Flywheel Energy Storage Emulation Using Reconfigurable Hardware Test-bed of Power Converters

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***Abstract* — The intermittent and unpredictable changes of power system load requires flexible generation of electricity that can rapidly adjust its output power to keep up with the fluctuations. However, many generators do not have this capability. Another option is to install utility scale energy storage. In order to evaluate the dynamics and benefits of a flywheel installation in a two-area system, a power converter based hardware test-bed platform realizing the emulation is established and tested.**

Keywords: flywheel, energy storage system, hardware test-bed, power system scenario emulation

I. Introduction

A power electronic converter can be controlled to emulate various kinds of dynamics in flexible ways. By manipulating the references given to the hardware controllers, converters are able to mimic different behaviors [1-3].

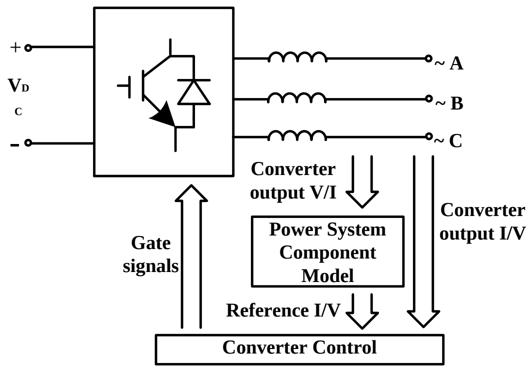


Figure 1. Power converter emulator structure.

Mathematical models of power system components such as a synchronous generator [5], load, induction motor [7], transmission lines, renewables (such as wind turbine and solar panels [6]) could be established using equations, whose transient behaviors are much slower than that of power electronics converters. The energy storage system, for example, usually has the time scale of seconds, minutes or even hours, while that of converters is typically milliseconds..

The structure of a proposed power converter emulator is presented in Fig. 1. By flexibly programming power system component electrical relations inside a controller, current/voltage command representing dynamics of a mathematical model could be calculated as references for the converter to track. Then, the power converter could behave exactly as designed, and by combining different kinds of emulators together, various scenarios of simulations could be initiated and studied [4].

The architecture of a power electronics emulator cluster unit representing a single power system area is shown in Fig. 2. The illustrated structure includes interconnected conventional generator emulator, load emulator in ZIP model and energy storage system emulator. The three phase side works as an emulated grid with desired power system dynamics while the DC bus allows the energy to circulate without being dissipated, which is especially beneficial for high power applications.

Larger emulated power system involving multiple areas could be formed by connecting a number of basic one-area units together.

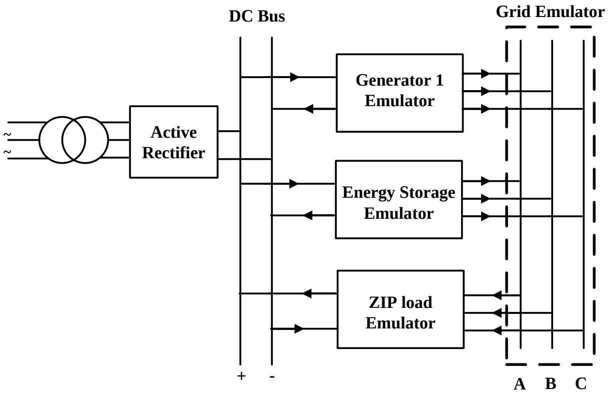


Figure 2. Single power system area emulator structure.

II. Flywheel Model

Its basic principle is to transform the surplus electricity generated into mechanical form with controlled motor and store the energy in large-inertia high-speed spinning kinetic device. The response time for 'discharging' the energy is impressively short, which is usually within seconds.

The structure of a single flywheel installation is illustrated in Fig. 3. The motor drive, consisting of a

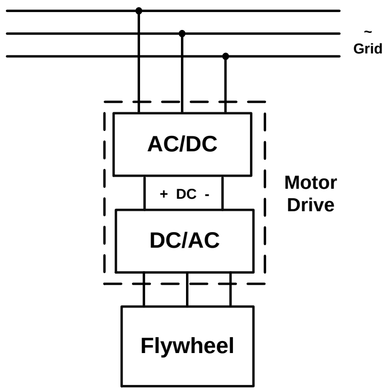


Figure 3. Flywheel energy storage structure.

back to back converter, determines the working modes for the flywheel as well as precise control of its speed, acceleration, and deceleration.

A flywheel system usually works in three modes: acceleration, deceleration, and standby.

Acceleration mode is triggered by surplus generation on the grid, when the generator provides more power than that's needed by the load. During the acceleration mode, the flywheel's speed increases, absorbing power from the grid.

The mathematical model related with the acceleration state is shown below where J means inertia, T_{st} means the starting up torque and P_{st} means the starting up power. Assuming ideal motor drive control and management, the rotating speed is designed to be charged with constant torque under 0.8 pu and constant power from 0.8 pu to 1 pu [13].

$$\omega = \begin{cases} \frac{1}{J}\int T_{st}\, dt & 0 < \omega < 0.8\, pu \\ \frac{1}{J}\int \frac{P_{st}}{\omega} dt & 0.8\, pu < \omega < 1\, pu \end{cases}$$

The flywheel, as one of the most widely installed energy storage methods, has played a crucial part in stabilizing and leveling daily load peaks and valleys [8-10].

Deceleration mode is the condition in which the flywheel's speed decreases, and it supplies power back to the grid. This mode is usually triggered by higher load demand during which generation together with flywheel system feed the load. In this model, it is assumed that the power needed by the load would be supplied instantaneously with full capacity.

Standby mode occurs when the generation and load are balanced or when the flywheel reaches minimum speed without a recharging opportunity. Speed drop due to wear and friction may occur during standby.

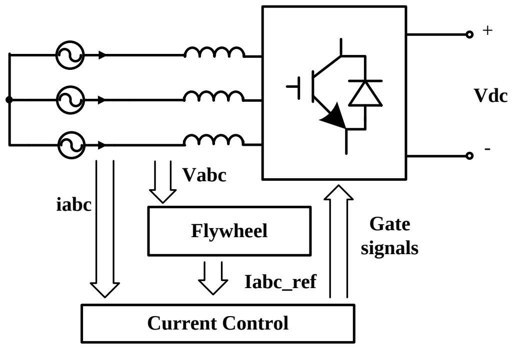


Figure 4. Flywheel emulator structure.

The duration of flywheel supplying power varies from seconds to minutes depending on various inertias for different applications.

III. FLYWHEEL EMULATOR

The electrical inputs to the flywheel system are three-phase AC stator voltage V_{abc} and electrical outputs are three-phase currents I_{abc}. The electrical characteristics are also determined by the mechanical relations with the rotation speed ω.

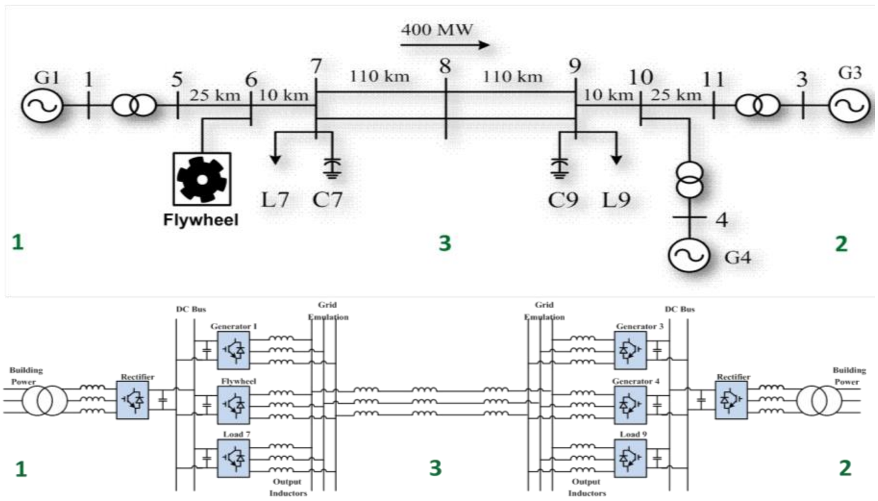


Figure 5. Two area system emulation with two areas and transmission line emulators.

As illustrated in Fig. 4, the calculation begins from sampling of three phase voltage V_{abc}. After PLL operation, frequency and angle are obtained and used as dq transformation angle reference.

The flywheel's model is described in dq domain with relations among voltage, current, and rotating speed. After each iteration cycle, i.e. each PWM calculation period in the DSP, references of three phase currents would be deduced and used as commands for the current controller to track. Finally, gate signals are generated accordingly and fed to the converter.

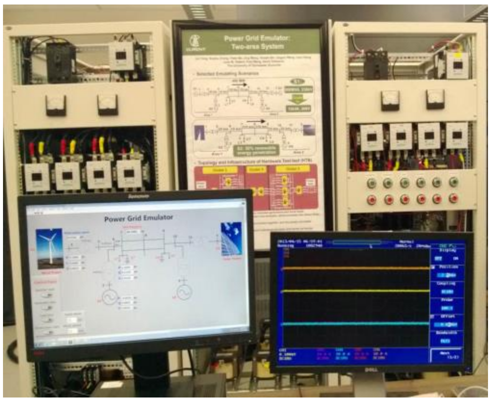


Figure 6. Actual hardware test-bed platform.

IV. Two Area System Emulation

With successful implementation of a single flywheel energy storage emulator, a two area system emulation is able to be realized to observe the energy storage's functionality inside the power system.

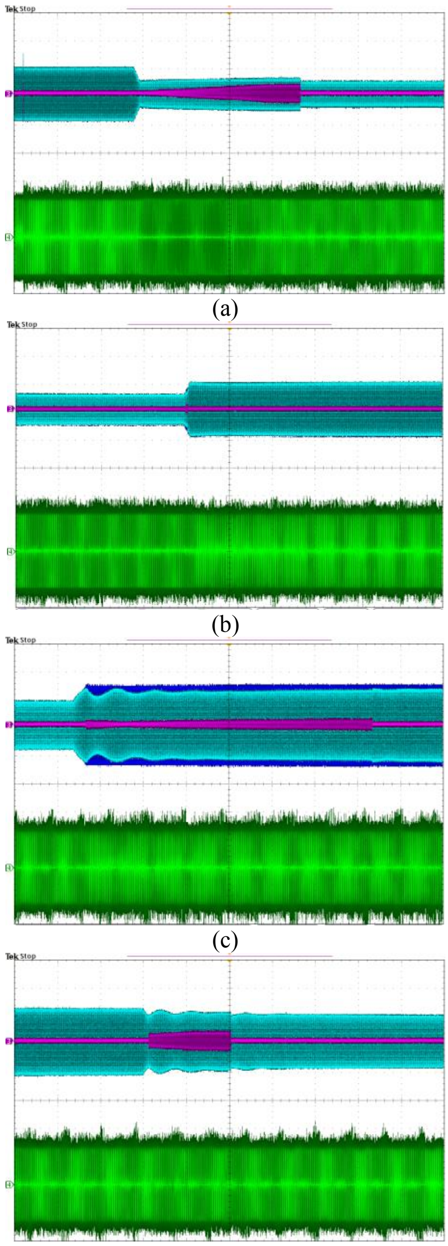
An emulation scenario shown in Fig. 5 has been established with hardware construction shown in Fig. 6. Each cabinet represents a single area unit with visualized control operations by Labview.

The test system represents a 400 MW power system. After scaling down the emulated grid ratings to per unit values, power electronics rated base power is used to accommodate the actual power flow in the hardware test-bed platform.

As could be observed from Fig. 7, the flywheel is operating in association with the generation and load units. Fig. 7(a) represents the acceleration procedure of the flywheel by means of constant torque followed by constant power. Figure 7(b) shows the standby mode (not absorbing or supplying) when the load and generation are balanced. The energy storage supplies power for a couple of seconds while the generator 1's output fluctuates a little because of the jumping up on load 7 bus until the flywheel decelerates to ω_{min} in Figure 7(c). Figure 7(d) represents a similar case as 7(c) but with larger feeding current leading to shorter duration.

V. Conclusion

With realization of the energy storage emulator, the related power system dynamics analysis and emulations could be designed and implemented in many ways. Some of these include percentage determination of the energy storage systems used in wind energy penetration for grid stablity, as well as the benefits and disadvantegs of different installation locations of energy storage systems, etc.



(a) (b) (c) (d)

Figure 7. Flywheel hardware test-bed experimental waveform

light blue: G1 output current, **purple:** flywheel output, **dark blue:** Load 7 current, **green:** bus 1 voltage.

(a) acceleration mode. (b) standby.

(c) deceleration until speed reaches ω_{min}.

(d) deceleration with shorter duration.

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