Voltage and Frequency Control in Smart Distribution Systems in Presence of DER using Flywheel Energy Storage System

Roya Ahmadi.A
Noushirvani Industrial University

Fatemeh Ghardashi
University of Science & Technology Babol

Dawood Kabiri
University of Science & Technology Babol

Abdolreza Sheykholeslami
Noushirvani Industrial University

Homayun Haeri
Tavanir Management Co.

ABSTRACT

The prerequisite for stable system frequency is to have instantaneous balance of demand and generation of active power. Inevitable energy oscillations due to presence of renewable energies in a smart grid, cause network frequency variations in power system. In this paper, we suggest a novel converter and control scheme for flywheel energy storage systems for the provision of energy balancing and grid frequency regulation in a smart grid consist of wind generators, PVs and typical thermal units. This scheme improves the system frequency response to disturbances. The validity of the proposed method is evaluated by computer simulation analyses using MATLAB Simulink.

INTRODUCTION

Energy market is directed strongly towards renewable energies. The facts of running out of conventional fuels like coal and oil beside the high rates of CO2 emissions have forced many countries to concentrate their research and future power generation planes in the field of clean renewable energies. That's why there is a great increase in the utilization of renewable energy sources such as wind generators, photovoltaic arrays, fuel cells and etc.
Companies and governments are always seeking for the renewable energies of the cheapest and easiest installations and operation methods, especially wind and solar energies. There are many isolated islands in the world and the power needs everywhere.[1] A microgrid can involve a wide range of energy sources. In an islanded operational, the key control issues include: voltage and frequency control, active/reactive power control, and the load-sharing control [2,3].
Moreover, wind velocity is a highly stochastic component which can diverge quickly. As the generated output power of the wind turbine system is proportional to the cube of wind speed, any deviation in wind velocity will cause a high fluctuation in the generated wind power. The power fluctuation may lead the frequency fluctuation and voltage flicker inside the power system [4].thus,there is a need of energy storage system which its purpose is to save energy during times when energy is plentiful and return it at some urgent times when energy is lacking. So it is necessary to install energy storage system in distribution network, which can improve power quality and supplying reliability of system. In Table 1 there is a comparison of Response times, for generation units and storage units who explain the idea briefly.

	Response Time	Energy	Control	Adds to Base-Load Generation
Generation Based	5 Mins	>1 Hr	AGC	Yes
Energy Storage	4 Sec	15 Mins	AGC (W/Managed	No

Table 1 - Comparison of Generation And Energy Storage assets for frequency Regulation

The Flywheel energy storage system system is superior to any other energy storage system in that it has 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.
Power electronic devices have capacities to be integrated with FESS.
The successful application in power electronics is due to the evolution of silicon voltage source converter (VSC) technology.
Flywheel storage integrated with solar Photo Voltaic (PV) and wind farm is one of the most beneficial approaches of providing solutions to existing network. Storage devices are capable of assisting in the distributed generation power which can be useful in implementing renewable energy to power systems and also facilitate the implementation of smart and micro grids. Such DC systems generation need to be combined with DC/AC conversion using a suitable means of power electronics commutations [5].

FLYWHEEL ENERGY STORAGE SYSTEM

After a major improvement in technology and power electronics, flywheel energy storage system (called 'FESS' hereinafter) has come around again and has been a promising alternative to traditional battery [6]. FESS is a kinetic energy storage device storing energy in a rotating rotor. The amount of energy storage depends on the mass, flywheel shape, and rotational speed of the rotor.
FESS or also called electromechanical batteries are typically comprised of the rotor, motor/generator, power electronics, controllers and bearings. In motoring mode

flywheel is speeded up to store rotational energy and is slowed down to release energy in generating mode by a motor/generator system. The FESS is superior to any other energy storage system in that it has 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.
The kinetic energy stored in a rotating mass is:

$$E_k = \frac{1}{2} J \omega^2 \qquad (1)$$

J= Moment of Inertia of the Flywheel and
ω= Rotational speed of the Flywheel
The moment of inertia is a function of the mass and shape of the flywheel:

$$J = \int x^2 dm \qquad (2)$$

where x is the distance of the differential mass dmx from the axis of rotation.
This equation (1) shows that high angular velocity is more important than mass to achieve high stored energy, Because the flywheel energy is proportion to the square of the rotating speed, light mass, high-speed units can be designed to provide high energy density [8].
To answer the question "why we prefer to use FESS instead of battery?" it should be mentioned that the battery system is suitable for power compensation with relatively long period like load leveling. However, since rapid response is necessary to compensate power variations in an small periods(less than second), the battery system may not be appropriate because charging or discharging speed of the battery is not so fast due to its chemical process.
Moreover, the same capacity of electronic power converter as that of the battery power rating is required. In addition life time of battery is, in general, not so long and thus frequent replacement of battery cell will be needed.
Also, the state of charge of a FESS is readily determined from its rotational velocity. Determining the state of charge for an electrochemical battery is more difficult.
These characteristics cause increase of cost. On the other hand, the application of FESS for power compensation is very effective. It can operate equally well on frequent shallow discharges and on very deep discharges. This type of load variation is usually challenging to batteries because the combination of low- and high-power loads makes their design difficult to optimize.

SYSTEM MODEL

Configuration of FESS

Fig.1 shows a model configuration of FESS. The FESS consists of the Permanent Magnet Synchronous Machine , the flywheel mass for kinetic energy storage, and speed control circuit.

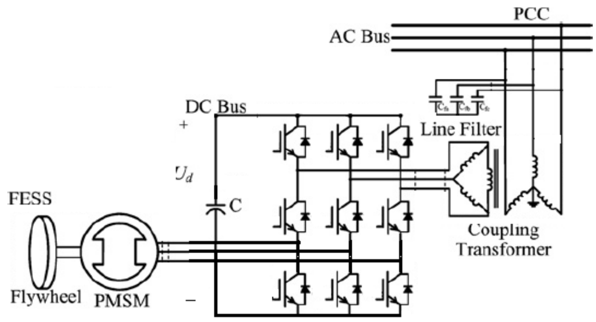

Fig.1. FESS circuit configuration

Power interface

The power interface includes the motor/generator, a variable-speed power electronics converter,and a power controller. The motor/generator is usually a high speed permanent magnet machine, integrated with the rotor. This is usually known as an integrated synchronous generator (ISG)[7].
Permanent magnet synchronous machine (PMSM) has become the most usual choice for FESS due to its high efficiency. PMSM has no rotor losses ,thus suitable for confinement in vacuum .permanent magnet machines also typically have a high power/weight ratio when compared with other machines.In orther to achive 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.

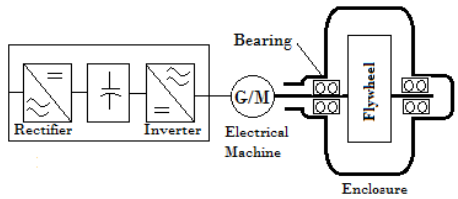

Fig 2. Components form a conventional FESS

The conventional power electronics interface is usually a pulse width modulated (PWM) bi-directional converter using insulated-gate bipolar transistor (IGBT) technology. The power electronics interface can achieve a full-load efficiency of greater than 90%, however this falls off at low loads. The converter may be single-stage (flywheel ISG a.c. ⇔ d.c. bus), or double stage (flywheel ISG a.c. ⇔ d.c. bus ⇔ a.c. network), according to the application requirements. Finally, a power controller is required to monitor the flywheel and control the power flow. The controller operation will depend on the application, for example where the system is interfaced to an a.c. network, reactive power as well as active power will be controlled FESS connects to a DC-link by means of a bidirectional power converter (DC/AC), see Fig 2, most often a three-phase bridge of semiconductor switches [8]. This results in a voltage source inverter (VSI) controlled by pulse width modulation

(PWM). Additional *LC*-based filters may be needed to connect inverter and electrical machine. This would be to supply sinusoidal currents without ripple into the machine and thus reducing losses, windings deterioration and EMI . The rotor-side converter is controlled to make the electrical machine behave as a generator or as motor according to the instantaneous necessity. Higher switching frequency reduces the electrical machine current and torque ripple and increases control bandwidth, but at expense of increasing switching losses.
In order to connect the FESS to an AC grid, another bidirectional power converter (DC/AC), working as a rectifier, is necessary. Most of the times another three-phase bridge of semiconductor switches is used with a capacitor acting as DC-link , see Fig 2, This rectifier allows supply/retrieve active and reactive power to/from the AC grid with sinusoidal currents. Higher switching frequency reduces current ripple, easing the connection filter design, and increases control bandwidth. Various losses in the system, including bearing losses, and electrical losses (stator losses, power converter losses), contribute to the overall conversion efficiency. The power electronics switching losses usually dominate the total losses, and the overall efficiency is a function of power . In this paper, The nine-switch inverter is proposed as dual output Inverter. The proposed nine-switch inverter is composed of two conventional inverters with three common switches. The extra voltage available for a given input dc-voltage, translates to a higher torque—a critical factor for defining the capacity of products in market place [9]. Also, in order to further reduce the cost of power devices and also thermal heat effect, and to reduce the number of semiconductor switching, this inverter is used in this study

A method of frequency stabilization by using FESS

The main objective of the grid-side converter is to control the power flow between the ac system and the dc link powered from the renewable resources. It offers several advantages such as bidirectional power flow capability and low distortions at the ac side current and the dc side voltage. Another promising feature is that it can independently control the active and reactive power exchanged with the ac network; therefore, it can improve the voltage profile, and is able to operate in weak ac systems. These advantages make the VSC a successful solution for grid integration of small-scale renewable energy sources. To regulate the frequency and exchange power with the grid, and at the same time, reduce the harmonic distortions in the ac current, different current control structures have already been proposed, such as current hysteresis control[10].
Reference of active power output of FESS, Pref, is determined according to the deviation of network frequency,which is detected by PLL at the terminal of FESS. When the frequency

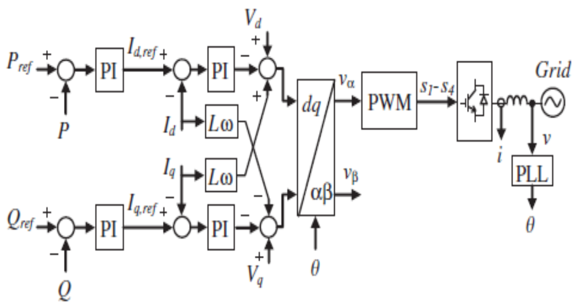

Fig.3. Simplified block-diagram of current hysteresis control

is decreased, FESS supplies active power to the network. When the frequency is increased, FESS absorbs active power from the network.

SIMULATION RESULTS

Dynamic simulation of hybrid system with a flywheel was implemented in MATLAB Simulink to study expected power quality.
The Topology of six-bus power system in this paper is illustrated in Fig.4 . This system consists of three generation bus and three load bus

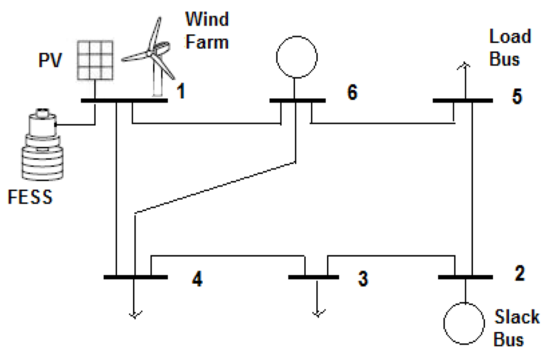

Fig.4 Topology of 6-Bus Test System

There are four kinds of generation units, one wind generation unit and one photovoltaic generation unit, both located in bus 1, and 2 thermal units located in buses 2, 6 respectively.
Wind turbine generator system use a doubly fed induction generator (DFIG), and all system generation/demand inputs including wind speed, sun radiation and load points are real data of IRAN grid.. Parameters of generation and load units have been illustrated in table 2 and table 3, respectively. Also there is a Flywheel energy storage system (FESS) at bus 1, to regulate system frequency.
Generation units supposed to meet the demand to have a stable power system. In addition, small power system is connected to large power network (infinity bus), although it is assumed that the isolated island can operated independently.

As mentioned before, this kind of system ,naturally suffer from frequency fluctuation, as told, the solution is to use storage energy to inorder to regulate frequency , which FESS Is used in this case.

Table 2 – SIX BUS SYSTEM CONFIGURATION

BUS	Device	Capacity
1	Wind farm	80MW
1	PV	30MW
6	Synchronous generator	150 MW
3,4,5	load	20 MW
1	FESS	20MW
2	Slack	1000MW

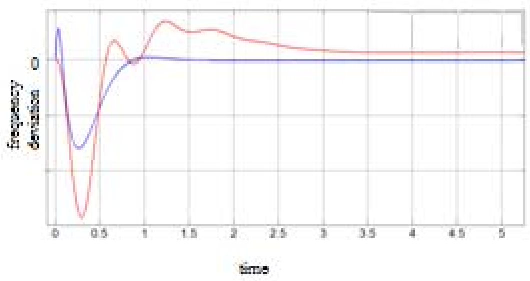

Fig.5. frequency deviation without(red) and with(blue) FESS

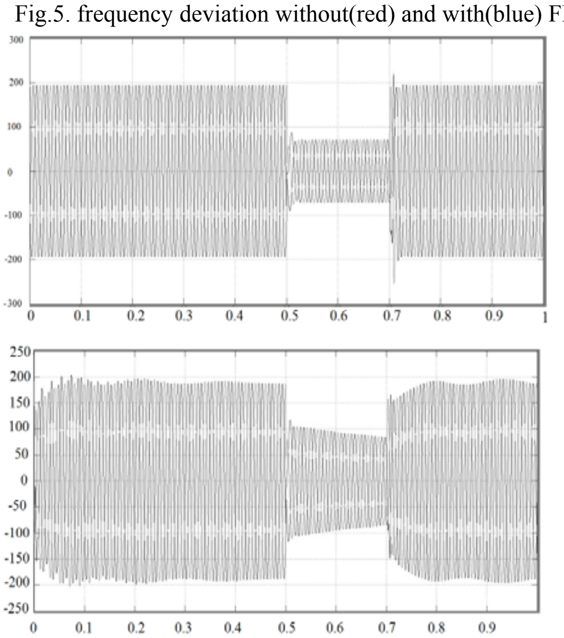

Fig.6. a voltage sag without and with FESS

the stability of frequency can be seen from figure 5. This figure illustrates the effect of 0.1 pu loss of sudden generation in the system.

Fig.6. shows a %35 voltage sag happens by occurring a fault in distribution system, in time 0.5 till 0.7 seconds. In this case the FESS is disconnected.

Conclusion

The power electronics switching losses usually dominate the total losses, and the overall efficiency is a function of power . In this paper, The nine-switch inverter is proposed as dual output Inverter. Also, in order to further reduce the cost of power devices and also thermal heat effect, and to reduce the number of semiconductor switching, this inverter is used in this study.

Simulation results shows the effectiveness and robustness of proposed method for application of Flywheel energy storage system in power grid, in presence of renewable energy resources.

REFERENCES

[1] Ibrahim H, Younes R, Basbous T, Ilinca A, Dimitrova M, " *Optimization of diesel engine performances for a hybrid wind-diesel system with compressed air energy storage* ", Energy 2011;36(5):3079e91

[2] Katiraei F, Iravani MR, Lehn PW. "*Micro-grid autonomous operating during and subsequent to islanding process*". IEEE Trans Power Delivery 2005;20(1):248–57.

[3] Sao CK, Lehn PW." *Control and power management of converter fed microgrids*". IEEE Trans Power Syst 2008;23(3):1088–98.

[4] Kamel RM, Chaouachi A, Nagasaka K ,2011"*Wind power smoothing using fuzzy logic pitch controller and energy capacitor system for improvement microgrid performance in islanding mode*".Energy 2010;35(5):2119e29.

[5] Hatim I. ELSAYED, Dr. Salman R. CHAUDHRY, AbdulAziz A. Al-MAHMOUD ," *monitoring and replanning approach for optimal energy management in micro grids*". Energy 2011;36(5):3429e36.

[6] Swett, D.; Blanche, J.; "*Flywheel Charging Module for Energy Storage Used in Electromagnetic Aircraft Launch System*" IEEE Transactions on Magnetics, Vol. 41, No. 1; January 2005.

[7] Dr Alan Ruddell "*Investigation on Storage Technologies for Intermittent Renewable Energies*" Project funded by the European Community under the 5th Framework Programme (1998 - 2002)

[8] R. Peña-Alzola, R. Sebastián, J.Quesada, and A.Colmenar,2011"*Review of Flywheel based Energy Storage Systems* Power Engineering, Energy and Electrical Drives,2011.IEEE

[9] T. Kominami, Y. Fujimoto, "*A Novel Nine-Switch Inverter for Independent Control of Two Three-Phase Loads*", Industry Applications Conference, pp. 2346-2350, 2007

[10] Mohammad Monfared , SaeedGolestan "*Control strategies for single-phase grid integration of small scale renewable energy sources:A review*" Renewable and Sustainable Energy Reviews 16 (2012) 4982–4993.