS. Various kinds of losses in a typical FESS are rotor-bearing losses, stator losses, power converter (switching) losses and rotational losses. Among them, Switching losses are the main one that directly affects the efficiency of the system.

In this study, a 9-switch inverter has been used as a bidirectional converter. Proposed inverter consists of two usual converters. each classic inverter has 6 switches. In order to reduce costs and negative impact of thermal power equipment, the number of semiconductor switches has been reduced and6 switches merged into 3 so the whole system has only 9 switch instead of 12[20].

Frequency regulation method using FESS

The main purpose of converter in FESS is to defined amount of power transfer between storage system and power grid. In other words, to control power flow exchanged between dc-link and ac power system.This strategy has many advantages, including the ability of power exchange in both directions and to minimal distortion in the network. Another positive feature would be the independency of active and reactive power exchange between the network and storage systems. FESS is able to improve the voltage profile in weak points of the system. Many control techniques have been recommended to adjust grid frequency and power exchange at the same time,in order to reducing harmonic distortion in ac side. hysteresis band current control is of the most popular methods among them [21]. Figure 3 shows a simplified block diagram of hysteresis current control method.

The amount of output power of FESS called P_{ref} that is associated with grid frequency variations. Frequency variations measure by a phase locked loop (PLL) at the output terminal of FESS. Since the main goal is to adjust frequency, when frequency decreases, FESS inject power to the grid and when frequency increases, FESS absorb energy from the grid.

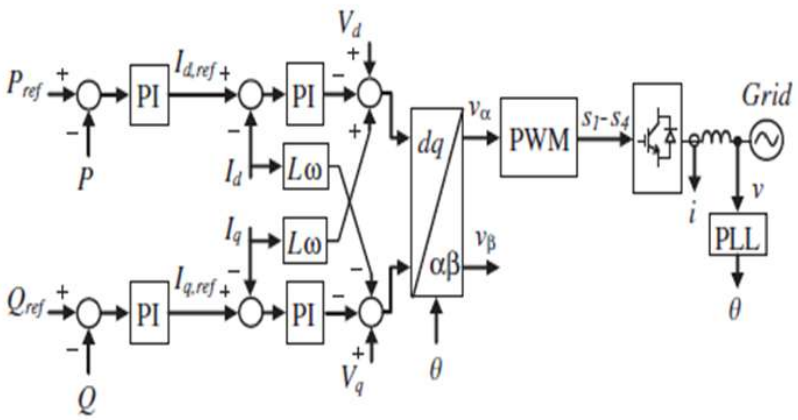

Fig 3. Simplified block diagram of hysteresis current control method

Simulation Results

Dynamic simulation of power system in presence of wind and PV generation units and FESS has been studied in Simulink/MATLAB software.Power quality of system has been examined in a 6-bus system consisting of 3 generation buses and 3 load buses. Figure 4 shows the topology of under study system. There are 4 generating units in this power system: one wind unit, one PV unit and 2 thermal units locating in buses 2 and 5. Best place for FESS installation would be bus 1 because wind and PV units would be in the same bus with FESS.

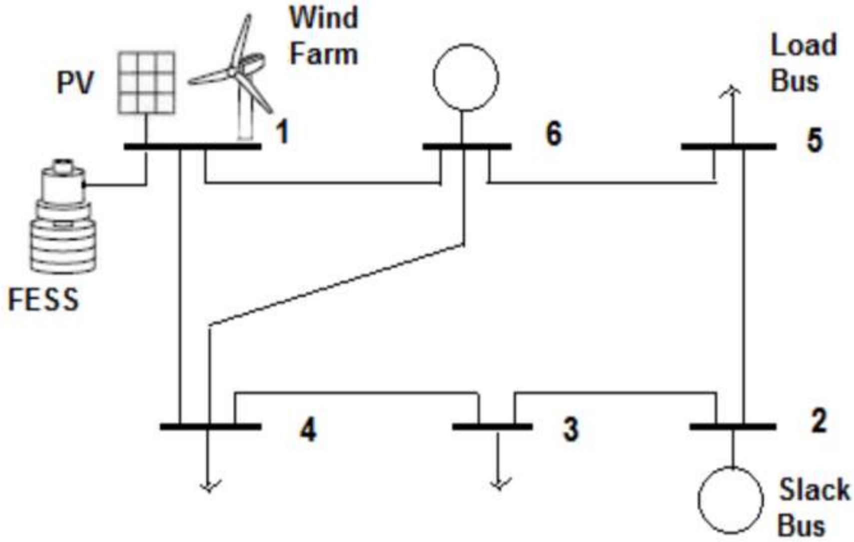

Fig 4. Topology of understudy 6-bus system

Wind turbine generator is a double-fed induction generator (DFIG). DFIG has been studied in [22-24]. All data of this study, including changes in load, wind speed, the amount of sunlight radiation of PV modules are based on real data belongs to a desert village named Moaleman, located in Amirabad District, DamghanCounty, Semnan Province, Iran. The basic parameters of the production units and have been shown in Table 2. Details of under study system configuration in Simulink environment has been illustrated in Figure 5.

Table 2 - Parameters of generation units and loads for under study system

Capacity (MW)	**Type of unit**	**Bus No.**
80 MW	Wind	1
20 MW	Photovoltaic	1
150 MW	Thermal	6
20 MW	Loads	3, 4, 5
20 MW	S FESS	1
1000 MW	Slack bus	2

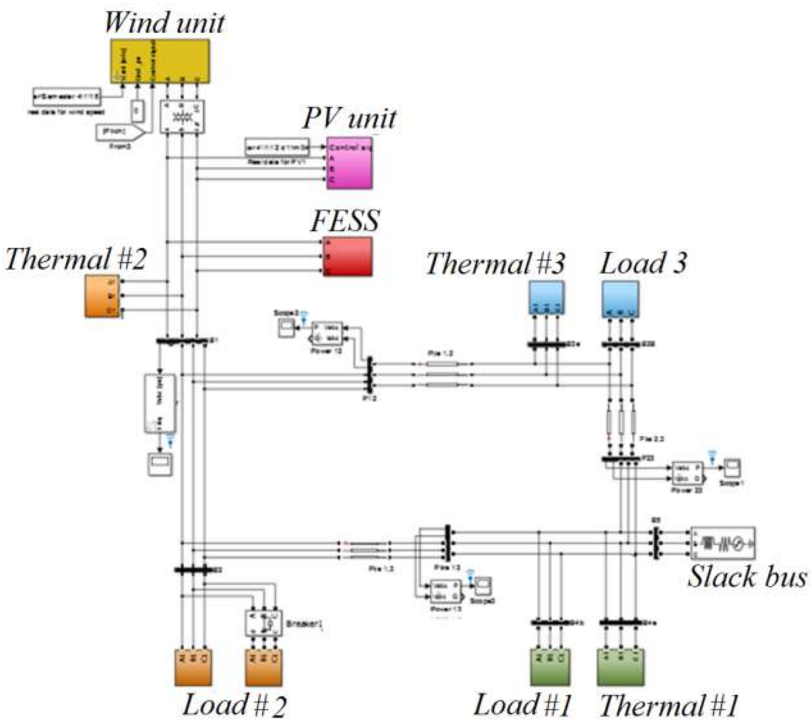

Fig 5.System configuration of 6-bus system in Simulink environment

In a stable system, generating units are expected to provide enough power for loads and track the load changes. In figure 6 it can be seen that under normal conditions of system, there are small oscillations in active power (grid frequency)of the system. These oscillations happen due to presence of PV and wind generation units in power system. In the presence of FESS, frequency variation greatly reduced and limited to an acceptable range. However, high frequency noises appeared on the frequency wave form, which is because of switching devices of FESS. These high frequency ripples can be removed by using appropriate filter. If the capacity of PMSM and implements be large enough, and control scheme would improve, high-frequency ripples can be dramatically improved.

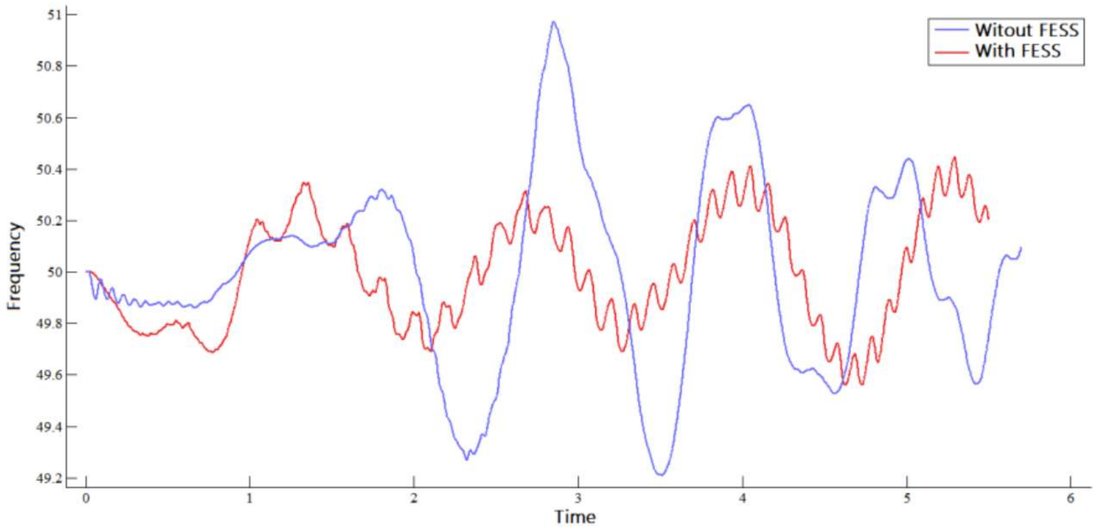

Fig 6.Comparison for system frequency with and without FESS

If an unexpected decrease in wind speed occurs, wind generation system will experience a loss of generation. This problem happen sat t=0.8. The results can be seen in Figure 7. Loss of generation will lead to a sudden decrease in frequency. Other generation units Respond to make it up and after a series of huge but damping oscillations the system returns to normal operating mode. In presence of FESS (Fig. 7), these oscillations are very limited and system barely feels the loss of generation.

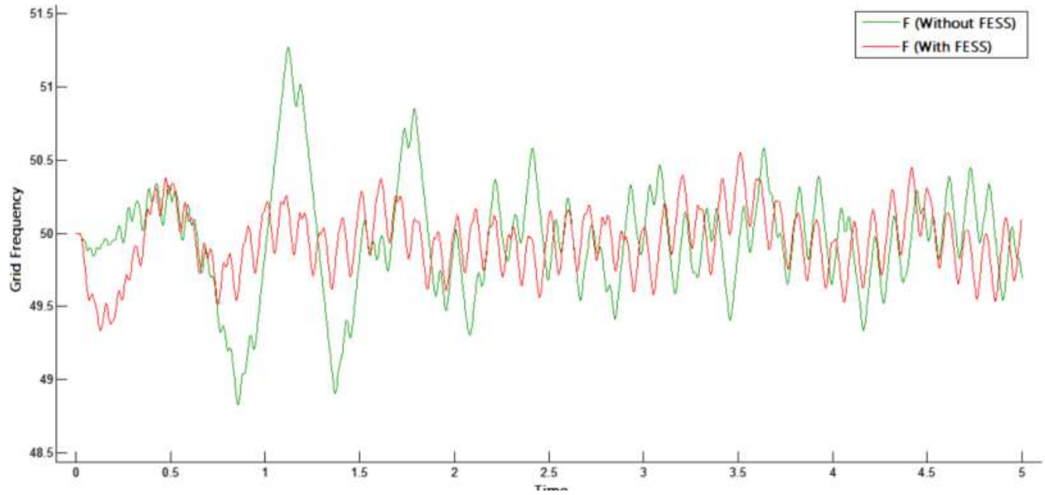

Fig 7.Comparison for system frequency with and without FESS during loss of generation (t=0.8)

An unexpected loss of load has been applied to the system at the time of t=0.8 by disconnecting load number 2. This load is about 15% of the total load of the system. Loss of load causes a sudden and huge increase in frequency that causes extreme variations in a way that the frequency will be out of its standard range. When FESS is present, the situation is quite satisfactory and FESS manage loss of load. Grid frequency presented in figure 8. it should be noted that the moment inertia of FESS and high nominal power of PMSM are key factors which improve frequency very much. In the case of using ordinary chemical batteries, it is not possible to achieve nice response such this.

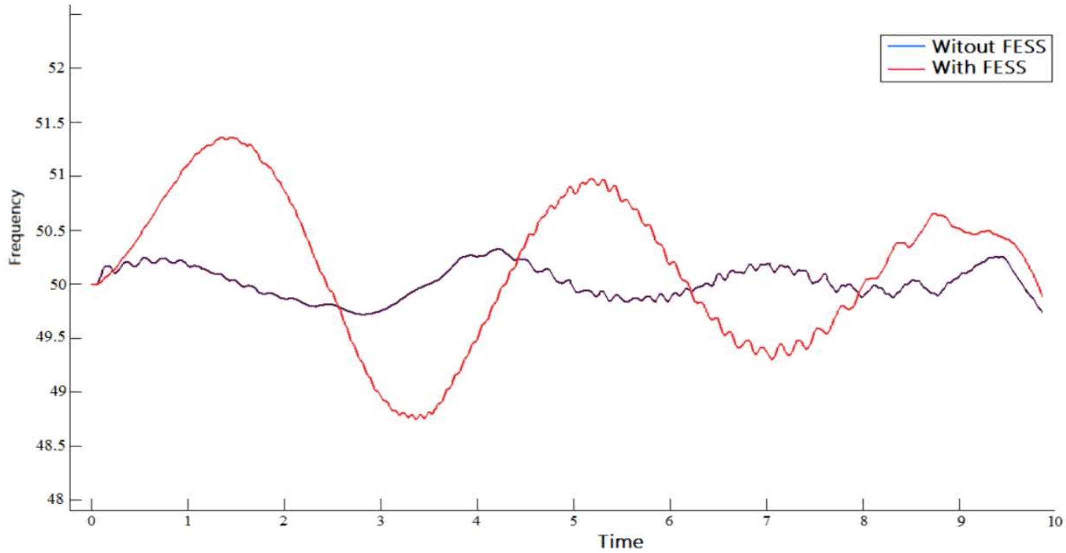

Fig 8.Comparison for system frequency with and without FESS during loss of load (t=0.8)

CONCLUSION

In this paper, FESS was used to regulate frequency oscillation of power system, In the context a dual converter with 9 switches was used to reduce total cost and losses of FESS. The results of FESS under normal condition and (minor fluctuations) and under loss of generation and loss of load conditions (major fluctuations) have been presented. Results indicate that moment inertia of flywheel make it easy for FESS to be a proper regulator in severe dynamic changes of active power (grid frequency).In the presence of FESS, there are some small ripples in frequency, which is because of switching in grid-side inverter. A proper LC filter can remove these ripples and improve frequency even more, although the cost of the filter will be added to FESS costs.

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