Simple Flywheel Energy Storage using Squirrel-Cage Induction Machine for DC Bus Microgrid Systems

Jae-Do Park
Dept. of Electrical Engineering
University of Colorado Denver
Denver, CO
Email: jaedo.park@ucdenver.edu

Abstract—A simple flywheel energy storage using a squirrel-cage induction machine is proposed in this paper. The suggested motor/generator system operates with an open-loop Volt/Hertz control scheme and utilizes only the nameplate data as machine parameters. Therefore complex controller tuning or machine parameter measurement is not required. Also, any communication between storage units or with other controllers is not necessary because the system uses bus voltage information for charge/discharge operations. The proposed system has an advantage on parallel operation because adding/replacing of units are straightforward. Hence it can easily operate with different types of storage or distributed energy sources in DC bus microgrid systems. Moreover, the proposed control scheme improves the overall stability of the DC bus system. The proposed system has been validated with Matlab simulation and an experimental setup is under construction for verification.

I. INTRODUCTION

Distributed generation systems have recently been intensively researched and developed, especially in conjunction with renewable energy sources such as wind turbines and photovoltaic systems. The advantages of distributed generation systems include the capacity relief of transmission and distribution, better operational and economical efficiency including effective use of waste heat, and improvement of reliability, eco-friendliness and power quality [1]–[3]. Considering the current energy situation and the energy policy of governments worldwide, the penetration of distributed generation using the renewable energy sources is expected to increase rapidly.

As a way to realize the distributed generation system, a "microgrid" system that combines distributed energy sources and loads as a small-scale power system can be used. The microgrid approach reduces or eliminates central dispatch and enhances the power quality to sensitive loads [4], [5]. A microgrid is controlled and operated quite differently than a conventional power systems: the distributed energy sources are connected through power electronics converters and the islanded operation is required as well as grid-connected operation [6].

Various kinds of dispatchable and non-dispatchable prime movers can be included in a microgrid system, such as diesel generators, microturbines, fuel cells, wind turbines and photovoltaics, to support different types of loads. Distributed energy storage systems including batteries, flywheels and supercapacitors are also included. The energy storage capability is important for microgrid operations because the stored energy can be utilized for different purposes such as load support, frequency control, power compensation, and voltage leveling. This is especially true for systems using a high portion of sustainable energy sources; for example, for a microgrid system that is operating in a remote area isolated from a power grid, storage devices play a critical role because of the intermittent and uncontrollable nature of the renewable energy sources.

A flywheel energy storage system using a squirrel-cage induction machine is proposed in this paper. The proposed system utilizes the squirrel-cage induction machine, which is widely available and inexpensive, and the simple Volt/Hertz control technique with just nameplate data as machine parameters. Therefore no complex parameter measurement is necessary and the system has an advantage on parallel operation because adding/replacing units are straightforward. Hence it...
can easily operate with different types of storage or distributed energy sources in DC bus microgrid systems. Moreover, the proposed control scheme improves the overall stability of the DC bus system. The proposed system has been validated with Matlab simulation and an experimental setup is under construction for verification.

II. SYSTEM CONFIGURATION

A. DC Bus Microgrid System

Among the microgrids that have been researched recently, low-voltage DC (LVDC) bus-based systems have received attention because of advantages such as fast control without need for communication, a variety of DC energy sources and loads, and efficiencies on system size and cost [7], [8]. A block diagram of a typical DC bus microgrid system is shown in Fig. 1.

The LVDC systems utilize the voltage droop technique, which uses the DC bus voltage as a command signal. DC bus systems do not have the functional issues of AC systems such as synchronization and reactive power compensation. Unlike the large scale distribution systems, the LVDC microgrid system does not have a resistive loss issue because the length of the bus is much shorter. Also, sharing a DC bus has a structural advantage because all the energy sources and loads are connected via DC/DC or DC/AC voltage-source converters that utilize DC voltage as their medium. Another layer of DC/AC converters is necessary for some subsystems to make an AC bus system.

Using the fast-acting power electronics converters, constant voltage can be supplied to the loads regardless of some fluctuations on the bus side and the renewable energy sources can readily generate maximum power with maximum power point tracking (MPPT) techniques.

As a small-scale power system, a microgrid can have relatively higher load fluctuations, especially when it is not operating in grid-connected mode. This is because the inertia of the generators is not as large as that found in the large-scale synchronous generators. Generation of power from the renewable energy sources relies heavily on natural conditions and they are intermittent. Hence energy storage devices are required for stable operation of a microgrid system in either grid-connected or islanded operations. A flywheel-based energy storage system is investigated in this paper.

B. Flywheel Energy Storage

Advances in power electronics, magnetic bearings and flywheel materials have made flywheel systems a viable energy storage option. Although it has higher initial cost than batteries, flywheel energy storage has advantages such as longer lifetime, lower operation and maintenance costs, and higher power density than several seconds [9] and storage devices needed to store the intermittent generation of renewable energy sources do not necessarily have to be fast if they are not focusing on transient performance improvement. Considering the overall cost, it would be more efficient for a microgrid system to use a combination of faster storage devices for short transient and slower but inexpensive storage units for massive energy charge and discharge with renewable energy sources such as wind turbines and photovoltaic systems.

To develop a cost-effective system, a squirrel-cage induction machine is selected for the motor/generator of the flywheel energy storage in this paper. Easy parallel operation is an important factor in energy storage for higher capacity.

C. Squirrel-Cage Induction Machine

1) Machine Modeling: A per-phase equivalent circuit of an induction machine is shown in Fig. 2. Machine torque can be derived as can be seen (1)-(4). The expressions can be applied to the integral horsepower induction machines where the speed is high enough for the resistive drop to negligible.

\[
\begin{align*}
  i_2 & = \frac{e_m}{jX_2 + \frac{R_2}{s}} = \frac{e_m}{\omega_c} \frac{s\omega_c}{jX_2 + \frac{R_2}{s}}.
\end{align*}
\]
where, $P_m$ is machine power, $P$ is machine poles, $s$ is slip, $\lambda_m$ is air-gap flux, $\omega_e$ is primary angular speed and $\omega_{sl}$ is slip angular speed.

As shown in (4), induction machine torque can be controlled with the slip frequency if air-gap flux $\lambda_m$ is kept constant, which can be accomplished by constant voltage and frequency ratio
\[ e_m \omega_e \approx \frac{v_1}{\omega_e}. \]
Although there are conditions such as machine’s power rating and speed to make the expressions valid, operating conditions of a flywheel energy storage system well satisfy the conditions.

2) Volt/Hertz Control: Volt/Hertz control has been widely used for induction machine speed control because of its simplicity for the applications that tight torque response for transient dynamics is not required. Field-oriented vector control technique has been utilized for the applications that need fast response, but it requires parameter measurements, current feedback, machine model and controller tuning. On the contrary, all of the information necessary to run an induction machine in rated condition, such as voltage, speed and slip, can be found on the nameplate of the machine for Volt/Hertz control.

Many researches on flywheel energy storage systems have utilized field-oriented controllers because the applications need quite fast energy flow, for example, UPS application compensating the voltage dip. However, if an energy storage system absorbs or releases the energy in slow dynamics, Volt/Hertz control can be a valid candidate due to its simplicity and inherent stability.

### III. CONTROL TECHNIQUE

#### A. Microgrid System Operation

The proposed microgrid system shown in Fig. 1 utilizes the DC bus voltage as a control signal. Hence, a prime mover, such as a grid-connected converter or microturbine unit, does not control the voltage tightly at a fixed reference voltage to reflect the energy flow on the bus voltage if it is in the nominal operating region above the minimum threshold.

All of the renewable energy source units are operating in the power mode, which is generating its maximum power when the energy is available. Hence the bus voltage will rise above the nominal operating range if the generation is larger than the load power consumption. The storage devices detect the excessive energy in the bus and absorb it. If the generated energy is large enough to exceed the maximum threshold, the grid-connected converter can push it back to the grid.

When the DC bus voltage gets lower than the discharge threshold due to the increased load or decreased generation, the energy stored in the storage units are discharged to the bus to maintain the bus voltage at the minimum level. If all the energy storages and generators are not able to hold the bus voltage at the minimum level, load shedding can be initiated by disconnecting some of the power electronic converters supporting lower priority loads. If there are different kinds of storage or load control units connected to the bus, the priority can be easily controlled by setting the thresholds differently. The units in the microgrid are autonomously operating using the bus voltage without communicating between units or to a central controller; hence addition, replacement or removal of the units can be done easily without any major change in the control configuration unlike the centrally controlled system.

#### B. Control of Flywheel Energy Storage System

The control block diagram of the proposed flywheel drive system is shown in Fig. 3. The controller is consisted of three parts, i.e. mode control, slip control and voltage control, to generate the proper voltage and frequency for the flywheel induction motor/generator. The low-pass filter filters out the high frequency voltage fluctuations.
The mode control determines the operating mode based on the bus voltage. The operating modes of the proposed flywheel energy storage system are as follows and the state machine of the mode control can be seen in Fig. 4. Each mode has associated voltage levels pre-defined in the mode control, as shown in Fig. 5.

- **IDLE**
- **CHARGE READY**
- **CHARGE**
- **DISCHARGE READY**
- **DISCHARGE**

The system is in IDLE mode when the bus voltage is in nominal range between mode thresholds for CHARGE READY and DISCHARGE READY. In IDLE mode, PWM is disabled and grid-tied converter or microturbine generator forms the grid depending on the operation mode, i.e. grid-connected or islanded mode.

When the bus voltage is increased above \( V_{chgR} \), the threshold of CHARGE READY mode, the voltage control starts to increase the voltage in order to build rated flux while maintaining zero slip. The rated flux will be built in the induction machine when the bus voltage reaches \( V_{chg} \),

\[
v^*_m = \frac{V_{rated}}{F_{rated}} \cdot \frac{v_{dc} - V_{chgR}}{V_{chg} - V_{chgR}} \cdot f_m
\]  

(5)

where \( v^*_m, f_m, V_{rated} \) and \( F_{rated} \) denote the machine stator voltage command, rotating frequency, rated stator voltage and rated frequency, respectively. If the operating speed is above the rated speed, \( V_{rated} \) needs to be reduced to operate in field weakening mode.

The machine voltage reaches the proper level for the rated flux according to the rotating speed when the bus voltage gets to the charge threshold and the machine is ready to absorb the power from the bus. In CHARGE mode, the slip control increases the slip based on the excessive voltage above \( V_{chg} \),

\[
f_{slip} = \left( K_{PS} + \frac{K_{IS}}{S} \right) \cdot (v_{dc} - V_{chg})
\]

(6)

\[
f^*_m = f_m + f_{slip}
\]

(7)

\[
\theta_e = \int 2\pi f^*_m dt
\]

(8)

where \( f^*_m, K_{PS}, K_{IS} \) denote the frequency command, proportional and integral slip control gain, respectively. Basically the slip control resets the slip to zero if the voltage decreases below the CHARGE threshold \( V_{chg} \). However, a hysteresis needs to be implemented between modes for smooth mode transition.

The voltage control receives the calculated slip frequency \( f_{slip} \) and machine rotating frequency \( f_m \) and generates appropriate voltage based on the rated Volt/Hertz ratio to maintain the rated flux in the machine so that the torque can be controlled just by slip. The direct and quadrature voltages in stationary reference frame and three-phase voltage commands can be generated as follows using \( v^*_m \) and angle information. Superscript ‘s’ denotes stationary reference frame.

\[
v^s_d = v^*_m \cos \theta_e
\]

(9)

\[
v^s_q = v^*_m \sin \theta_e
\]

(10)

\[
v^s_s = v^*_s
\]

(11)

\[
v_{ds} = -\frac{1}{2} v^s_d + \frac{\sqrt{3}}{2} v^s_q
\]

(12)

\[
v_{cs} = -\frac{1}{2} v^s_d - \frac{\sqrt{3}}{2} v^s_q
\]

(13)
Similarly, in DISCHARGE_READY mode, slip is kept at zero, and the voltage command will be given as

$$V_m^* = \frac{V_{\text{rated}}}{F_{\text{rated}}} \cdot \frac{V_{dc} - V_{\text{disR}}}{V_{\text{disR}} - V_{\text{dis}}} \cdot f_m.$$  (14)

And slip frequency is calculated as follows in DISCHARGE mode.

$$f_{\text{slip}} = \left( K_{PS} + \frac{K_{IS}}{S} \right) \cdot (V_{dc} - V_{\text{dis}}).$$  (15)

Although a speed sensor is assumed in the proposed system, a speed estimation technique is readily applicable, especially if the speed is changing slowly due to the large inertia.

All the control variables such as, $V_{\text{rated}}$, $F_{\text{rated}}$, rated slip and slip limiter can be obtained or calculated from induction machine nameplate. The service factor of the machine can be used to determine the slip limiter so that the machine can be operating safely in overload range.

Energy storage system’s input and output impedance can be controlled by the gains and limiter in slip control because the slip determines the power the system takes or releases.

C. Stability Consideration

It is well known that DC power distribution systems can have stability issues due to the negative impedance of the connected converters, even if the individual subsystems are stable [17], [18]. The input impedance of the converter can be expressed as follows, where $\Delta$ denotes the deviation from the steady state operating point values. The input impedance of the converters becomes negative when they are operating in constant power mode.

$$Z_i = \frac{\Delta V_{dc}}{\Delta i_{dc}} = \frac{(v_{dc})^2}{P_o}.$$  (16)

The power electronics converters can tightly control their output power as almost constant, and the negative impedance...
affects the DC bus stability adversely. It has also been suggested that the output impedances of the sources \( Z_o \) should be smaller than input impedance of the loads \( Z_i \) for the overall stability of the DC bus [19].

\[ |Z_o| << |Z_i| \]  

(17)

Although this is not a direct issue for the proposed energy storage system because it does not operate in constant power mode, its effect on overall system stability needs to be considered. The proposed system controls the power with the slip and constant Volt/Hertz ratio, which keeps the torque proportional to the slip. When the flywheel energy storage system charges the energy from the bus, slip is proportional to the bus voltage. Hence, the power that storage system takes from the bus is proportional to the bus voltage and the impedance of the system is always positive. On the other hand, the slip is inversely proportional to the change of the bus voltage which lowers the overall source impedance because the DC current the storage system discharges increases as the bus voltage decreases. Therefore, the energy storage system can improve the overall stability of the system in either operating mode.

IV. SIMULATION RESULT

The proposed flywheel energy storage system has been simulated with Matlab. A 50Hp induction machine as the rotor/generator and a flywheel with 23.5 \( \text{kgm}^2 \) moment of inertia has been utilized. The simulated system can store 2220 \( \text{kJ} \) at 4150 \( \text{rpm} \) and supply rated power for 1 minute. The parameters for the system simulation are shown in Table I and II.

The 20 kW and 30 kW of load increase and renewable generation is simulated at 0.1 sec, 2 sec, 5 sec and 7 sec, respectively. As voltage decreases below \( V_{disR} \), the machine voltage increases to build up the flux then slip decreases to generate power. Likewise, when the bus voltage increases over \( V_{chgR} \) and \( V_{chg} \), machine voltage and the slip increase.

As can be seen in Fig. 6, the bus voltage is maintained at \( V_{dis} \) and the load current is compensated in DISCHARGE mode and the flywheel storage takes the energy generated by renewable energy sources in CHARGE mode. The output of the voltage control and slip control is shown in Fig. 7. The machine torque and the variation of the flywheel speed show the energy exchange in Fig. 8.

V. CONCLUSION

A Volt/Hertz control-based flywheel energy storage using a squirrel-cage induction machine has been suggested in this paper. The proposed energy storage system is simple and cost-effective. It has utilized only the nameplate data as machine parameters and does not require complex measurements and tuning. The charge/discharge operation that is based only on bus voltage information without any communication between storage units or with other controllers has an advantage of parallel operation and makes adding/replacing units straightforward. The proposed system has been validated with Matlab simulation and an experimental setup is under construction for verification.

REFERENCES