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A new flywheel energy storage system for distributed generation

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ABSTRACT

It is necessary to install flywheel energy storage (FES) system in distributed generation, which can improve the quality and the reliability of electric power. The proposed system is composed of four parts: flywheel, magnetic bearing, motor/generator, and power converter. A permanent magnet motor-generator is incorporated in a composite flywheel, running at high speed in a vacuum containment to minimize air friction losses. The flywheel is to be suspended on magnet bearings. A 3-phase, switch mode bridge inverter, driven by a pulse width modulation board, achieves the variable speed control for the motor/generator and the control for the DC bus voltage.

The presentation will explain the schematics of the flywheel battery, control diagram, power electronics and motor/generator. The overall operation will be described.

INTRODUCTION

It is particularly important in distributed generation not connected to the grid to develop sustainable power supplies coupled to environmentally friendly and sustainable energy storage, for example in rural electrification programs in developing countries. These storage technologies also have the potential to impact the sustainability of power systems in developed countries, particularly with the increasing interest in wind, solar and other advanced distributed sources. Other areas of application relate to transportation micro-grids in developing countries.

Economic power supplies to rural areas and border areas in China, often takes the form of photovoltaic cells connected to a lead-acid battery. The battery lifetime is about two years and efficiency is 60% or less. There are serious environmental problems associated with the use of lead acid batteries, particularly in the developing countries where the recycling infrastructure is minimal or nonexistent. The availability of high strength fibre composites, low cost rare earth magnets and microelectronics makes it possible to produce a durable, non-polluting, cost effective battery. These materials are readily available in China, including the magnetizers for the magnets and the machine tools for prototyping or production.

This paper presents the design and simulation of a solar energy generation plant with a flywheel energy storage unit. This generation plant is conceived to supply electric power to an isolated load not connected to the electrical network. A permanent magnet motor/generator is incorporated in a composite flywheel, running at high speed in a vacuum containment to minimize air friction losses. The flywheel is to be suspended axially on a permanent magnetic bearing and radially on an electrodynamic magnetic bearing. A composite flywheel requires a simple containment to sustain the vacuum for the moving parts, since most of the energy is dissipated in the fracture process in case of catastrophic failure. A rotor's design is used to maximize the inertia and energy storage capability. The rotation is around the vertical axis to minimize the required containment. A 3-phase, switch mode bridge inverter, driven by a pulse width modulation board, achieves the variable speed control for the flywheel and the control for the DC bus voltage. As the PV output reduces, the converter allows the PM machine to generate power back into the dc bus, using the freewheeling diodes of the inverter as an uncontrolled rectifier. A simple micro-controller is used to control the entire system.

SYSTEM DESCRIPTION

Fig.1 shows the main power conversion circuit of the proposed flywheel energy storage system for distributed generation. It consists of a photovoltaic (PV) array, a boost converter, two inverters, a PM motor/generator and a high-speed flywheel. According to the possible power flow conditions among these system components, there are 4 modes of operation as shown in Fig.2:

1. Mode 1: No energy is required by the load, and all energy generated by the PV array is stored in the flywheel.

2. Mode 2: The PV energy is greater than the load and the surplus is stored in the flywheel.
3. Mode 3: The PV energy is less than the load and the flywheel supplements the necessary energy to match the load.
4. Mode 4: No PV energy is generated and the flywheel supplies the load until fully discharged.

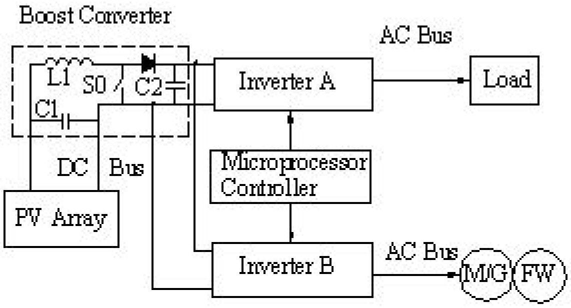


Fig.1 Configuration of main power conversion circuit.

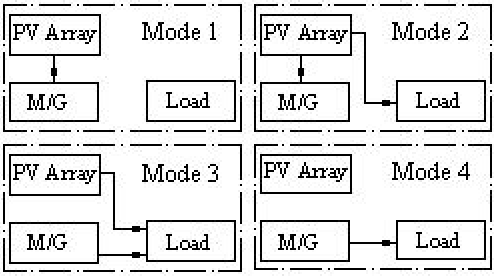


Fig.2 Modes of operation

PHOTOVOLTAIC CELL

One of the many ways to exploit the solar resource is through the photovoltaic (PV) effect. A PV cells is a device, in which electromagnetic energy, such as sunlight, produces an electrical current. PV stands for photo (light) and voltaic (electricity), whereby sunlight photons free electrons from common silicon. A PV cell is a large-area P-N junction forward bias with a photo-voltage and structure designed for efficient conversion of sunlight into electric current. The photo-voltage is created from the dissociation of electron hole pairs created by incident photons within the build-in field of the junction.

A P-N junction is commonly manufactured by diffusing boron onto one surface of an N-type silicon crystal. Electrons wander from the N-type to the P-type area until the N-type area acquired a localized positive charge and the P-type area acquires a localized negative charge. After equilibrium is established, there is a "barrier potential" which sweeps all local free electrons out of the "depletion region" region between the areas of localized charge. This P-N junction now behaves as though it had a built-in voltage; in silicon, this voltage is ~0.5V.

Electron hole pairs created anywhere other than in the depletion region will eventually recombine. However, when an illuminated P-N junction is placed in a circuit, photo-generated electrons and holes within the depletion region are sent in opposite directions by the barrier potential.

By connecting cells together in series and/or parallel, an array can be constructed which will yield a voltage and current appropriate to the load. The typical individual silicon solar cell has the potential of generating about half a volt, so 36 individual cells will produce about 18 volts. The immediate output of a PV array is, by its nature, direct current (DC). The size of the individual cell is what determines the amount of current of amps that a solar panel can produce.

FLYWHEEL ENERGY STPRAGE UNIT

Some loads that are powered by PV array only need to operate when the sun in shining, for example, certain cooling systems. However, energy storage is required whenever energy supply and demand are out of phase. The choice of storage method is affected by the duration of storage, the quantity and/ or density of energy to be stored, the form of energy needed for consumption, and the variation in the rate of consumption. The ideal energy storage scheme is highly efficient, non-polluting, easily sited, reliable, long-lived, easily and inexpensively maintained, and safe.

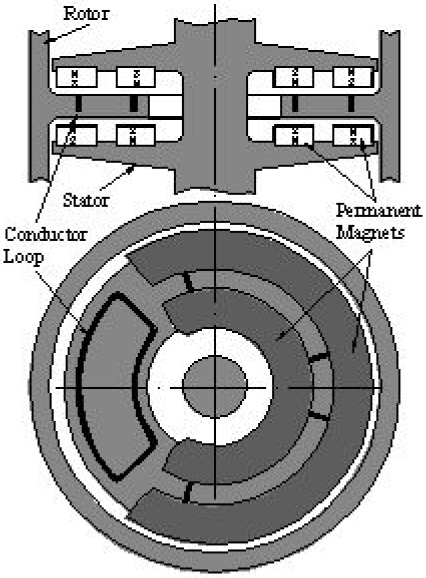


Fig.3 Flywheel energy storage unit

A rotating flywheel can accumulate and store mechanical energy in an inertial, kinetic form. A flywheel energy storage system consists of these components: a rotor complete with suspension system, a motor/generator system to couple energy to and from the rotor, and a containment enclosure. In contrast to conventional lead-acid batteries, it has these merits:

1. Much higher charging and discharging rate.
2. Able to cyclic discharged to zero energy without degrading whatsoever.
3. Durability comparable to that of the PV array, which means lower overall costs.

4. Fewer hazards to personnel and the environment, particularly at the time of disposal.
5. The storage capacity is independent of temperature fluctuations.
6. Much higher energy storage efficiencies.

Fig.3 shows a new-type of economical flywheel energy storage unit, the rotor of which is supported radially by the elctrodynamic magnetic bearing and axially by the permanent magnetic bearing (not shown in this figure). Without any active magnetic bearing, there is no need to employ any sensor to measure the rotor's position, and no need to use any control system to control the rotor's position. So, this system is most cost-effective and stable.

In order to understand the operational principle of the electrodynamic magnetic bearing [1], we first survey its schematic diagram in Figure 3, where three conductor loops are uniformly distributed on the rotor, magnetic field is arranged in axial direction, and the magnetic fields near the inner arc and the outer arc of the conductor loops are opposite. Whenever the rotor is shifted radially, there is a change of the magnetic flux through the conductor loops, so that the induced electromotive force in the loop is created. Because the conductor loops are close, the inductive electric current on the loops will be generated. As the electrifying object moves in a magnetic field, it will generate the electromagnetic force to prevent the rotor from moving away. It is judged from the disposal of magnetic field that, as long as the rotor's centre moves away from the distribution centre of the magnetic field, the electromagnetic force acting on the conductor loops will be generated, which compels the rotor to come back the scheduled position again.

Extractable flywheel energy is expressed as:

$$\Delta E = \frac{1}{2} \cdot J \cdot (\omega_{\max}^2 - \omega_{\min}^2) \tag{1}$$

where:

ΔE = extractable flywheel energy
J = flywheel moment of inertia
$\omega_{\max}$ = maximum flywheel operating speed
$\omega_{\min}$ = minimum flywheel operating speed

The formulation in (1) illustrates the advantage of high-speed flywheel operation. Since the extractable energy is proportion to the squire of the operating speed, low mass and high-speed units can be designed to provide high energy densities. Therefore, new composite material with high σ_B / γ parameter can greatly increase the speed of the flywheel, and accordingly the capacity of the flywheel energy storage system will increase. The optimal material for flywheel is carbon fibre, the linear velocity of which can exceed 1000m/s.

POWER REGULATION AND CONDITIONING

Regulator circuitry is required to cyclically bring the energy storage system on- and off-line to maintain a constant supply of energy available to the load. For example, if the PV array output dropped below a certain threshold, the PV would be disconnected from the load to be replaced by the flywheel battery, which would begin to decelerate and discharge. The generator output varies in amplitude and frequency as the flywheel decelerates; this 3-phase output can be converted into DC using the converter B in Fig.4, which shows the proposed motor/generator drive for flywheel energy storage. Likewise, if the PV output rose above a certain threshold, the flywheel battery would be disconnected from the load and would begin to accelerate and charge from a port of the array's output. The rate of charge would be controlled so as not to rob the load of its share of the power output of the array. Once the flywheel reached its design speed, it would not require any further charging due to its long rundown time-constant.

In many cases, the electrical output of the PV array/FES system requires further conditioning to meet the requirements of the load. For example, power conditioning must compensate for the fluctuations in the PV array output voltage that may occur with temperature. In addition, one needs to ensure that maximum power is being transferred to the load. A maximum power tracker (a boost converter shown in Fig.1) can be modeled as a "black box" which samples the output of the PV array and changes the apparent impedance of the load to obtain maximum power transfer. Naturally, systems that minimize power conditioning requirements (e.g. purely resistive loads), are the most efficient and cost-effective.

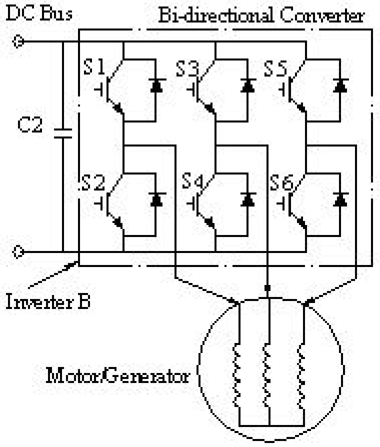


Fig.4 Proposed motor/generator drive

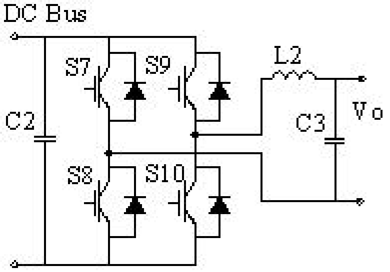


Fig.5 Single-phase inverter A

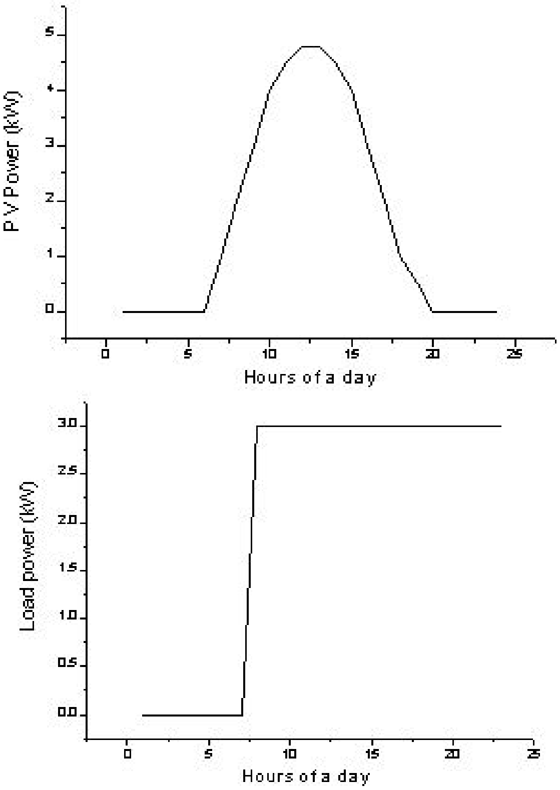
Because most civil loads are single-phase, the inverter A in Fig.1 adopts the configuration of the single-phase voltage regulator in Fig.5. The switches operate on a PWM pattern to shape both the input current and output voltage to follow the reference commands. The inductor L_2 and capacitor C_3 provide filter operation of the output voltage. The dc-link capacitor C_2 acts as a dc voltage source and provides filtering operation.

SYSTEM SIMULATION

A civil building in China is used to exemplify the proposed system. The corresponding computer simulation results are shown in Fig.6. It can be found that the PV power behaves like a half-cycle sinusoid, which neglects the real situation that the solar radiation varies with passing cloud or other environmental effects.

Making an assumption that the load power is a constant lighting load starting from 8 am. The permanent magnet motor/generator is the difference between the PV power and the load. When the load power is 3 kW, the PV power is insufficient to satisfy the load and the PM motor flywheel serves as a generator to supply the necessary power to match the load. When the PV array power continues to increase, the flywheel (or rotor) switches back to motoring to store kinetic energy. When the PV power drops below the load, the PV array and flywheel simultaneously supply power for the load.

With the proposed system, the PV array can satisfy the load from 8 am to beyond 9 pm, hence lengthening the lighting period.



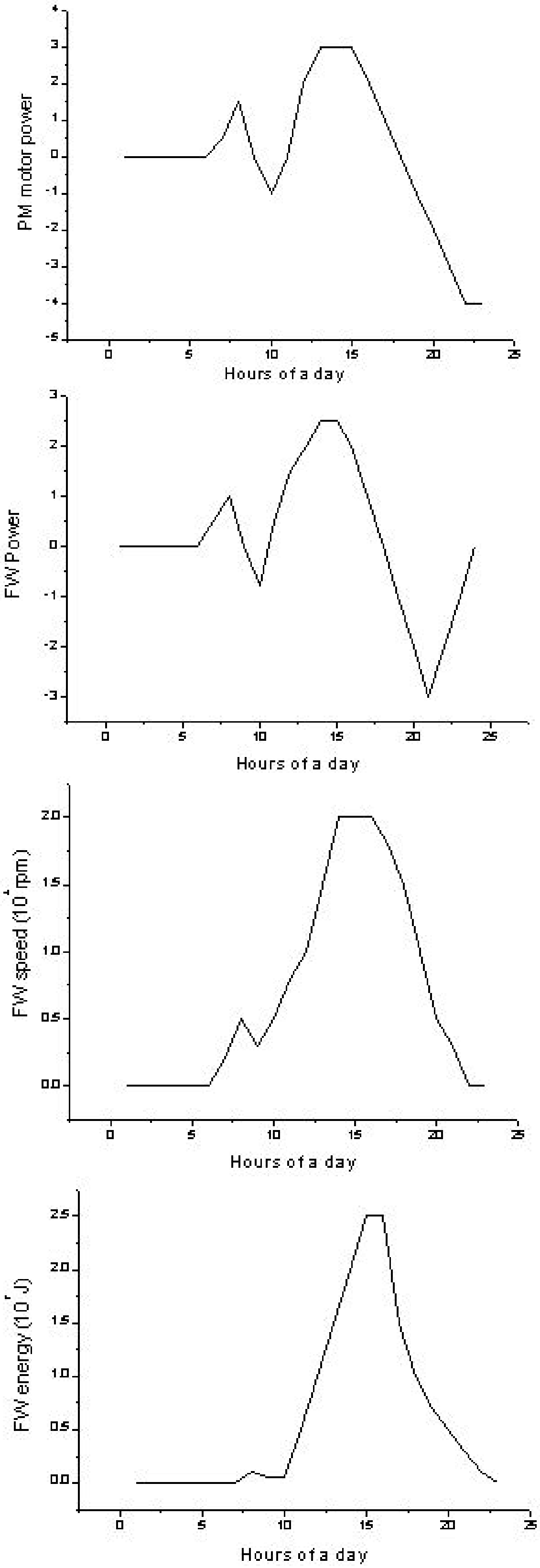


Fig.6 Computer simulation result

CONCLUSION

This paper has newly proposed the flywheel energy storage system for distributed PV generation, which keeps away from the use of those environmentally harmful batteries. The PV array makes the system flexible in power usage, so that all powers in the system can be utilized in a cost-effective manner. Simulation results have been provided to demonstrate the operation and effectiveness of the proposed system.

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