Flywheel Energy Storage Systems for Ride-through Applications in a Facility Microgrid

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***Abstract*—Flywheel energy storage (FES) has attracted new interest for uninterruptable power supply (UPS) applications in a facility microgrid. Due to technological advancements, the FES has become a promising alternative to traditional battery storage technologies. This paper aims at developing a tool to demonstrate the use of FES units for securing critical loads during a utility outage in a microgrid environment. The FES is modeled, simulated and evaluated in the MATLAB/SIMULINK® environment. A data center is used to represent a facility microgrid case study. It illustrates how an FES can help improve the load serving capability and provide a highly reliable ride-through capability for critical loads during a utility disturbance. In comparison with batteries, the application of FES for power security is new on the horizon. This limits the availability of experimental data. The simulation model presented in this paper will enable the analysis of short-term ride-through applications of FES during an islanded operation of a facility microgrid. As a result, it can provide a guideline for facility engineers in a data center or other types of facility microgrids to better design their backup power systems based on FES technology, which can be used in combination with traditional fuel-based generators.**

***Index Terms*—Data centers, energy storage, flywheel, islanded operation, microgrid.**

NOMENCLATURE

E :	Energy of flywheel (kW-s).
$E_{\rm stored}$:	Stored energy in flywheel (kW-s).
P :	Power of flywheel (kW).
m :	Rotating mass (kg).
v :	Linear speed (m/s).
ω :	Angular speed (rad/s).
$\omega_{\max}$:	Maximum angular speed (rad/s).
r :	Radius of flywheel(m).
J :	Polar moment of inertia (kg.m^2).
ρ :	Density of rotating mass (kg/m^2).
l :	Length of flywheel (m).
K_0 :	Torque conversion factor.
$\eta_{\rm fw}$:	Efficiency of flywheel.

Manuscript received August 15, 2011; revised October 12, 2011, May 09, 2012; accepted July 23, 2012. Date of publication September 04, 2012; date of current version December 28, 2012. This work was supported in part by the U.S. National Science Foundation under Grant ECCS-0901410. Paper no. TSG-00351-2011.

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Digital Object Identifier 10.1109/TSG.2012.2212468

I. INTRODUCTION

FLYWHEEL energy storage (FES) devices are appearing as viable alternatives to other types of battery storage technologies for securing critical loads during momentary power interruptions. Flywheel refers to a rotating mass that stores energy in the form of kinetic energy. It can serve as a short-term backup power source when the main energy source fails. The FES has been deployed in many applications, which include—but are not limited to—space systems, telecommunications, and data centers.

This paper discusses specifically the application of FES in a data center microgrid. Due to the proliferation of the Internet and web-based activities together with cloud computing, data centers have become a significant and growing power consumer. Data centers cannot tolerate even a momentary interruption. Therefore, backup power is a vital part of such microgrids.

Conventionally, backup power units consist of batteries and diesel generators. Batteries handle critical loads before diesel generators startup. Batteries are mature technologies, but flywheels have better characteristics in terms of higher efficiency, compactness, footprint, and operation temperature for data center applications [1].

This paper focuses on developing a software tool to model, analyze and simulate the use of FES units in a facility microgrid. The proposed tool includes a library of selected commercial FES systems. A user can also create any customer-defined flywheels by entering certain parameters. The tool is developed in the MATLAB/SIMULINK® environment with a user friendly graphical user interface (GUI). MATLAB/SIMULINK® is a powerful simulation environment that has the ability to model and simulate different power systems. Therefore, the developed FES model can be integrated into different microgrid architectures. It is expected that the proposed software tool can compensate for the lack of real data of FES through modeling and simulation.

Section II discusses review of previous work. Section III describes the competitiveness of FES as compared to traditional battery energy storage in a facility microgrid. Section IV discusses mathematical formulation of FES in MATLAB/SIMULINK®. The FES simulation model is discussed in Section V, together with the model validation. The case study of a facility microgrid, based on a data center, is presented in Section VI to demonstrate how a FES can help improve the load serving capability during an islanded operation of a microgrid.

II. Review of Previous Work

Along with the rapid increase in electricity demand in data centers, many previous publications focus on topics related to their power management, which are, for example, approaches for determining demand reduction [2] or minimizing total electricity costs using selected optimization techniques and demand response [3], [4]. There are not many publications that address issues of back-up power and energy storage units in data centers. These systems are crucial for maintaining continuous operation of a data center microgrid and can provide ride-through capability for sensitive loads.

Traditionally, energy storage systems in data centers are battery-based [5]. Available literatures in this field are related to energy storage modeling and analysis for stand-alone power systems or uninterruptable power sources. Authors in [6], [7] discuss different control approaches for battery-based back-up power systems. While most of data center energy storage technologies are based on batteries, flywheels have gained more attention in recent years as they can provide ride-through capability for critical loads in a data center.

Previous works on modeling and analysis of flywheel applications is available in the literature. Some have applied flywheels to prevent voltage sag and improve power quality [8]. Authors in [9] propose a rotary uninterruptable power supply (UPS) system based on the flywheel storage unit. Authors in [10] introduce appropriate electric machines to drive flywheels. Authors in [11] present new designs for the power electronics interface of FES. There are also papers focusing on the mechanical aspects of FES [12], [13]. Existing literatures on flywheels do not provide an insight into how FES can be used to provide ride through applications in data centers.

III. Comparison of Flywheels and Batteries

Flywheels are emerging technology with specific characteristics that make them viable energy storage system in comparison to batteries. This section investigates the competitiveness of flywheels against batteries.

Flywheels have higher efficiency. They can cause overall energy cost reduction in data centers [1]. Flywheels have higher life cycle with little decrease in efficiency [14]. Flywheel has fewer footprints and generates less heat than batteries. Also, flywheels operate in ambient temperature. These factors can result in the tremendous less cooling system requirements. Furthermore, battery rooms need separate ventilation system for toxic gases evacuation [15].

Above all, batteries are susceptible to undetectable internal failures, even with regular maintenance [15]. Such these unnoticeable failures are the reason for 20% of battery based energy storage failures in data centers. The research on flywheel and battery systems' operation indicates that the failure possibility of lead-acid battery is seven times more than that of the flywheel [16].

From environmental point of view, creation, maintenance and disposing of batteries have dramatic effects on natural environment. Flywheel is a large step toward green data centers [17].

Although flywheels have many advantages over traditional battery systems, there are some challenges for deployment of flywheels in facility microgrids. Firstly, flywheels can only serve loads for a short period of time, i.e., in tens of seconds. They should therefore be used in conjunction with other types of power generation to serve the loads for longer period of time. Secondly, flywheels involve a more complex installation because they are new on the technology horizon. Furthermore, there are no established standards for operation, safety regulations for flywheels. The lack of historical operational data is also another challenge for flywheel performance analysis.

To economically compare batteries and flywheels, life cycle cost analysis, including both capital and maintenance costs, should be used. This is to account for the fact that the life of flywheels is estimated at 20 years [18], whereas that of batteries is estimated at three to five years. Therefore, batteries will need to be replaced every three to five years. The internal stand-by power consumption is 0.01% of capacity for battery and it is 1% of capacity for flywheel [19]. Based on the operational cost analysis by California Energy Commission presented in [20]—for a lead acid battery and a flywheel that have the same capacity of 250 kW (note that the battery system has 15 min backup time, while the flywheel can serve loads for 20 s at its rated capacity)—although the initial capital cost of the flywheel is more that of the battery of equivalent size, the 20-year life cycle cost calculation shows that flywheels have less cumulative ownership cost than batteries after three to four years.

IV. Short-Term vs. Long-Term Energy Storage Systems for a Data Center Microgrid

To provide power for continuous operation during a utility outage, data centers typically deploy diesel generators coupled with a battery UPS system. Critical loads (IT and some lighting loads) are connected to the battery UPS, and backed up with diesel generators. At the moment of outage, UPS will handle the transient and momentary interruption until the diesel generator output achieves proper voltage and frequency. The recommended ride-through time for a battery UPS system is 15 min. Alternatively, a backup power system can be designed with less ride-through time using a more reliable storage technology, like flywheels, in combination with back-up generators [21]. A flywheel unit can typically serve connected loads at its rating for 10–20 s depending on its specifications. This is enough time for a diesel generator to startup.

This section focuses on the idea that 15 s energy storage is enough for data center applications. In fact, the 15-min ride-through time of batteries is superfluous for the following reasons: Firstly, 1 min was assumed for a "soft shutdown" of protected computer loads. However, for a data center a "soft shutdown" is intolerable [16]. Secondly, it is not logical to perform a "second crank" on a standby diesel generator after waiting 15 min. In the rare case that the engine does not start during the first 5–6 s, it is unlikely it will start in the next 15 min [21]. Finally, the 15-min ride-through time has a destructive impact on the thermal runaway in the servers. After outage, IT loads have the highest priority to serve with batteries. Therefore, cooling system shutdowns and it cause dramatically temperature increase in servers. The research on data centers [16] shows that in a reliable designed backup power system, diesel generators should start within 5–6 s after outage to avoid thermal runaway in servers. Therefore, backup generators starts in case of any failure and emergency without considering the type of energy storage system. The 15-s flywheel operation time should provide sufficient starting up time for diesel generators.

V. Mathematical Formulation of Flywheel Energy Storage (FES)

The FES consists of a flywheel and a machine that acts both as a motor and a generator. During normal operation, the flywheel system converts electrical energy from the grid to kinetic energy using the motor. The kinetic energy is stored in the spinning flywheel. During outages or emergencies, the stored kinetic energy is converted back into the electrical energy by the generator. This energy is then transferred to the connected electrical loads.

In this paper, the flywheel model is developed based on the mathematical equations for kinetic energy in a rotating mass. Two components affect the flywheel performance: the polar moment of inertia and the rotational speed [22], [23]. Equation (1) represents the kinetic energy formula. This is the equation to calculate the stored energy in a body of mass m moving in a straight line with the velocity v [22]:

$$E = \frac{1}{2} m \cdot v^2 \tag{1}$$

The above formula implies that a body of mass m can store more energy within a higher velocity. A flywheel is a rotating mass; therefore, (1) can be rewritten based on the angular speed ω, as shown in (2). The flywheel radius is r:

$$E = \frac{1}{2} m \cdot (r \cdot \omega)^2 \tag{2}$$

The other important factor used to model the flywheel energy storage is the polar moment of inertia J. It has the unit of mass multiplied by the radius squared. For the straight solid cylinder with radius r, the polar moment of inertia is [23]

$$J = \int r^2 \cdot dm = m \cdot r^2 \tag{3}$$

Flywheel mass m with density ρ and length l can be represented as

$$m = \pi \cdot \rho \cdot l \cdot r^2 \tag{4}$$

Substituting (4) into (3), polar moment of inertia can be represented as (5).

$$J = \pi \cdot \rho \cdot l \cdot r^4 \tag{5}$$

Considering (2), (4), and (5) the stored kinetic energy in a flywheel can be achieved from (6), where J is the polar moment of inertia and $\omega_{\max}$ is the maximum angular speed of flywheel.

$$E_{\text{stored}} = \frac{1}{2} \cdot J \cdot \omega_{\max}^2 \tag{6}$$

$\omega_{\max}$ depends on the material characteristics of the flywheel and is available from flywheels datasheets. For design purposes, $\omega_{\max}$ can be calculated from (7). In (7), σ is tensile strength; ρ is the density of flywheel rotor material; s is safety margin for flywheel healthy operation which is also available from manufacturers' datasheets [24].

$$\omega_{\max} = s \cdot \frac{1}{r} \cdot \sqrt{\frac{\sigma}{\rho}} \tag{7}$$

Equation (8) shows that the angular speed during a discharge period yields to a piecewise-defined function [11]. Flywheel discharging has two regions: the constant speed and exponential reduction speed.

$$\omega(t) = \begin{cases} \omega_{\max} & t \leq T \\ \omega_{\max} \cdot e^{-\frac{K_0}{J} \cdot t} & t \geq T \end{cases} \tag{8}$$

K_0 is the torque conversion factor from mechanical to electrical energy. T is the time duration of flywheel rotation in the $\omega_{\max}$ speed. For commercial flywheels, T is available in datasheets. To find T in design cases, the engineering rule of thumb is applied in (9) [25]. The $P_{\max}$ is the maximum nominal power of the flywheel.

$$T = \frac{J \cdot {\omega_{\max}}^2}{2 \cdot P_{\max}}. \tag{9}$$

The flywheel discharging characteristic is explained with the (10) and (11) [11]. Replacing ω in (6) with $\omega(t)$ from (8) leads to (10):

$$E = \frac{1}{2} \cdot J \cdot \omega(t)^2 \tag{10}$$

The power of flywheel at exponential region is the derivative of energy in (9) with respect to the time:

$$P = \begin{cases} P_{\max} & t \leq T \\ \eta_{\text{fw}} \cdot \omega_{\max}^2 \cdot e^{-\frac{2K_0}{J} \cdot t} & t \geq T \end{cases} \tag{11}$$

The η_{fw} is efficiency of flywheel. This factor takes into account the required energy in order to keep the flywheel spinning, or the flywheel standby loss. The full load standby loss of a flywheel is from 0.2% to 2% of the total capacity depending on manufacturers [26]. Flywheel UPS consists of the flywheel and the power electronics components. According to the literature and the manufacturers' data sheets, flywheel UPS efficiency is in the range of 95% to 98% [27].

VI. FES Modeling and Simulation Tool

A. Overview of the FES Simulation Tool

Equations (10) and (11) are the basis for the proposed flywheel modeling and simulation tool. The tool is developed in the MATLAB/SIMULINK® environment with a user friendly GUI. Several commercially available flywheels have been modeled as a part of the proposed FES simulation tool. Users have two choices for FES simulation, either to use commercial FES models in the developed flywheel library or to customize their own FES.

Fig. 1 illustrates the generic block diagram of the FES model developed in MATLAB/SIMULINK®. As shown, the FES

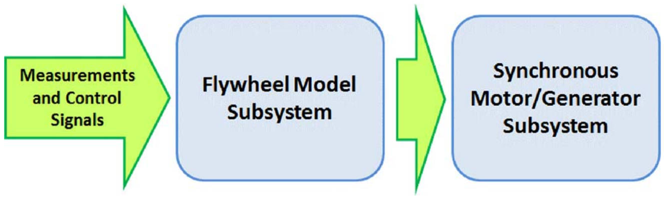

Fig. 1. Generic block diagram of the proposed FES model in MATLAB/SIMULINK®.

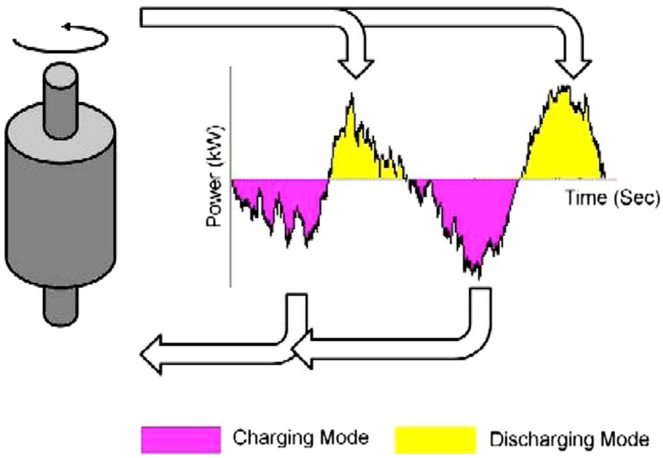

Fig. 2. Flywheel control signal for charging and discharging modes.

model is composed of two subsystems, namely the flywheel subsystem and the generator/motor subsystem.

Inputs to the FES simulation tool are: voltage and current measurements at the load bus which are the signal to control flywheel power output. For a customized flywheel model, additional flywheel characteristics are required as user-defined inputs, including flywheel maximum and minimum rotating speeds (rad/s), power capacity (kW), energy capacity (kW*s), efficiency, charging duration, discharge duration at maximum power (s), and discharge duration at half of maximum power (s). Outputs of this model are the flywheel power output (kW), energy output (kW-s) and rotating speed (rad/s).

B. The Flywheel Subsystem

The typical discharge time of a flywheel ranges from 10 to 30 s [27]–[29]. Flywheel charging from the totally discharged point to the totally charged point needs 1 to 10 min, depending on FES technologies and manufacturer designs [29], [30].

The control of FES is based on the balance of power supply and demand. If the available power is more than the load, flywheel starts charging to absorb the excess power. During a utility disturbance or lack of power, the flywheel is discharged to handle critical loads. Then, after diesel generators start and the system voltage and frequency are stabilized (ramp-in time), flywheels are recharged from the diesel generators. Fig. 2 depicts flywheel charging and discharging cycles.

The flywheel subsystem consists of the discharge and charge sections. The exponential function shown in (11) is the basis for the calculating the charging and discharging power. Figs. 3 and 4 represent the implementation of power discharging and charging functions, respectively, in the MATLAB/SIMULINK® environment.

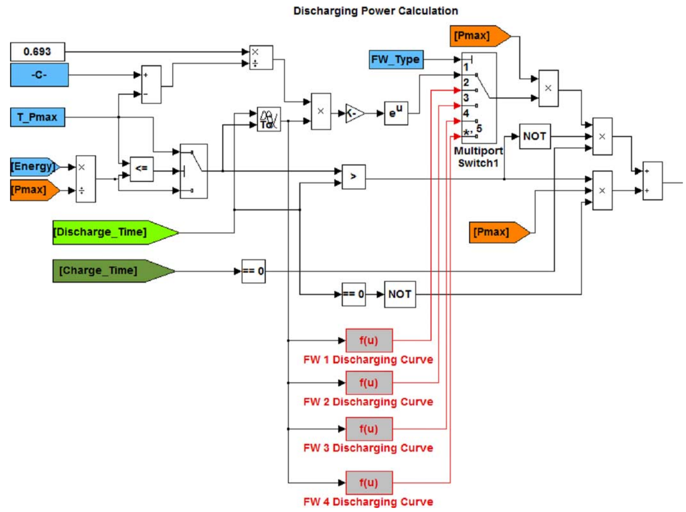

Fig. 3. Discharging section of the flywheel model.

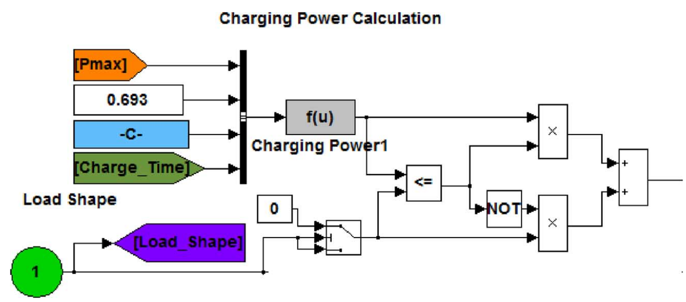

Fig. 4. Charging section of the flywheel model.

The discharging section consists of the mathematical function in (11) and a switch that is controlled by the external signal from the load bus. The discharging of FES is activated when the voltage and current measurements on the load bus indicate shortage of power.

The charging power calculation is presented in Fig. 4. This part of the model consists of the mathematical function (11) and a switch that is controlled by the signal from the load bus. The charging of FES is activated when the voltage and current measurements on the load bus indicate excess power.

The flywheel rotational speed can be calculated based on (6), which is shown in (12).

$$\omega = \sqrt{\frac{2E}{J}} \tag{12}$$

On the right hand side of (12), the flywheel energy E can be determined from the output of the developed FES model. The polar moment of inertia J can be calculated using (5) based on the manufacturer supplied information.

C. Motor Generator Subsystem

Different types of electric machines can be used in an FES. The most common types are induction machines [31], and permanent magnet synchronous machines (PMSM) [32]. In this paper PMSM is used for the FES model.

To model the motor-generator subsystem of the FES in MATLAB/SIMULINK®, the synchronous machine (SM) excitation system is performed by the standard excitation block

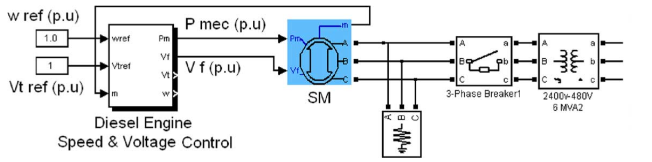

Fig. 5. MATLAB/SIMULINK® model of a synchronous motor/generator unit.

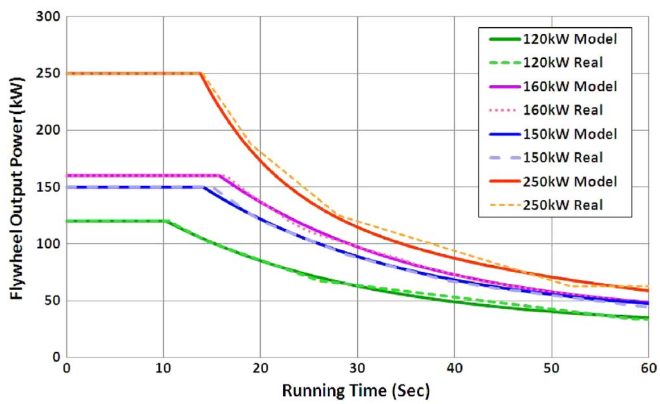

Fig. 6. Flywheel discharging characteristics for four different flywheel units.

provided in the MATLAB/SIMULINK® library. The model of diesel engine is presented in Fig. 5.

D. FES Simulation Results and Model Validation

To validate the proposed FES model, authors have developed four flywheel models of different sizes, following the specifications of four commercial flywheels available from different manufacturers: i) a 120 kW flywheel unit, ii) a 150 kW flywheel unit, iii) a 160 kW flywheel unit, and iv) a 250 kW flywheel unit.

The model outputs are compared with the manufacturers' data as presented in Fig. 6. The dashed lines are the manufacturers' data, while the solid lines are the simulation results. Fig. 6 indicates that simulation results are consistent with the flywheel's experimental data from the manufacturers. These four flywheel units are built-in into the flywheel library as mentioned earlier. Based on (11), flywheel discharging has two operation regions. In the first region, output power is constant. In the second region, output power has exponential decreasing trend.

Each flywheel unit has a specific running time. If there is a need for a longer running time, more flywheel units can be paralleled.

The tool developed and presented in this paper also helps the user to find a sufficient number of flywheels for a specific running time. The tool can demonstrate the output of multiple flywheel units connected in parallel. It calculates the running time for each case. Fig. 7 illustrates how additional flywheels in parallel can meet the load for a longer time. In this case, to achieve 750 kW power for 20 s, at least three 250 kW flywheels should be paralleled. Four 250 kW flywheels can serve the 750 kW load for 33.4 s.

VII. The Case Study

The developed FES model is coupled with a diesel generator in the case study of a data center, as described below. This case study aims at demonstrating the impact of flywheel on the load serving capability and frequency of a data center power system during a utility disturbance.

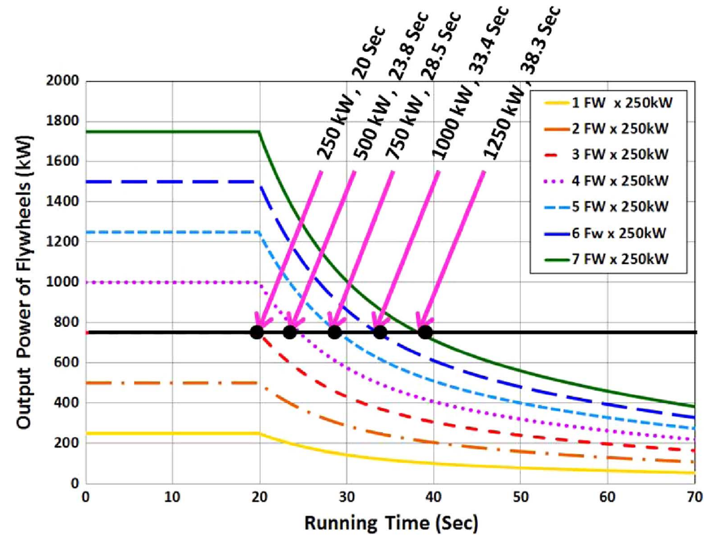

Fig. 7. Different running times for different numbers of 250 kW flywheel units connected in parallel.

TABLE I
Specifications of A Data Center

PEAK LOAD	1.55 MW
BACKUP SYSTEM	• Flywheel UPS
COOLING SYSTEM	• Evaporative chilled water system
POWER	• Secured from two substations • Northern Virginia Electric Cooperative (NOVEC) supplies power
ELECTRICAL INFRASTRUCTURE	• N+1 system • 2x2.1 MW diesel generators • Primary voltage: 34.5 kV • Secondary voltage: 480 V • Multiple power and cooling paths • 120 hours diesel fuel storage at full load

A. The System Specification

To analyze the impact of a flywheel operated in parallel with a diesel generator to provide backup power for data center loads, a realistic set of specifications from a data center in Virginia is taken into account. Table I presents electrical specifications of the case study [33].

Since the power system configuration of any data center is confidential, the $N+1$ power system architecture, available in the IEEE 493-2007 standard [34], is used to allow modeling and simulation of the FES in a data center presented in this study. See Fig. 8. In this system, the primary system voltage is 34.5 kV, and the secondary voltage is 480 Volts.

As shown in Fig. 8, there are two parallel diesel generators that connect to the generator switchboard to provide backup power for a data center. One of the two generators operates in emergency conditions $(\mathrm{N_{gen}}+1, \mathrm{N_{gen}}=1)$. The other generator serves as a backup. There are four parallel flywheel systems and at any given time. Three of them are connected to sensitive

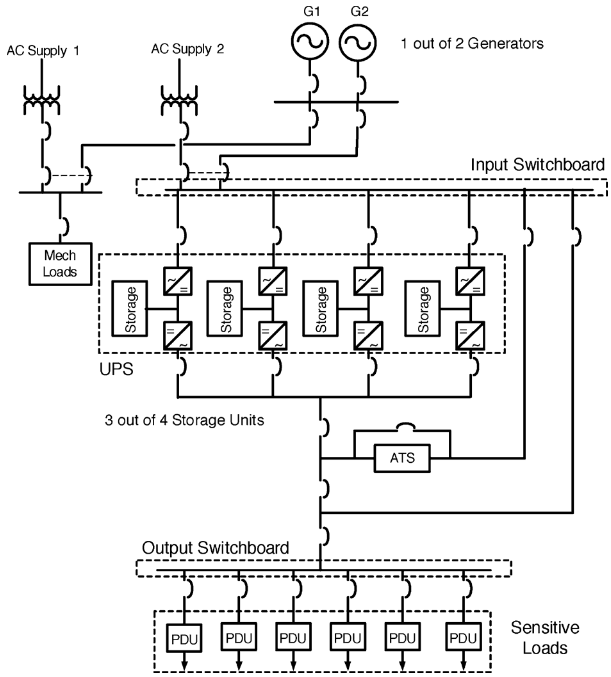

Fig. 8. (N + 1) backup power architecture for a data center in accordance to the IEEE 493-2007 [35].

loads ($\mathrm{N_{FW}} + 1, \mathrm{N_{FW}} = 3$) and one is an extra unit; therefore it has the $\mathrm{N} + 1$ architecture. "G" represents diesel generator, "ATS" represents automatic transfer switch, and "PDU" is power distribution unit.

B. Scenario Description

Of all data center loads, the HVAC loads—which constitute about 50% of the total load-can be interrupted momentarily. On the other hand, all IT and computing hardware, such as computers, servers, routers, storage devices, telecom devices and some lighting loads, need uninterruptible power supply. These critical loads constitute approximately the other 50% of the total data center loads. Therefore, the size of flywheels should be designed accordingly to cover all critical loads in the data center, which is 750 kW (three out of four 250 kW units operating at the same time) during back-up generator startup in the test case being studied.

During a disturbance, the FES systems operate to support critical loads. If the outage lasts for more than 5 s, the diesel generator will start and take over all data center loads. This time is typically 10 s [35]. After the electricity is restored, the diesel generator should be operated for extra 5 to 15 min. This extra operation time helps the generator to have the "cool-down period" before shutting down [36]. The cool-down period is vital for the diesel generator life cycle. Additionally, the flywheel will be charged by the generator during this time, if needed.

VIII. Simulation Results

Fig. 9 illustrates the simulation results, showing the operation of the flywheels and the diesel generator when a utility outage occurs at $\mathrm{t} = 0$ s. The solid line is the total load of the system (kW) and the dashed line is the diesel generator power output (kW). At the time of the power outage ($\mathrm{t} = 0$), flywheels operate to provide ride-through capability for the critical loads

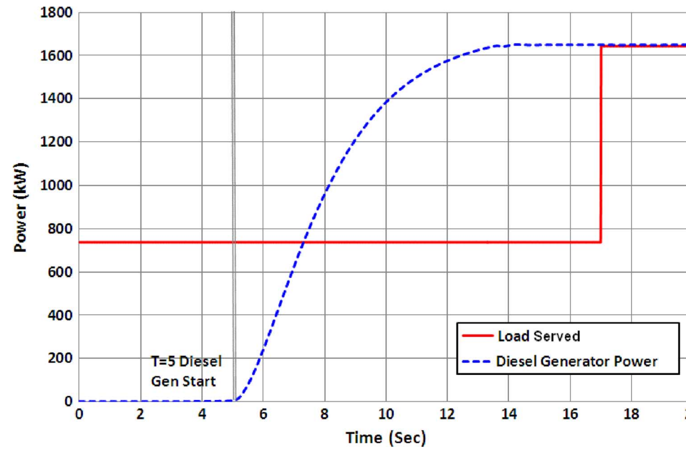

Fig. 9. Snapshot of electrical power (kW) at the load bus after the outage.

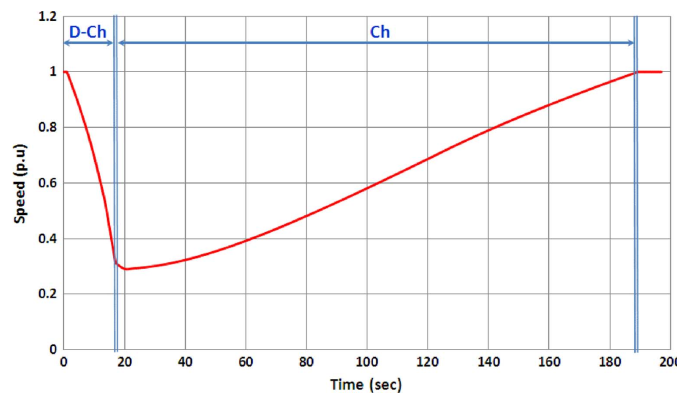

Fig. 10. Flywheel speed during charging and discharging periods: D-Ch and Ch indicate flywheel discharging and charging periods, respectively.

(750 kW). Since the outage is longer than 5 s, the diesel generator starts ($\mathrm{t} = 5$ s). After the diesel generator has synchronized with the system ($\mathrm{t} = 17$ s), the rest of the data center loads are served, and the flywheel changes from its discharging mode to its charging mode.

At this time, the load served (the solid line) is the total data center load plus the flywheel charging. The generator output (dashed line) matches both the data center load and the flywheel charging load. Once the flywheel is fully charged ($\mathrm{t} > 190$ s—not shown), the diesel generator output will decrease to the total data center load level.

Fig. 10 shows the flywheel speed during its operation. During the first 5 s, the flywheels discharge to serve the critical loads and the flywheels' speed decreases. The system waits for 5 s to confirm that it is the real power outage before starting the diesel generator. Once the generator starts at $\mathrm{t} = 5$ s, it takes some time—as shown in the simulation results—before it can fully synchronize with the system and serve the loads at $\mathrm{t} = 17$ s. After picking up the loads, the generator charges the flywheels until $\mathrm{t} = 190$ s. The flywheels charging time is in accordance with the charging range, 2–3 min, indicated by the flywheel manufacturer [36]. During the charge period, the flywheels speed increases, as indicated in Fig. 10.

In addition to providing continuous power supply, flywheels also stabilize the frequency at the load bus. Fig. 11 presents frequency deviation at the load bus during the simulation. The solid line represents frequency response of the system with flywheels.

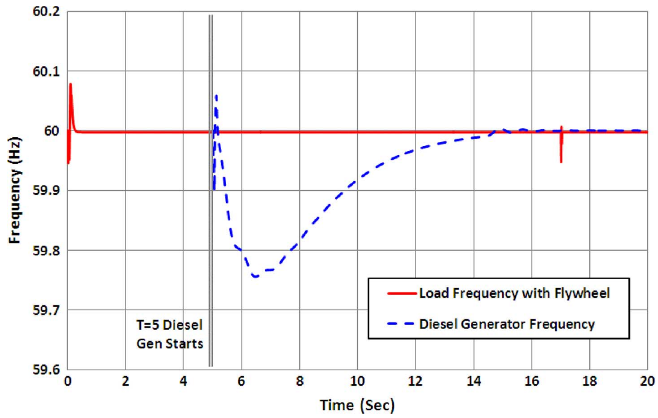

Fig. 11. The frequency deviations after the power outage with flywheels (solid) and without flywheels (dashed).

The dashed line shows frequency response of the diesel generator after it starts at $t = 5$ s. Note that the frequency is stabilized at around $t = 16$ s before the diesel generator synchronizes with the system at $t = 17$ s.

Fig. 11 indicates that flywheels can significantly decrease the system frequency deviation. During its startup ($t = 5$–17 s), the generator frequency goes down as low as 59.75 Hz. This results in the system frequency deviation of 0.25 Hz from the nominal frequency of 60 Hz. With the flywheels, the maximum frequency deviation decreases to 0.06 Hz. This deviation meets the maximum allowable frequency deviation for sensitive loads of 0.12 Hz or 0.2% of the normal frequency [37].

IX. Conclusion

This paper presented a tool for modeling and simulation of a flywheel energy storage (FES) system in a microgrid environment. The FES model was validated by comparing simulation results with manufacturer supplied data. To demonstrate the use of the developed FES model, a case study of a facility microgrid based on a data center application was presented. This study showed the operation of the FES coupled with a diesel generator to serve the data center's critical loads during a utility outage. Results indicated that the FES, coupled with the generator, can deliver secure and resilient power to support critical loads during a utility outage. Since FES applications to provide power security and resiliency for a mission-critical facility are new on the horizon, there is a lack of experimental data for use in microgrid studies. The proposed software tool bridges this gap by enabling facility engineers and system designers to run several what-if analysis scenarios—that is, to analyze the operation of a facility microgrid with the incorporation of a FES system coupled with traditional fuel-based generators as a backup power source.

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