A Simple Flywheel Induction Motor for Large Power Short Time Compensation in Inverter-Driven Stand-Alone Power Systems

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1. Introduction

The shortage of worldwide conventional resources and the necessity to reduce the environmental impact add bigger significance to distributed energy resources. For the DC distributed generation systems, such as fuel cell or photovoltaic systems, inverters are necessary to convert the direct current to alternating current at required voltage and frequency. Inverter control also contributes a reliable power quality as well as efficient utilization. However, the short-time overload capacity of the DC generation systems is limited by the current carrying capacity of the inverters and the stored energy of DC link capacitors, thus blocks their application in supplying highly fluctuating load or results low utilization efficiency [1]. For example, it is reported by the EXPO.2005 that even the transformer magnetizing inrush current might trip the fuel cell inverters [2].

To solve the above problems, energy storage system is usually used for balancing the supply and demand. However, the general energy storage devices, such as EDLC, NaS batteries, are equipped with power electronic device as interface to the AC load. Therefore, large capacity of semiconductors is required for large power compensation. Getting rid of the semiconductor’s limitations, a simple flywheel induction motor composed by connecting a flywheel disk to a general squirrel cage induction motor is proposed for large power short time compensation in the inverter-driven stand-alone power systems [3]. Compared to other energy storage systems, flywheel energy storage is superior in large power short time application due to its high power density [4]. Furthermore, the overload capability of the induction motor, which is generally 2~3 times of its rated capacity, is also focused for the application in this paper.

Based on the above considerations, this paper presents the proposed flywheel induction motor for improving the short-time overload capacity of the inverter-driven stand-alone power supply. For the highly fluctuating load or inrush current load, the flywheel induction motor is expected to supply with large power in short time, thus reduce the overload pressure on the power-side inverter or stand-alone power supply. The main contains are as follows: 1) the characteristics of the flywheel induction motor as well as the proposed system operation are described in Section 2. 2) In section 3, validation experiments are performed on step resistive load and motor direct starting respectively. The experimental results are presented to prove the effectiveness and validity of the proposed system. 3) In section 4, on basis of comparisons with other solutions, some conclusions are drawn in the final.

2 System descriptions

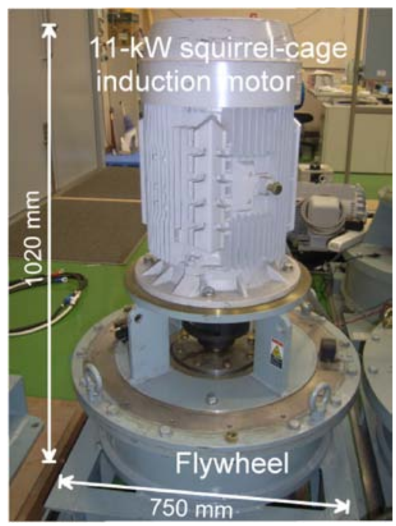
2.1 The flywheel induction motor

The proposed flywheel induction motor has a simple configuration. It is composed of a rotating iron disk and a general-purpose squirrel cage induction motor: 1) the iron disk is used for storing energy by rotating, the quantity of its stored energy is proportional to the square of the rotating velocity; 2) the induction motor is used as the power interface by converting the energy between rotating energy and electric energy. Therefore, the flywheel induction motor has the following characteristics:

a) Low construction cost; the iron disk has a price of 1 dollar per kg and the general-purpose squirrel cage induction motor is about 70 dollars per kW at the market.
b) Reduced idling loss due to the low speed; the mechanical loss consists of windage loss and bearing loss. The windage loss is proportional to the third power of the rotating velocity and the bearing loss is proportional to the rotating velocity. In the case of the prototype device for the validation experiment, an 11-kW 2-poles induction motor is used. Its specifications are shown in Table 1. When supplying with AC electricity with 50 Hz, it idling loss is about 600W, 5.4% of its rating. Furthermore, the idling loss can be decreased by optimizing the flywheel capacity according to the particular application.
c) Direct connection to the load; Due to the AC generation, the flywheel induction motor can be connected to the AC load without semiconductor interface. This configuration brings in advantages such as maintenance-free, robust as well as less numbers of devices. Furthermore, automatic load sharing can be realized when connecting the flywheel induction motor units in parallel in order to get large compensation capacity.

Table 1: Specifications of the proposed flywheel induction motor

Flywheel	
Mass	208 kg
Dimensions	D=500 mm, H=135 mm
The moment of inertia	6.73 kgm^2
The Stored energy	331 kJ at idling speed of 3000 rpm
Induction Motor	
Rated power	11 kW
Rated voltage	200 V
Rated current	40.2 A
Rated frequency	50 Hz
Poles	2



2.2 System operation and control strategy

The system configurations are shown in Fig. 1. The flywheel induction motor is connected to the stand-alone power supply directly, in parallel to the fluctuating load. Shunt capacitors are installed in order to improve the power factor of the induction motor. Before applying a heavy load, the flywheel induction motor is started up by performing either constant V/F control or constant power control on the inverter of the stand-alone power supply. Energy is stored in the rotating flywheel beforehand in order to protect an overload trip for the stand-alone power supply in case of the load fluctuating.

The power in/out of the flywheel induction motor is realized by controlling the generated frequency of the inverter on the stand-alone power supply's side. The flywheel's rotating speed always follows the induction motor's synchronous frequency. Therefore, by controlling the inverter's generated frequency increase/decrease, the flywheel's rotating speed as well as its stored energy changes in the same way, realizing power charge/discharge. With a limited output current of the power-side inverter as the control target, the following control method as shown in Fig.2 is developed: the inverter current i_u, i_w and the inverter's generated voltage v_{uv}, v_{wv} are detected and transferred to the frequency controller. According to the inverter current RMS and the power flow direction, the frequency controller will signal an output frequency command to the power-side inverter. The diagram for the frequency controller is composed of current feedback loop and reverse power detection, as shown in Fig.3. First, the power flow direction is judged by calculating the generated power of the power side inverter p_{inv}. 1) A reverse power flowing into the inverter side (p_{inv}<0) might be caused by power over-compensate from the flywheel induction motor. In that case, the frequency command will be given by applying proportional control (K) on the active power $|p_{inv}|$ in order to prevent this reverse power quickly and effectively. 2) Under normal power flow conditions (p_{inv}>0), PI control is applied on the inverter current i_{rms} in order to limit the inverter current below its threshold value.

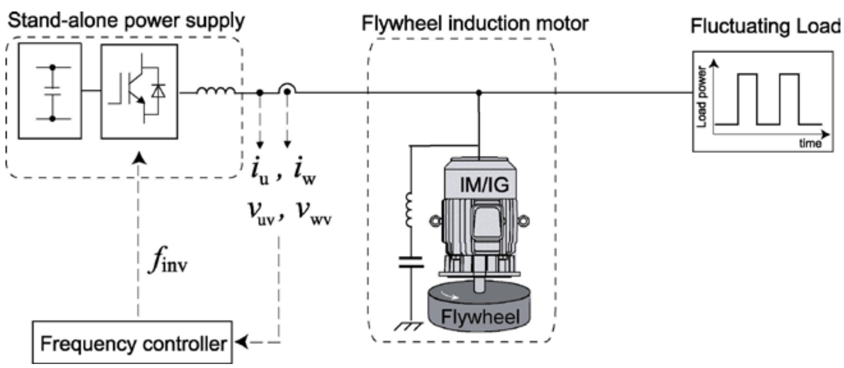


Fig.2 System configuration by using the proposed flywheel induction motor

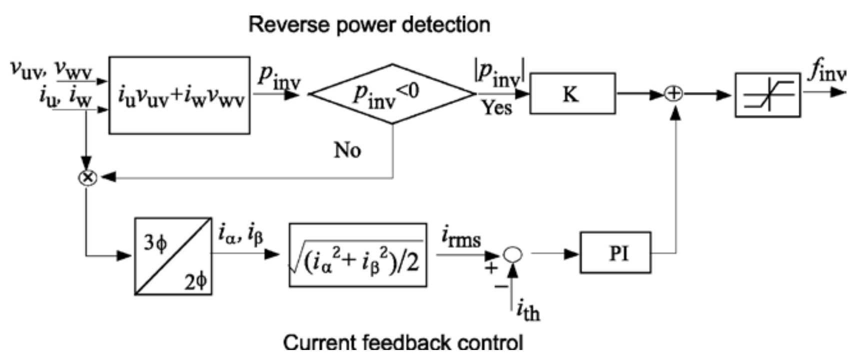


Fig.3 The diagram for the frequency controller

3 Experimental verifications

Experiments are executed to prove the proposed system to be effective for the short time high power load. First, the effect of the proposed system on step changing resistive load is discussed. This load pattern is common in mechanical factories such as metal processing, robot operation, lift, etc. Furthermore, since many power factor improve technologies are developed, there are lots of loads can be idealized as time changing resistive load. Then, the application of the proposed system in direct starting up motor load is studied by experiment. A broad application for induction motor is ranging from industry application to house electric appliances. The proposed system is expected to improve the inrush current problems caused by motor direct starting.

3.1 Validation experiment on step changing resistive load

1) Experimental conditions:

Stand-alone power supply's capacity: 2.4 kVA;

Step changing resistive load: 1.1 kW $\Rightarrow$ 6.6 kW (1 sec) $\Rightarrow$ 1.1 kW;

Inverter's output line voltage: 200 V;

2) Control target:

Inverter's current i_{th}: $2.4\times10^3/200/\sqrt{3}\approx 7$ A;

3) Experimental results:

The charge/discharge of the flywheel induction motor is performed to achieve the control target by using the above frequency control method. Following, the swing of the flywheel's speed must produce frequency variation. Therefore, both the power flow of the system and the generated frequency are detected to study the feasibility of the proposed system. The experimental results are shown in Fig.4.

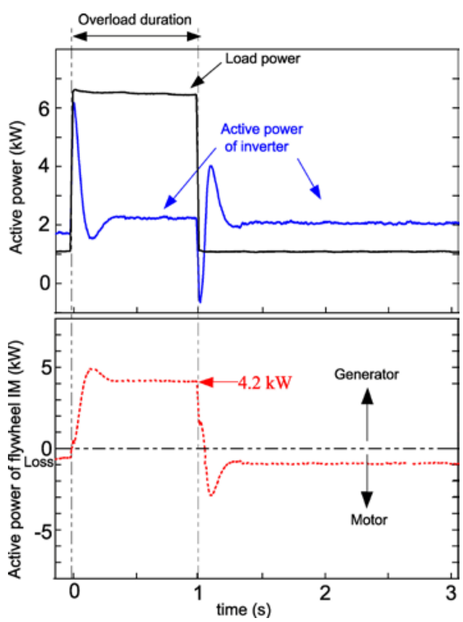


Fig.4 (a) Power flow of the system

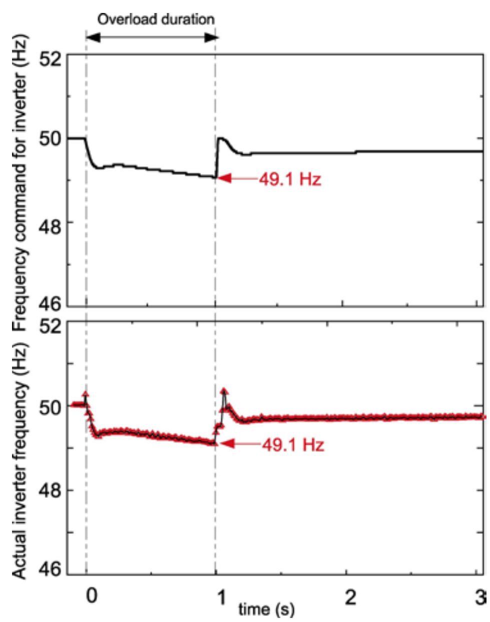


Fig.4 (b) Inverter's output frequency

As one can see from Fig.4, the control target, inverter current i_{inv} is limited to the threshold value, 7A. As a result, the inverter supplies 2.4 kW to the load when there is a peak load power of 6.6 kW. The other 4.2-kW load is provided by the flywheel induction motor. After the overload, the inverter current is controlled to maintain at 7 A while the flywheel induction motor is charged again to full energy state. As for the inverter's output frequency, it shows about 2% of variations, from 50 Hz to 49.1 Hz. It proves that the proposed system improves the overload capability of the stand-alone power system at a cost of frequency variation. However, a little frequency variation is allowed for most kinds of load. A further calculation shows that the 11-kW, 2-pole flywheel induction motor with an inertial moment of 6.73 kgm^2 can compensate an active power of 11 kW for 4.2 s with the frequency change less than 10%.

3.2 Validation experiment on motor starting

As for starting a motor load, not only active power but also reactive power should be taken into account. Magnetization of the motor windings requires reactive current, the quantity of which is determined by the transient impedance of the particular motor. On the other hand, the active power requirement composes of winding loss and torque demand, which differs by the motor type and capacity class of the motor. Generally, the starting current is almost 4 ~7 times of its rated current. It might trip the power side inverter, resulting the other loads which are connected in the same power line be powered off. The proposed flywheel induction motor provides a solution for this problem by injecting both active and reactive current to the motor load.

1) Experimental conditions:

Stand-alone power supply's capacity: 5.2 kVA;

Motor load for direct starting: 1.5 kW (rated), starting power of 9 kVA with power factor of 0.8;

2) Control strategy:

Some improvements are made to the above frequency control strategy in order to provide both active power and reactive power compensation by the proposed flywheel system. The control mechanism is as follows: 1) Active power compensation, as described in above. 2) Reactive power compensation: as well known, the motor starting current will produce a voltage drop on the inductive power lines. The flywheel induction motor will respond to this voltage drop by injecting reactive current to the load because of the trapped leakage flux. Therefore, an active voltage drop at the time of motor starting can get the flywheel system provide reactive power compensation, which will then prevent the stand-alone power supply from overload trip.

3) Experimental results:

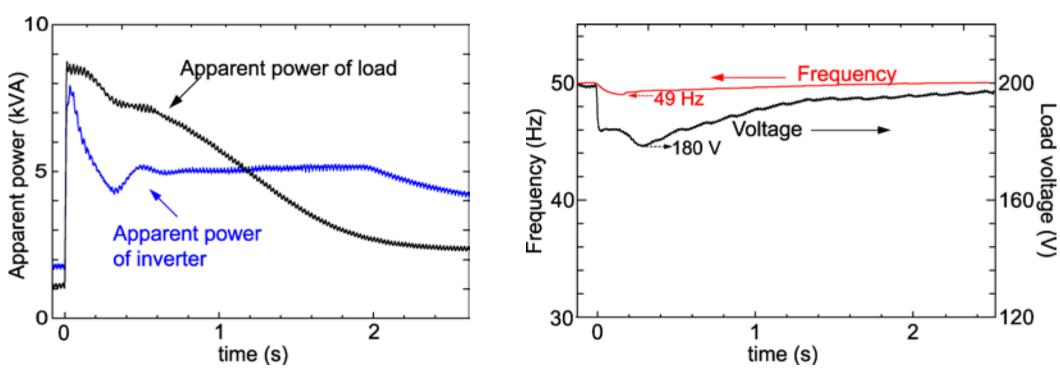


Fig.5 Experimental results on starting a motor load

As shown in Fig.5, the inverter power is limited below its capacity threshold, 5.2 kVA for direct starting the 1.5-kW motor load. The frequency variation and voltage drop are 2% and 10% respectively. The power flow of the flywheel system is shown in Fig.6. The proposed system proves to be effective to lessen the current pressure on the stand-alone power supply when used for motor load direct starting.

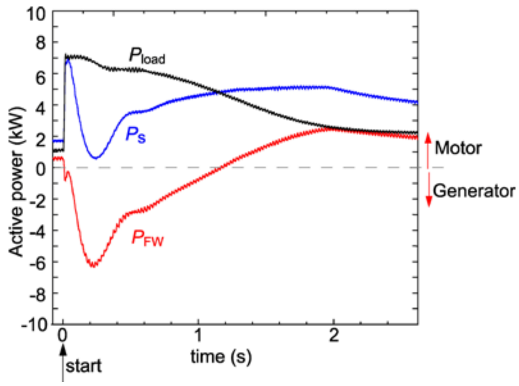


Fig. 6 (a) Active power flow

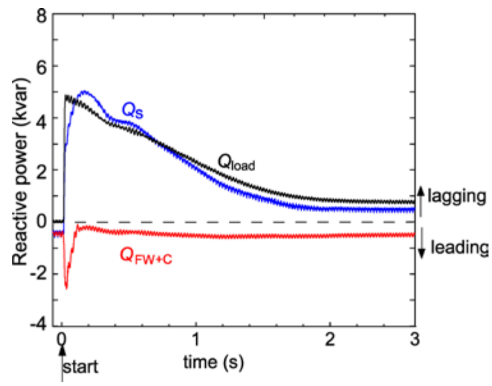


Fig.6 (b) Reactive power flow

4 Conclusions

A flywheel induction motor is proposed for large power short time compensation in inverter-driven stand-alone power system. Validation experiment on step changing resistive load and direct motor load starting have proven the feasibility and validity of the proposed method. Comparisons to some other energy storage technologies are carried out for the proposed flywheel induction motor, as described in follows.

1) Complexity; Power converter-less is a big advantage of the proposed flywheel induction motor, which also brings in simple control and less components number.
2) Performance; It includes the following aspects: active /reactive power controllability, frequency variation as well as overload capability. The proposed method shows a good overload capability because of the direct connection of the induction motor. However, its application for frequency sensitive case would be limited.
3) Cost and environmental effect; The proposed method has advantages in long life time and no need for waste disposal. Also, both the construction cost and operation cost (idling loss) can be reduced by a proper capacity design for the proposed flywheel induction motor.

Above all, the proposed system is characterized with simple configuration and simple control at the cost of frequency variation. It is a good solution for improving short time overload capacity of stand-alone power systems.

Reference

[1] D.Audring and G.Balzer. “Operating stationary fuel cells on power system and micro grids”. Bologna Power Tech Conference, June 23-26, Bologna, Italy.

[2] Kawakami, N. Sumita, J. Nishioka, K. Noro, Y. Shinohara, H. Ito, Y. Yabuki, M. “ Study of a Control Method of Fuel Cell Inverters Connected in Parallel and Verification Test Result of an Isolated Micro Grid.” PCC’07, Nagoya, pp.471-476. 2-5 April 2007.

[3] M. Cheng, S. Kato, H. Sumitani and R. Shimada. “ A Novel Method for Improving the Overload Capability of Stand-alone Power Generating Systems Based on a Flywheel Induction Motor.” PESC08, 39th IEEE Annual Power Electronics Specialists Conference, 15-19 June 2008, Rhodes, Greece.

[4] Darrelmann, H. “Alternative power storages.” The Second International Telecommunications Energy Special Conference, Telescon'97, pp.33-40(1997-4).